RESEARCH PAPER

Nanoparticle and Microplastic Exposure in Textile Manufacturing: Neurotoxicological Mechanisms, Occupational Mental Health, and a Public Health Research Agenda for South Asia

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Abstract

Textile manufacturing is one of the world's largest employment sectors, with the International Labour Organization estimating approximately 90 million workers in the global textile and garment industry, more than half of whom are women and many of whom are concentrated in South and Southeast Asia (International Labour Organization, 2025). Workers involved in textile finishing, stitching, coating, and mechanical processing may experience occupational exposure to engineered nanoparticles and nanoscale microplastic fragments generated during textile production and processing. Despite growing concern regarding such exposures, their potential implications for workers' psychological and neurological health remain insufficiently understood.

This narrative review synthesizes four interconnected evidence streams—occupational exposure assessment, mechanistic nanotoxicology, human biomonitoring, and textile-worker mental health—to examine whether a testable public health question emerges at their intersection. Experimental evidence from animal and cell-culture studies indicates several biologically plausible pathways through which nanoparticle exposure may influence neurological and behavioral functioning, including blood–brain barrier translocation, oxidative stress, and neuroinflammatory processes. However, the exposure levels used in many experimental studies substantially exceed those documented in occupational settings, limiting direct extrapolation to workers. Human biomonitoring studies among nanomaterial-exposed workers have demonstrated physiological changes, but available evidence has not established significant neurobehavioral associations and has rarely integrated exposure biomarkers with validated psychological assessment instruments. In parallel, research on textile workers has documented elevated levels of depression, anxiety, and occupational stress, although these outcomes have predominantly been attributed to psychosocial and organizational working conditions rather than potential environmental or nanomaterial exposures.

This evidence gap highlights the need for an integrated occupational health framework that simultaneously considers chemical, physical, and psychosocial determinants of workers' mental health. Pakistan's Sialkot region represents a potentially valuable setting for such research because of its extensive textile and adjacent manufacturing activities and the availability of relevant occupational and biomonitoring infrastructure. We therefore propose a staged cohort study that combines objective exposure biomarkers with validated psychological and neurobehavioral instruments while controlling for psychosocial job strain and other relevant occupational and demographic confounders. Such an approach could help determine whether occupational exposure to engineered nanoparticles and nanoscale textile-derived particles is associated with measurable psychological or neurobehavioral outcomes and, ultimately, facilitate evidence-based occupational health policy and preventive strategies in resource-limited settings.

Keywords: nanotoxicology; engineered nanoparticles; microplastics; textile industry; occupational exposure; blood–brain barrier; neuroinflammation; occupational mental health; South Asia

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Introduction

Textile manufacturing is one of the world's largest employment sectors. The International Labour Organization estimates that approximately 90 million people are employed globally in the textile and garment industry, with women comprising a substantial proportion of the workforce and employment concentrated heavily in South and Southeast Asia (International Labour Organization, 2025). Although textiles are not traditionally considered a major focus of nanotoxicological research, nanoscale materials are increasingly incorporated throughout the textile production chain. Nanoparticle-based coatings, including silver, titanium dioxide, zinc oxide, and silica, are used to impart antimicrobial, odor-resistant, ultraviolet-protective, and other functional properties to fabrics. Nanoscale photocatalysts are also increasingly investigated for applications in dye degradation and textile-effluent treatment. In addition to intentionally engineered nanomaterials, mechanical processes such as cutting, weaving, brushing, washing, and abrasion can release synthetic microfibers and potentially nanoscale plastic fragments into workplace air and wastewater. These materials may subsequently enter surrounding environmental systems, including rivers, soils, and food chains, raising broader occupational and environmental health concerns.

Nanotoxicological research has provided substantial evidence regarding the biological behavior and potential toxicity of engineered nanoparticles following exposure. Particle characteristics, including size, morphology, surface charge, and surface chemistry, influence absorption, distribution, metabolism, clearance, and tissue accumulation. Importantly, some nanoparticles may overcome biological barriers that were historically considered highly restrictive, including the blood–brain barrier (Karmakar et al., 2014; Boukholda et al., 2026). Following entry into neural tissues, nanoparticles may induce oxidative stress, neuroinflammation, microglial activation, mitochondrial dysfunction, and alterations in neurotransmitter systems, providing biologically plausible pathways through which particulate exposure could influence neurological and behavioral functioning (Boukholda et al., 2026; Win-Shwe & Fujimaki, 2011). Evidence involving silver, titanium dioxide, zinc oxide, and silica nanoparticles further suggests that, despite differences in physicochemical properties and toxicokinetic profiles, oxidative stress and inflammatory signaling represent recurrent mechanisms of nanoparticle-associated neurotoxicity (Chen et al., 2026; Sanchez-Cano et al., 2024; Song et al., 2015).

Despite advances in experimental nanotoxicology, an important gap remains between mechanistic evidence and human occupational research. Boyes and van Thriel (2020) noted the limited availability of standardized neurobehavioral assessment among workers occupationally exposed to engineered nanomaterials, despite evidence of alterations in inflammatory and oxidative-stress biomarkers in exposed populations. Similarly, Bencsik et al. (2018) identified nano-neurotoxicology as an emerging field and highlighted the scarcity of epidemiological research specifically examining neurological outcomes among nanomaterial-exposed workers. Consequently, evidence demonstrating that nanoparticles can affect neural systems under experimental conditions has not yet been adequately translated into evidence concerning psychological and neurobehavioral outcomes in occupationally exposed human populations. This distinction is particularly important because experimental studies frequently involve exposure concentrations or routes that may differ substantially from those encountered in real-world workplaces.

The present review addresses this evidence gap through an interdisciplinary perspective integrating analytical and environmental chemistry with clinical psychology and occupational mental-health research. One component of the research partnership focuses on heavy-metal analysis, green nanomaterial synthesis, and photocatalytic dye degradation, areas directly relevant to textile production and wastewater treatment. The psychological component focuses on psychological well-being and mental-health outcomes among populations experiencing occupational and environmental stressors. This interdisciplinary approach provides a framework for examining whether occupational exposure to nanoscale particulate matter may represent an overlooked contributor to psychological health in textile workers, while recognizing that psychosocial working conditions remain important determinants of occupational mental health.

Pakistan provides a particularly relevant context for developing this research agenda. Textile production represents an important component of the country's industrial economy, while several industrial regions have experienced documented environmental contamination and occupational exposure concerns. In Sialkot, for example, more than a decade of biomonitoring research in adjacent industrial sectors, including leather processing and surgical-instrument manufacturing, has documented exposure to heavy metals and related environmental contaminants

(Junaid et al., 2016; Junaid et al., 2017a; Junaid et al., 2017b). However, this existing infrastructure should not be interpreted as evidence that the specific relationship between textile-related nanoscale exposure and psychological well-being has already been investigated. Rather, the established biomonitoring capacity in adjacent industrial settings makes Sialkot a potentially feasible location for extending occupational exposure research to the textile sector. To our knowledge, the critical question of whether exposure to engineered nanoparticles and textile-derived microplastic or nanoplastic particles is associated with workers' psychological well-being remains insufficiently investigated in Sialkot and comparable South Asian textile-producing regions.

Importantly, nanoscale exposure in textile environments should not be conceptualized as a single homogeneous hazard. As summarized in Table 1, three broad exposure classes can be distinguished. **Exposure Class A** comprises engineered nanoparticles, including silver, titanium dioxide, zinc oxide, and silica, that may be deliberately incorporated into textile finishing and related applications. **Exposure Class B** comprises synthetic microfibers and potentially nanoplastic particles generated unintentionally through mechanical processing, abrasion, washing, and laundering of synthetic textiles. **Exposure Class C** comprises chemically distinct co-exposures, including potentially endocrine-disrupting compounds associated with dyes and finishing agents. The primary focus of this review is Exposure Classes A and B because both represent particulate exposures for which oxidative stress, inflammatory signaling, and potential interactions with the blood–brain barrier provide plausible mechanistic pathways relevant to neurological and psychological outcomes. Exposure Class C is therefore considered primarily as a potential co-exposure and confounding factor rather than as a component of the nanoscale particulate exposure construct.

Taken together, the available evidence identifies a critical translational gap between experimental nanotoxicology, occupational exposure assessment, and textile-worker mental-health research. Experimental studies provide plausible biological mechanisms linking nanoscale particulate exposure with neural effects, while occupational studies have documented physiological responses to some nanomaterial exposures. Separately, research among textile workers has reported psychological difficulties associated with demanding and stressful working environments. However, these evidence streams have rarely been integrated within a single empirical framework. Addressing this gap requires research that combines objective exposure assessment with validated psychological and neurobehavioral measures while accounting for established psychosocial and occupational risk factors. Such an approach could determine whether nanoscale particulate exposure represents an independent or contributory factor in workers' psychological health and could provide evidence relevant to occupational-health surveillance, exposure prevention, and public-health policy in textile-producing regions of South Asia.

Review Methods

This study employed a narrative review design. A formal review protocol was not registered, study selection was not conducted through independent dual screening, and a standardized quality-appraisal instrument was not applied systematically to every included study. Accordingly, the review should not be interpreted as a PRISMA-compliant systematic review. These methodological limitations are acknowledged explicitly, and a future publication-track systematic review should incorporate protocol registration, independent duplicate screening, and formal risk-of-bias assessment.

The literature search covered five closely related domains. The first focused on engineered nanoparticles used in textile manufacturing and associated occupational exposure pathways. The second examined the generation, release, and environmental dissemination of microplastic and nanoplastic particles during textile production, mechanical processing, washing, and laundering. The third addressed nanotoxicological mechanisms potentially linking nanoscale particulate exposure with neurological and neurobehavioral outcomes, with particular attention to blood–brain barrier translocation, oxidative stress, neuroinflammation, and the gut–brain axis. The fourth domain examined occupational mental-health outcomes among textile and garment-sector workers, including depression, anxiety, psychological distress, and work-related stress. A fifth, more geographically focused search examined heavy-metal exposure and industrial biomonitoring research conducted in Pakistan, particularly in and around the Sialkot region, to assess the feasibility and contextual relevance of extending exposure-monitoring approaches to textile workers.

Searches were conducted using PubMed/MEDLINE, ScienceDirect, Frontiers journals, and literature indexed through Google Scholar. Because the fields of nanotoxicology, microplastic research, and digital exposure assessment are rapidly evolving, the search emphasized literature published between 2020 and 2026. Earlier studies were retained when they represented foundational or otherwise primary evidence for a specific mechanism, exposure-assessment method, or occupational-health finding. The final searches across the five domains were completed in June 2026. Following application of the predefined eligibility criteria, 51 sources were retained and cited in the present review.

Sources were considered eligible when they provided original empirical evidence, experimental or mechanistic findings, or systematic/scoping reviews directly relevant to at least one of the principal domains of the review: engineered-nanoparticle or microplastic toxicology, occupational exposure assessment, textile-related particulate exposure, or mental health among textile and garment workers. Relevant publications from recognized regulatory, governmental, or standards organizations were also considered where they provided authoritative occupational-health or exposure information, including material from agencies such as the Occupational Safety and Health Administration (OSHA) and relevant Government of Punjab sources. Conference abstracts without accessible full-text reports, non-peer-reviewed preprints, publications unavailable in English, and sources lacking sufficient information to evaluate their relevance were excluded. Where multiple publications appeared to report substantially overlapping findings from the same cohort or dataset, the most complete or methodologically informative report was prioritized to minimize duplication.

The evidence was synthesized narratively rather than quantitatively because the included literature differed substantially in study populations, exposure characteristics, particle types, experimental models, outcome measures, and methodological approaches. Particular attention was given to convergence and divergence across experimental, occupational, environmental, and psychological evidence streams. Mechanistic findings were interpreted cautiously in relation to human occupational exposure, recognizing that experimental exposure conditions may not correspond directly to workplace concentrations. Similarly, associations between occupational stress and mental-health outcomes were considered alongside, rather than replaced by, the proposed contribution of nanoscale particulate exposure.

The methodological approach has several limitations. Because this was a narrative review, the search and selection process may be subject to publication, selection, and reviewer bias. The absence of independent duplicate screening and a formal study-level risk-of-bias assessment limits the extent to which the review can provide systematic estimates of the strength or consistency of the evidence. Furthermore, the heterogeneous nature of the available literature prevents direct quantitative comparison across exposure categories and outcomes. These limitations are particularly important when translating mechanistic evidence from experimental models into hypotheses concerning human occupational health.

A future systematic review designed for independent publication should build on this preliminary synthesis by prospectively registering a protocol, reporting the search and selection process in accordance with PRISMA guidance, conducting independent duplicate screening and data extraction, and applying validated risk-of-bias or methodological quality-assessment instruments appropriate to each study design. For observational occupational-health studies, for example, an instrument such as the Newcastle–Ottawa Scale could be considered alongside more contemporary risk-of-bias frameworks. Such an approach would provide a more reproducible assessment of the available evidence and help determine the strength of evidence linking nanoscale occupational exposures with psychological and neurobehavioral outcomes among textile workers.

Nanomaterials in the Textile Industry

Why Nanotechnology Entered Textile Manufacturing

Nanoscale Materials in Textile Manufacturing

Nanoscale additives address a longstanding challenge in conventional textile chemistry: achieving durable functional properties—such as antimicrobial activity, stain resistance, ultraviolet (UV) protection, and self-cleaning capacity—without substantially altering the fabric's texture, breathability, weight, or appearance. The exceptionally high surface-area-to-volume ratio of nanoparticles allows relatively small quantities of material to interact with large fiber surfaces, facilitating their incorporation into functional textile products (Occupational Safety and Health Administration [OSHA], 2013). Among these materials, silver nanoparticles are among the most extensively studied because of their broad-spectrum antimicrobial properties and have been incorporated into sportswear, medical textiles, and odor-control garments (Koivisto et al., 2024). Titanium dioxide and zinc oxide nanoparticles have also received considerable attention because of their UV-absorbing, photocatalytic, and self-cleaning properties, particularly in outdoor and technical textiles (Table 2).

Occupational Exposure During Nanomaterial-Enabled Finishing

The greatest potential for direct occupational exposure occurs during textile-finishing operations in which nanoparticle-containing formulations are applied to fabrics through processes such as padding, spraying, and exhaustion. These activities may generate airborne aerosols and create opportunities for inhalation and dermal exposure. A control-banding assessment conducted in a textile-finishing facility using two nanomaterial-containing products identified potential occupational hazards associated with handling these formulations and recommended engineering controls, including local ventilation and enclosed application systems, together with appropriate personal protective equipment. Importantly, the study also highlighted a limitation in conventional hazard communication: safety data sheets for nanomaterial-containing products may provide insufficient information regarding the specific hazards associated with the nanoscale component, particularly when nanoparticles are incorporated within a larger chemical formulation (Ramos et al., 2019).

Occupational exposure may not be restricted to the period during which nanomaterials are actively applied. Nanoparticles incorporated into finished textiles can subsequently be released through abrasion, washing, and other forms of mechanical stress. Experimental leaching studies have demonstrated the release of silver nanoparticles from antimicrobial fabrics during simulated use, indicating that workers and consumers may encounter nanoparticles through multiple exposure pathways (Koivisto et al., 2024). For workers, inhalation and dermal exposure during finishing may therefore occur alongside secondary exposure arising from contaminated surfaces, clothing, or personal protective equipment. In particular, particles deposited on protective garments may become airborne again when contaminated clothing is removed or handled, potentially creating short-duration exposure peaks that may not be adequately captured by conventional area-based air monitoring (Tsai, 2015).

Accurately characterizing occupational nanoparticle exposure remains challenging. Conventional occupational exposure assessment often relies on mass concentration; however, particle number concentration and surface area may provide complementary information because biological activity for some nanoparticles appears to be related to surface characteristics rather than mass alone (O'Shaughnessy, 2013). This issue is particularly important for nanoparticles because particles with substantially different surface areas may have similar mass concentrations but markedly different biological reactivity. Recent exposure-assessment research has increasingly emphasized task-based and activity-based approaches to identify specific work processes associated with elevated airborne concentrations. Such approaches may reveal short-duration, high-intensity exposure events that can be obscured when exposure is represented only by an average concentration across an entire work shift (Galey et al., 2023). At the same time, the existing engineered-nanomaterial exposure literature remains concentrated on a relatively limited number of materials, including carbon nanotubes, titanium dioxide, and selected metal oxides, resulting in considerable extrapolation when estimating exposure in textile-specific settings (McCormick et al., 2021). This highlights the need for direct exposure characterization within textile-finishing environments rather than reliance solely on evidence generated in unrelated industrial sectors.

Microplastics and Nanoplastics From Synthetic Fibers

Alongside deliberately engineered nanoparticles, textile workers may encounter a second and largely unintentional source of nanoscale particulate exposure: microplastic and nanoplastic fragments generated from synthetic fibers. Early research primarily examined fiber release during domestic laundering; however, increasing attention is now being directed toward earlier stages of the textile life cycle. Mechanical operations such as cutting, sewing, brushing, sanding, weaving, and wet processing can subject synthetic fibers to repeated mechanical stress and may generate airborne and wastewater-associated particulate material before finished garments reach consumers (Hossain et al., 2025).

The quantity and characteristics of released fibers vary according to textile composition, construction, processing history, and degree of wear. Experimental evidence indicates that polyester fleece may release substantially more fibers than plain-woven polyester under comparable washing conditions (Carney Almroth et al., 2018). Similarly, loosely constructed knitted fabrics may shed more fibers than tightly woven materials, while damaged or chemically degraded fibers may be more prone to fragmentation than new fibers. Some evidence also suggests differences in shedding between recycled and virgin polyester, although the magnitude and direction of these differences vary according to material characteristics and experimental conditions (Akyildiz et al., 2024; Carney Almroth et al., 2018; Periyasamy & Tehrani-Bagha, 2022).

Once released into the workplace or wider environment, synthetic fibers and smaller plastic particles may interact with other contaminants. Their surfaces can adsorb metals and organic pollutants, potentially facilitating the transport of co-contaminants through wastewater, soil, aquatic systems, and ultimately food and respiratory exposure pathways (Allen et al., 2024). The scale of textile-associated microplastic release has consequently become an important environmental-health concern (Hossain et al., 2025). Industrial textile centers may represent particularly relevant exposure settings because production activities, mechanical fiber shedding, wastewater generation, and worker exposure can occur within the same localized environment. Nevertheless, the magnitude and health significance of occupational exposure to textile-derived microplastic and nanoplastic particles remain insufficiently characterized, particularly in low- and middle-income countries (Vassilenko et al., 2021).

From an occupational-health perspective, the coexistence of engineered nanoparticles and textile-derived micro- and nanoplastics is especially important. These represent distinct sources with different physicochemical properties and exposure pathways, but both may contribute to particulate exposure among workers. Consequently, exposure assessment in textile settings should distinguish between intentionally incorporated engineered nanomaterials and unintentionally generated polymeric particles rather than treating all nanoscale materials as a single exposure category. Such differentiation is essential for identifying material-specific hazards while also examining the possibility of combined or cumulative exposure.

Nanomaterials as Remediation Tools

An important complexity is that nanomaterials are not solely potential occupational hazards within the textile sector; they are also increasingly investigated as tools for reducing environmental contamination generated by textile production. Nanoparticles and nanostructured materials can function as photocatalysts for degrading dyes and other persistent organic contaminants in textile effluents, creating opportunities for more efficient wastewater treatment (Boruah & Jose, 2025). This dual role creates a critical occupational-health consideration: nanomaterials introduced into wastewater-treatment systems may themselves require appropriate containment, monitoring, and end-of-life management. Therefore, risk assessment should follow nanomaterials throughout the textile production chain—from synthesis and formulation, through textile finishing and wastewater treatment, to environmental release and disposal—rather than evaluating individual applications in isolation.

Taken together, these findings indicate that textile workers may experience exposure to nanoscale materials through multiple interconnected pathways. Engineered nanoparticles may be deliberately introduced during finishing, while Microplastic and nanoplastic particles may be unintentionally generated during mechanical processing. Nanomaterials may also be employed in wastewater treatment, creating additional occupational handling requirements. This convergence reinforces the need for integrated exposure assessment that combines task-based workplace monitoring, particle characterization, and biological measures with assessment of relevant psychological and neurobehavioral outcomes.

Principles of Nanotoxicology
Physicochemical Determinants of Toxicity

Nanoparticle toxicity is not an intrinsic and uniform property of a material; rather, it is influenced by a combination of physicochemical characteristics and the biological environment in which exposure occurs. Key determinants include particle size, shape, surface charge, surface chemistry, aggregation state, and interactions with biological media (Karmakar et al., 2014). Particle size is particularly important because it influences cellular uptake, systemic distribution, clearance, and tissue accumulation. Smaller particles may be cleared more efficiently through renal pathways, whereas larger or differently functionalized particles may preferentially accumulate in organs such as the liver and spleen, resulting in distinct exposure and toxicity profiles. Particle shape can also independently influence biological responses. High-aspect-ratio or plate-like particles may interact differently with cellular membranes and intracellular structures than spherical particles of comparable chemical composition. Similarly, surface charge affects nanoparticle–cell interactions, with positively charged particles generally exhibiting greater affinity for negatively charged cellular membranes. These physicochemical properties help explain why nanoparticles with similar chemical compositions can produce substantially different biological effects (Boukholda et al., 2026).

The biological consequences of these properties are particularly relevant to neurotoxicity because particle characteristics can influence the ability of nanoparticles to interact with, penetrate, or disrupt biological barriers. Recent mechanistic evidence suggests a recurring sequence in which nanoparticle exposure may involve barrier interaction or penetration, disruption of components of the neurovascular unit, altered cellular signaling, oxidative stress, and ultimately synaptic or neurotransmitter dysregulation (Boukholda et al., 2026). However, these mechanisms should not be interpreted as universal across all nanoparticle types. Toxicological responses depend on the specific material, physicochemical characteristics, exposure concentration, duration, route of exposure, and susceptibility of the exposed organism.

Routes of Entry and Biodistribution

In textile manufacturing environments, inhalation and dermal contact represent the principal occupational exposure pathways for engineered nanoparticles and textile-derived particulate matter. Inhalation is of particular toxicological interest because airborne nanoparticles can penetrate deeply into the respiratory tract due to their small aerodynamic dimensions. Depending on particle characteristics, deposition site, and biological interactions, inhaled nanoparticles may subsequently enter systemic circulation or undergo transport through the olfactory system, providing a potential route to the central nervous system (Karmakar et al., 2014; Tsai, 2015). Dermal exposure may occur during the handling of nanoparticle-containing formulations, treated fabrics, contaminated surfaces, or personal protective equipment. Although the extent of dermal penetration varies considerably according to particle properties and skin condition, dermal exposure remains relevant when assessing total occupational exposure.

The toxicological significance of these pathways depends on the relationship between external exposure and internal dose. Workplace measurements of airborne particle concentrations alone may therefore provide an incomplete representation of biological exposure. Particle size distribution, number concentration, surface characteristics, deposition patterns, duration of exposure, and the efficiency of workplace controls can all influence the internal dose ultimately available to target tissues. Consequently, occupational nanotoxicology requires exposure characterization that links workplace conditions with biologically relevant measures of dose wherever feasible.

Blood–Brain Barrier and Central Nervous System Translocation

The blood–brain barrier (BBB) is a highly selective neurovascular interface that restricts the entry of many circulating substances into neural tissue. Nanoparticles present a particular challenge to this protective system because their small dimensions and modifiable surface properties may permit interactions with endothelial cells, tight-junction structures, transport systems, and other components of the neurovascular unit. Experimental evidence indicates that some nanoparticles may cross the BBB directly or reach the brain through alternative pathways, including transport along the olfactory system following inhalation (Karmakar et al., 2014; Song et al., 2015). The extent to which these mechanisms operate under realistic human occupational exposure conditions, however, remains uncertain.

Animal studies provide important mechanistic evidence. For example, repeated exposure to titanium dioxide nanoparticles through intratracheal administration has been associated with detectable accumulation of particles in brain tissue in mice, accompanied by histopathological alterations and impairments in recognition, spatial memory, and learning (Song et al., 2015). Similarly, experimental exposure to zinc oxide nanoparticles has been associated with central nervous system effects involving potential direct translocation, axonal transport, and gut–brain signaling, with reported alterations in learning, memory, and motor functioning in animal models (Chen et al., 2026). In vitro evidence further indicates that silica nanoparticles may interfere with cellular processes associated with glutamate regulation within BBB-related cell systems, suggesting a possible pathway through which barrier dysfunction could contribute to neuronal excitotoxicity (Sanchez-Cano et al., 2024).

These findings provide biological plausibility for investigating neurological consequences of nanoparticle exposure but should be interpreted cautiously. Most experimental studies employ controlled exposure conditions, concentrations, routes, and durations that may differ substantially from those experienced by occupationally exposed workers. Evidence of nanoparticle accumulation or neurobehavioral effects in experimental animals therefore establishes a mechanistic possibility rather than demonstrating an equivalent risk in human textile workers. This distinction is central to translating experimental nanotoxicology into occupational-health research.

Oxidative Stress and Neuroinflammation as Convergent Mechanisms

Across different nanoparticle classes, oxidative stress and inflammatory signaling emerge as recurrent mechanisms of experimental neurotoxicity. Nanoparticle exposure can increase the generation of reactive oxygen species (ROS), potentially overwhelming cellular antioxidant defenses and producing oxidative damage to lipids, proteins, DNA, mitochondria, and cellular membranes. Persistent oxidative imbalance may subsequently activate inflammatory pathways and contribute to alterations in neuronal function. These processes are of particular interest because oxidative stress and neuroinflammation are also implicated in several neurological and neurodegenerative conditions, although the presence of shared mechanisms does not establish that occupational nanoparticle exposure causes such diseases (Manoharan et al., 2016).

Silver nanoparticles, for example, have been shown in experimental models to increase ROS generation and oxidative DNA damage in neural tissues (Manoharan et al., 2016). Microglia, the principal resident immune cells of the central nervous system, represent another important potential target. Experimental evidence involving particulate pollutants indicates that particle-induced microglial activation can increase the production of reactive species and inflammatory mediators, potentially affecting neuronal survival and neurovascular integrity. Diesel-exhaust-derived particulate matter, for instance, has been reported to activate microglia and increase superoxide production, with particular effects on dopaminergic neurons, while also contributing to disruption of BBB integrity (Win-Shwe & Fujimaki, 2011). Although diesel exhaust is chemically distinct from engineered textile nanoparticles, these findings illustrate a broader biological principle: nanoscale or ultrafine particulate exposure may initiate interacting oxidative and inflammatory processes within the neurovascular and neural systems.

The convergence of oxidative stress, neuroinflammation, and barrier dysfunction provides a plausible mechanistic framework linking nanoscale particulate exposure with altered neurological functioning. However, mechanistic plausibility should be distinguished from demonstrated occupational risk. The majority of available evidence remains derived from animal and in vitro models, and the exposure levels used in these studies frequently exceed those documented in occupational environments. Accordingly, the critical unresolved question is whether the biological pathways demonstrated experimentally are sufficiently activated at realistic workplace exposures to produce measurable neurobehavioral or psychological effects in humans. Addressing this translational gap requires studies that simultaneously characterize occupational exposure and assess validated psychological, cognitive, and neurobehavioral outcomes while accounting for relevant psychosocial and occupational confounders.

Particle-Specific Evidence Relevant to Textile Processing

Silver, titanium dioxide, zinc oxide, and silica nanoparticles represent important examples of engineered nanomaterials used or investigated in textile-related applications and illustrate the broader mechanistic framework summarized in Table 3. Human occupational evidence provides some support for systemic biological responses following exposure. Workers exposed to silver- and silica-containing nanomaterials have demonstrated alterations in inflammatory cytokine gene expression as well as dermatological effects, suggesting that occupational exposure can produce measurable biological responses beyond those observed exclusively in experimental models (Babaei et al., 2024). Experimental studies of titanium dioxide and zinc oxide nanoparticles have further demonstrated potential central nervous system effects, including blood–brain barrier interaction and impairments in learning and cognition (Chen et al., 2026). Zinc oxide has additionally been implicated in pathways associated with pathological protein aggregation, including tau-related mechanisms (Chen et al., 2026). Silica nanoparticles have also been shown experimentally to interfere with glutamate transport within BBB-associated cellular systems, providing another potential mechanism through which nanoparticle exposure could influence neuronal functioning (Sanchez-Cano et al., 2024). Collectively, these findings indicate that different nanoparticle types may converge on overlapping biological pathways while retaining material-specific toxicological profiles.

Gut–Brain Axis and Microbiome-Mediated Pathways

The potential neurological effects of nanoscale particulate exposure may extend beyond direct interactions with the brain. Microplastics and nanoplastics can enter the gastrointestinal system through contaminated food and water or following mucociliary clearance of inhaled particles. Experimental evidence suggests that ingestion of these particles may alter gut microbial composition, increase intestinal permeability, and disrupt intestinal barrier function, thereby providing a potential indirect pathway to neurological and behavioral effects through the gut–brain axis (Al Noman et al., 2025; Shi et al., 2024). Reviews of microplastic-associated gut–brain effects have reported alterations in microbial diversity, intestinal integrity, inflammatory signaling, and pathways involved in neurotransmitter metabolism in animal models (Pan et al., 2024). These findings are biologically relevant to textile workers because occupational exposure may involve simultaneous inhalation and incidental ingestion of particulate matter. Nevertheless, the extent to which such experimental gut–brain mechanisms occur following realistic occupational exposure remains uncertain and requires direct investigation in human populations.

Endocrine Disruption as an Interacting Pathway

Textile manufacturing also involves exposure to a range of chemicals that are mechanistically distinct from engineered nanoparticles and microplastics but may interact with their effects. Textile dyes, plasticizers, and finishing agents can contain or involve endocrine-disrupting compounds, including phthalates and other chemicals capable of interfering with hormonal signaling (Kaimal et al., 2025). Occupational research among textile dye workers has reported alterations in reproductive hormone profiles associated with exposure to certain dye-related compounds (Soyinka et al., 2024). This pathway is potentially relevant to psychological health because endocrine systems, including the hypothalamic–pituitary–adrenal and reproductive hormone axes, participate in the regulation of stress, mood, cognition, and emotional functioning. In addition, microplastics and nanoplastics may adsorb environmental chemicals onto their surfaces or release associated compounds under particular conditions, creating the possibility of combined exposure (Guo et al., 2026; Kaimal et al., 2025; Moon et al., 2025).

Accordingly, the neurotoxicological effects of nanoscale particles should not necessarily be considered in isolation from other occupational exposures. In real-world textile environments, workers may encounter mixtures of engineered nanoparticles, polymeric particles, dyes, finishing chemicals, metals, and psychosocial stressors. Future empirical research should therefore clearly define the primary exposure of interest while measuring major co-exposures where feasible. Depending on the research objective and available resources, a multipollutant framework may provide a more realistic representation of occupational exposure than an approach examining a single substance in isolation.

The Translational Gap Between Experimental and Occupational Evidence

A major limitation across the existing literature is the uncertain relationship between experimental exposure conditions and the doses and routes encountered by textile workers. Many studies demonstrating neurotoxic effects of titanium dioxide and other nanoparticles have used intratracheal instillation, intravenous administration, or direct central nervous system exposure at concentrations designed to produce measurable biological effects over relatively short experimental periods. These exposure paradigms do not closely reproduce the low-level, intermittent, and potentially chronic exposures experienced by workers across years of occupational activity. Consequently, experimental findings provide important evidence of biological plausibility but cannot, by themselves, establish that comparable neurological or psychological effects occur in occupationally exposed humans.

This distinction is particularly important when interpreting evidence concerning blood–brain barrier disruption, oxidative stress, neuroinflammation, and cognitive impairment. The consistency of these mechanisms across experimental models supports their consideration as testable hypotheses, but their relevance to human occupational health depends on exposure magnitude, duration, particle characteristics, route of exposure, individual susceptibility, and the presence of co-exposures. Human biomonitoring studies demonstrating inflammatory or oxidative changes strengthen the argument that some occupational nanomaterial exposures produce measurable systemic biological responses; however, physiological changes should not automatically be interpreted as evidence of clinically meaningful neurobehavioral impairment.

The translational challenge is consistent with broader occupational neurotoxicology, where subtle cognitive or psychometric changes may occur before clinically recognizable neurological disease. Research involving occupational exposure to established neurotoxicants such as lead, manganese, and organic solvents illustrates the importance of considering subclinical outcomes and cumulative exposure over time (Hogstedt & Lundberg, 1992; Yoon & Ahn, 2015). Cross-sectional studies may be particularly limited in detecting such relationships because they provide little information about temporal ordering, cumulative exposure, or individual changes in cognitive and psychological functioning.

For textile-related nanotoxicology, the evidence therefore currently supports a **biological plausibility framework rather than a conclusion of demonstrated occupational neurotoxicity**. Closing this translational gap requires task-specific exposure measurements conducted under actual textile-finishing conditions, characterization of particle size and composition, assessment of relevant biological biomarkers, and validated psychological and neurobehavioral testing. Prospective cohort designs would be especially valuable because they can examine cumulative exposure and changes in functioning over time while controlling for psychosocial job strain and other occupational and demographic confounders. From a clinical neuropsychological perspective, such longitudinal approaches are essential for determining whether subtle changes in cognition, mood, or psychological well-being precede clinically significant impairment and whether these changes are associated with objectively measured occupational exposure.

From Mechanism to Behavior: What the Evidence Actually Shows

Animal and In Vitro Evidence for Nanoparticle-Induced Behavioral Change

The mechanisms described above have produced a substantial, if still largely preclinical, body of behavioral evidence. Reviews cataloguing micro- and nanoplastic neurotoxicity report anxiety-like behavior, depressive-like behavior, social deficits, and, inconsistently across studies, impaired spatial learning and memory across rodent, fish, and invertebrate models (Vojnits et al., 2025). Reviews focused specifically on depression-relevant mechanisms describe polystyrene micro- and nanoplastics disrupting dopamine, serotonin, glutamate, and GABA signaling, with dopamine depletion linked to anhedonia and reduced motivation in treated animals (Vojnits et al., 2025; Shi et al., 2024). A registered clinical trial (NCT06247579) with a completed study period (January–May 2024) tested dietary polystyrene microplastic exposure against anxiety- and depression-like outcomes; peer-reviewed results were not yet identified at the time of writing (Northern Jiangsu People's Hospital, 2024).

The Occupational Nanotoxicology Literature: Measured, but Not on the Brain

Human occupational studies of nanomaterial-exposed workers do exist and deserve to be taken seriously on their own terms. A systematic review identified 27 epidemiological investigations of workplace exposure to engineered nanomaterials, covering workers exposed to carbon black, silica, titanium dioxide, multiwalled carbon nanotubes, silver, and other metal oxides, with inhalation the dominant route and respiratory and cardiovascular outcomes the primary endpoints studied; most found limited evidence of overt clinical disease but measurable changes in inflammatory markers, oxidative stress markers, and antioxidant enzyme levels (Boyes and van Thriel, 2020). Table 4 summarizes the key human occupational studies discussed here. A four-year panel study of 206 nanomaterial-handling workers found dose-dependent antioxidant enzyme changes but no significant neurobehavioral association, though modest exposure levels and healthy-worker effects complicate interpretation (Wu et al., 2019).

What none of these studies did is administer standardized psychological or mental-health instruments to nanomaterial-exposed workers. Read plainly, the Wu et al. (2019) panel study is the closest existing human analogue to the question this review asks, and it found no significant association between nanomaterial exposure and neurobehavioral markers. That null result deserves to be weighted as real evidence against a measurable effect at the modest exposure levels the study captured, not set aside. The healthy-worker effect is a plausible, literature-supported alternative explanation — workers who develop early symptoms may transfer out of nanomaterial-handling roles or leave the workforce, leaving a cross-sectional sample of relatively resilient, currently employed workers, which would bias findings toward the null regardless of the true exposure-outcome relationship — but it remains an untested hypothesis in this specific literature, not a demonstrated mechanism, and we present it as a reason the cross-sectional design cannot adjudicate the question rather than as a reason to discount the null finding itself. This is why the design proposed later in this review uses a hire-order or historical-cohort structure capable of testing the healthy-worker explanation directly, rather than assuming it. Occupational neurotoxicology has faced this problem before: manganese-exposed worker cohorts have needed prospective, tenure-stratified designs to detect subclinical neurobehavioral decrements that cross-sectional comparisons miss (Yoon and Ahn, 2015).

Textile and Garment Worker Mental Health: The Parallel, Unconnected Literature

Set against the nanotoxicology literature is a separate and substantial body of research directly measuring depression, anxiety, and stress in textile and garment-sector workers, research that has, to our knowledge, never referenced nanomaterial or microplastic exposure as a candidate explanatory factor. A systematic review of work-related health problems among textile and fashion factory workers found psychological stressors recurring alongside respiratory and musculoskeletal complaints, with workplace pressure linked to elevated depression and anxiety (Seidu et al., 2024). Systematic reviews of garment-industry workers have estimated pooled depression prevalence around 6% and work-related stress prevalence around 14% (Seidu et al., 2024). A clinic-based cross-sectional study of workers presenting with musculoskeletal disorders found substantially higher rates, a reminder that estimates vary widely with sampling frame (Ben Afia et al., 2023). Prevalence estimates vary from approximately 6% in general workforce samples to 46% in clinic-referred populations (Seidu et al., 2024; Ben Afia et al., 2023). Shift work and extended hours have independently been linked to anxiety and depression through circadian disruption, offering another psychosocial explanatory pathway current studies invoke instead of chemical exposure (Dey et al., 2016).

Psychosocial job strain is not a minor confound to be controlled for in passing but a genuine competing explanation. The Effort-Reward Imbalance model predicts that sustained mismatch between job demands and rewards produces chronic stress-response activation and, over time, depression; textile and garment production, with its piece-rate output requirements and low job security, is close to a textbook case of this mismatch, and the ERI and Job Content Questionnaire literatures will be measured as covariates in the design proposed later in this review rather than treated as nuisance variables.

Bridging the Two Literatures

One literature has biomarker-confirmed nanomaterial exposure in workers and a well-developed mechanistic case for neurobehavioral effects but has never measured psychological outcomes directly. The other has repeatedly measured depression, anxiety, and stress in a closely related worker population but has never measured nanomaterial or microplastic exposure. Closing that gap does not require abandoning either literature's methods; it requires combining them — biomarker-confirmed exposure assessment paired with validated psychological instruments, in the same workers, at the same time.

Human Microplastic Brain Burden: The 2025 Postmortem Evidence

Everything described so far argues from plausibility. One additional, human, piece of evidence is worth weighing carefully rather than leaned on heavily. A 2025 postmortem study analyzed liver, kidney, and frontal-cortex tissue from decedents at autopsy in 2016 and 2024, using pyrolysis gas chromatography-mass spectrometry with electron microscopy to quantify microplastic and nanoplastic burden (Nihart et al., 2025). Brain tissue carried substantially higher concentrations than liver or kidney in both years, and the brain concentration itself rose over time; brain samples from decedents with a confirmed dementia diagnosis carried far higher concentrations still, though the authors are explicit that this association does not establish that microplastic accumulation causes or accelerates dementia. The study carries a published author correction and has drawn substantive published criticism concerning its quantification method, and its precise concentrations remain contested; we treat it as suggestive corroboration that nanoscale plastic particles are not confined to laboratory-dosing scenarios, not as a load-bearing piece of this review's argument, which does not depend on this single study holding up.

None of this is occupational evidence, and none is specific to textile-derived microfibers rather than the broader environmental plastic burden every participant carried regardless of trade. What it does is close off the objection that blood-brain-barrier translocation of nanoscale plastic particles is confined to controlled animal-dosing studies with unclear human relevance. A textile-belt cohort with both exposure biomarkers and validated psychological instruments would be far better positioned to speak to occupational risk than the general-population autopsy data reviewed here.

Regional Context: Textile-Industrial South Asia and Pakistan's Sialkot Belt

South Asia hosts some of the largest textile- and leather-manufacturing clusters in the world, and Pakistan's Sialkot region is among the best-documented examples from a heavy-metal exposure standpoint, even though nanomaterial and microplastic exposure in the same population remain essentially unstudied. Biomonitoring work in Sialkot's surgical-instrument and leather-manufacturing sector has found significantly elevated chromium, cadmium, nickel, and lead concentrations in blood, urine, saliva, and hair samples from exposed workers relative to unexposed controls, with cutting, polishing, welding, and stitching identified as the principal contributors to worker heavy-metal body burden, and elevated blood lead levels documented among child laborers in the same industrial clusters (Junaid et al., 2016; Junaid et al., 2017a; Junaid et al., 2017b).

This literature establishes that Sialkot is a genuine, measurable, high-exposure industrial environment; as noted in the Introduction, it does not yet extend to nanoparticle or microplastic exposure assessment, or to psychological outcome measurement, in textile finishing specifically. The Punjab Occupational Safety and Health Act 2019 covers dangerous substances broadly but does not define nanomaterials as a distinct hazard category (Government of the Punjab, 2019), leaving a regulatory gap discussed further below.

Women make up a meaningful share of Pakistan's textile-sector workforce nationally, and disproportionately occupy stitching, finishing, and quality-assurance roles rather than being distributed evenly across the production line (Sustainable Development Policy Institute, 2010), precisely the finishing-adjacent tasks associated with the highest engineered-nanoparticle exposure. A comparable South Asian garment-sector study found that women working in finishing sections paradoxically reported higher Work Ability Index scores than sewing or administrative staff, but remain the highest-exposure occupational group for engineered nanoparticle contact (Zohra et al., 2025). Any protocol should record age at hire and treat the possibility of underage workers as an ethical planning requirement.

Evidence Gaps and a Research Agenda

Four gaps stand out as both real and addressable. First, there is no published human biomonitoring study quantifying nanoparticle or microfiber body burden in textile-industry workers specifically, as distinct from the heavy-metal biomonitoring literature already established for adjacent Sialkot industries (Junaid et al., 2016; Junaid et al., 2017a). Second, no identified study pairs nanomaterial or microplastic exposure biomarkers with validated psychological wellbeing instruments in the same worker sample, the combination needed to distinguish a nanomaterial-attributable effect from psychosocial job strain (Seidu et al., 2024). Third, occupational exposure-assessment methodology for nanoparticles and microfibers remains immature and non-standardized even in well-resourced settings (Galey et al., 2023; Luzi et al., 2025; McCormick et al., 2021). Fourth, essentially all of the mechanistic neurobehavioral evidence reviewed above comes from animal models using doses well above likely real-world human exposure levels, a translational gap the field itself acknowledges (Vojnits et al., 2025). Table 5 summarizes these gaps alongside proposed design elements. Two of these gaps warrant a provisional position rather than remaining fully open. On exposure-assessment methodology, because silver and silica — two of the particle types most directly relevant to textile finishing — show the clearest evidence that toxicity tracks surface area rather than mass (Table 2; Koivisto et al., 2024), we recommend that Stage 1 prioritize surface-area-based sampling as the primary dose metric, retaining mass and particle count as secondary metrics for comparability with the wider occupational hygiene literature; Table 5 reflects this. On the mechanistic side, the direct neurotoxic and endocrine-disruption pathways described earlier are unlikely to be independent within the same exposed worker, which means the Stage 1 covariate structure cannot treat endocrine measures as optional: the design must include a measured endocrine panel (at minimum, cortisol and a reproductive hormone marker) alongside the job-strain instruments, so that any observed nanomaterial-behavior association can be checked against endocrine mediation rather than attributed to a single pathway by default.

A concrete research program addressing these gaps is best staged rather than attempted as a single design. Stage 1 should be a hire-order or historical-cohort design, recruiting workers at or shortly after hire and following the cohort forward, or reconstructing exposure and tenure retrospectively from personnel records, combined with current biomarker and psychological assessment. This addresses the healthy-worker effect that a purely cross-sectional current-workforce sample cannot rule out. Because textile and garment-sector work is already independently associated with elevated depression and anxiety through psychosocial job strain, this stage cannot simply compare exposed workers to population norms; it needs stratification or matching on job-strain instruments such as the Job Content Questionnaire or the Effort-Reward Imbalance model, and comparisons within the same facility between workers who differ in task-level exposure intensity, rather than comparing an exposed factory to an ostensibly unexposed one.

No South Asian textile-sector data currently exist to power this design properly, so we do not report a target sample size here; doing so would risk the figure being cited as though it rested on real variance estimates rather than borrowed ones. As an order-of-magnitude sanity check only, comparable manganese-exposed worker cohorts have detected subclinical neurobehavioral decrements with samples in the low hundreds per arm (Yoon and Ahn, 2015), which is the right neighborhood to plan around but not a substitute for a proper calculation. A pilot phase (n = 30–40 per arm) will be conducted first to estimate the local PHQ-9 standard deviation and baseline prevalence in this specific worker population, using the nearest available occupational benchmark (Yassin et al., 2022) only to sanity-check pilot results, and the formal Stage 1 sample size will be calculated from those pilot-derived parameters before recruitment begins. A longitudinal or prospective extension would meaningfully strengthen causal inference beyond a single cross-sectional snapshot and should be built into the design from the outset.

Stage 2, contingent on Stage 1, would test oxidative stress, inflammatory, and endocrine biomarkers as the mechanistic bridge described earlier via mediation analysis, statistically meaningful only once Stage 1 has established a measurable association. A community-level extension, sampling residents of industrial belts rather than only occupationally exposed workers, would be a natural later addition given that microplastic and effluent contamination extends past factory walls into surrounding neighborhoods. Figure 3 sets out the proposed Stage 1 cohort design, built specifically to isolate a nanomaterial-attributable effect from the psychosocial job-strain effects already documented in this workforce. The Stage 1 battery comprises the PHQ-9, GAD-7, PSS-10, JCQ short form, and ERI short form.

Ethical review, underage-worker protection protocols, and same-sex assessment provisions will be established before data collection begins.

Implications for Occupational Health Policy and Practice

Even in advance of the dedicated research this review argues for, some practical implications follow directly from what nanotoxicology already knows. Safety data sheets for nanomaterial-containing textile finishing products should specify nanomaterial-specific hazard information rather than defaulting to bulk-chemical hazard categories, since this information gap is a real, current barrier to worker protection (Ramos et al., 2019). Ventilation, personal protective equipment, and, where feasible, closed-booth handling with dedicated extraction should be treated as a floor rather than an aspiration (Ramos et al., 2019). Personal protective clothing itself should be recognized as a potential secondary exposure source during doffing, which argues for dedicated changing protocols (Tsai, 2015). Because exposure-assessment methodology remains genuinely unsettled — mass versus surface area versus particle count as the relevant metric is still an open question (O'Shaughnessy, 2013) — occupational health programs should not wait for a single settled measurement standard before beginning to monitor exposure with whichever validated method is currently available.

Pakistan's Punjab Occupational Safety and Health Act 2019 covers dangerous substances broadly but does not define nanomaterials as a distinct hazard category (Government of the Punjab, 2019). An interpretive guidance note from the Punjab OSH Council could close this gap without new legislation.

It is worth being direct about a question this review has raised but not yet answered: whether nanoparticle and microfiber exposure is likely to add a clinically meaningful increment of depression or anxiety risk on top of what psychosocial job strain already produces in textile and garment work. The psychosocial job-strain literature in garment work reports large, consistent effects against which any chemical-exposure increment must be judged, and nothing in the mechanistic literature reviewed here licenses an expectation that nanoparticle exposure will rival job strain as the dominant driver of mental health outcomes in this workforce; the mechanistic case is for a real but plausibly modest additional pathway operating alongside psychosocial strain, not a competing explanation for it. This is precisely why the research design above treats job-strain measurement as a mandatory covariate.

Three interventions are implementable within Pakistan's existing legal and institutional framework in the meantime. Factory health officers can be trained to read safety data sheets for nanoparticle content and communicate nanomaterial-specific hazards during existing safety briefings. The heavy-metal biomonitoring infrastructure already operating in Sialkot's surgical-instrument and leather sectors can be extended to include nanoparticle exposure metrics such as induced sputum or nasal lavage for inhaled particles and urine for systemic markers. The PHQ-9 and GAD-7 — both freely available, validated in Urdu, and scorable in under five minutes — can be integrated into routine occupational health screenings, creating a mental-health surveillance baseline against which any future nanomaterial-attributable effect could be judged.

Strengths and Limitations of This Review

This review's main contribution is bringing together literatures that have not previously been read against one another: textile nanomaterial and microplastic exposure science, mechanistic nanotoxicology with a focus on neurobehavioral endpoints, human occupational nanomaterial biomonitoring, and occupational mental health research in the textile and garment sector. Doing so identifies a specific, currently unaddressed research gap with direct relevance to South Asian textile-industry settings, described precisely enough to design a study around.

As noted in Review Methods, this is a narrative rather than a registered systematic review, and our search coverage leaned toward recent publications, possibly under-sampling older foundational literature published before approximately 2010. Should the empirical study proposed above proceed, a companion PRISMA-compliant systematic review will be registered with PROSPERO and conducted to update and formalize the evidence synthesis presented here.

A final limitation concerns framing. Because the authors intend to pursue the interdisciplinary cohort study described above, this review functions partly as a justification for that research agenda, and a gap-identification narrative that concludes by proposing the authors' own study to fill that gap carries an inherent risk of motivated emphasis. Readers evaluating that risk should look specifically at how this review treats evidence that complicates its own case: whether the null neurobehavioral finding in Wu et al. (2019) is given real evidentiary weight rather than explained away, whether the Sialkot connection is presented as documented or, correctly, as proposed and unconfirmed, and whether the mechanistic sections' confidence is calibrated to the preclinical, high-dose nature of the underlying studies. We have tried to meet that standard throughout rather than only in this paragraph, but readers, not the authors, are the right judges of whether we succeeded.

Conclusion

Nanotoxicology has, in a relatively short span of years, built a genuinely detailed mechanistic case for how engineered nanoparticles and unintentionally generated microplastics can reach the brain and alter behavior: through blood-brain barrier translocation, oxidative stress, neuroinflammation, gut-brain axis disruption, and endocrine interference, each documented across multiple particle types relevant to textile manufacturing specifically. What the field has not yet done is test any of this in the workers most plausibly exposed to it, using the standardized psychological instruments that would let a mechanistic hypothesis become an empirical finding. Textile and garment-sector workers, meanwhile, are already known, through an entirely separate research tradition, to experience elevated depression, anxiety, and stress, currently attributed only to psychosocial job strain. South Asian textile-manufacturing hubs, where heavy-metal occupational exposure is already well characterized through more than a decade of biomonitoring work, offer a natural and currently unexamined setting in which to ask whether nanoparticle and microplastic exposure contribute something measurable to psychological wellbeing outcomes, above and beyond the psychosocial stressors already documented.

Data Availability Statement

No primary data were generated for this narrative review. All cited sources are publicly available via the DOIs and URLs provided in the reference list.

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Table 1

Three-Class Comparison of Nanoscale and Near-Nanoscale Exposure in Textile-Industry Settings

Exposure Class	**Source in textile setting**	**Primary size range**	**Main exposure route**	**Key mechanism**	**Evidence quality (human)**
A: Engineered nanoparticles	Finishing, coating	1–100 nm	Inhalation, dermal	BBB translocation, ROS	Limited; biomarker only
B: Micro/nanoplastics	Mechanical processing, laundering	1 μm–5 mm (fragments to fibers)	Inhalation, ingestion	Gut-brain axis, particle translocation	Emerging (2025 postmortem evidence)
C: Endocrine-disrupting chemicals	Dyes, plasticizers, finishing agents	Molecular (not particulate)	Dermal, inhalation	HPA axis, hormone disruption	Moderate (occupational hormone studies)

Note. BBB equals blood-brain barrier. ROS equals reactive oxygen species. HPA equals hypothalamic-pituitary-adrenal. Exposure Class C is treated as a co-exposure and potential confounder rather than a third particulate class. This table compares exposure classes at the category level; see Table 2 for particle-specific toxicological findings within Exposure Class A. Evidence quality (human) reflects the maturity of human-subject evidence specific to each exposure class, not the strength of the mechanistic case overall: Limited indicates human data confined to dermal-release or biomarker studies with no epidemiological outcome data; Emerging indicates a small number of human studies not yet independently replicated (here, a single postmortem tissue analysis); Moderate indicates multiple independent occupational studies with consistent biomarker, clinical, or hormonal findings.

Table 2

Particle-Level Toxicological Profiles of Engineered Nanoparticles in Textile Finishing

Nanoparticle	**Textile function**	**Typical products**	**Key toxicological concern**
Silver (Ag)	Antimicrobial, odor control	Sportswear, socks, medical textiles	ROS generation; BBB translocati

Nanoparticle	Textile function	Typical products	Key toxicological concern
			on; toxicity scales with positive surface charge (Koivisto et al., 2024)
Titanium dioxide (TiO_2)	UV-blocking, self-cleaning, photocatalytic finishing	Outdoor/technical fabric; effluent treatment	BBB accumulation; microglial inflammation; impaired memory in rodents (Song et al., 2015)
Zinc oxide (ZnO)	UV protection, antimicrobial	UV-protective apparel	BBB, axonal, and gut-brain routes; tau aggregation (Chen et al., 2026)
Silica (SiO_2)	Finishing agent, carrier matrix	Various finishing formulations	Reduced glutamate uptake at the BBB (Sanchez-Cano et al., 2024)

Note. BBB equals blood-brain barrier. ROS equals reactive oxygen species. UV equals ultraviolet. Concerns listed are drawn from animal and in vitro models at doses not yet shown to be equivalent to real-world occupational exposure. Whereas Table 1 compares exposure classes at the category level, this table details particle-specific toxicological findings within Exposure Class A.

Table 3

Evidence Summary of Nanoparticle-Induced Neurotoxicity Across Model Systems Relevant to Textile-Industry Particle Classes

Particle	Model system	Key finding	Reference
Titanium dioxide	Mice, repeated intratracheal instillation	BBB accumulation; inflammatory cell aggregation, necrosis; impaired recognition and spatial memory	Song et al. (2015)
Zinc oxide	Rodents	BBB, axonal, and gut-brain routes; impaired learning/memory/ motor function; tau aggregation	Chen et al. (2026)
Silica	BBB cell components (in vitro)	Reduced glutamate uptake, relevant to excitotoxic injury	Sanchez-Cano et al. (2024)
Silver + silica	Human industrial workers	Elevated inflammatory cytokine gene expression; skin lesions	Babaei et al. (2024)

Note. BBB equals blood-brain barrier. Animal and in vitro findings come from high-dose or non-physiological-route models. The Babaei et al. (2024) finding is from human biomonitoring. None has yet been replicated at estimated occupational exposure levels.

Table 4

Human Occupational Nanomaterial Biomonitoring Studies Discussed in This Review

Study	Population / design	Key finding	Reference
Systematic review	27 epidemiological studies; CB, silica, TiO_2, MWCNT, Ag, Fe_2O_3, and other exposures	Limited overt clinical disease; measurable inflammatory/oxidative stress marker changes; no neurobehavioral testing identified	Boyes and van Thriel (2020)
Panel study	206 exposed / 108 controls, 14 plants, 4-year follow-up	Only antioxidant enzymes (SOD, GPx) significantly associated with exposure; neurobehavioral markers not significant	Wu et al. (2019)

Study	Population / design	Key finding	Reference
Cross-sectional companion study	227 exposed / 137 controls, same 14 plants	Altered antioxidant enzyme activity tracked exposure risk level	Liou et al. (2012)
Methodological review	First-generation nanomaterial worker studies	Cross-sectional: positive biomarker associations; longitudinal: mixed, modest exposure levels	Liou et al. (2015)

Note. CB equals carbon black. MWCNT equals multiwalled carbon nanotube. SOD equals superoxide dismutase. GPx equals glutathione peroxidase.

Table 5

Evidence Gaps Identified in This Review and Proposed Design Elements

Gap	Why it matters	Proposed design element
No biomonitoring of NP/microfiber body burden in textile workers	Existing heavy-metal biomonitoring does not capture nanoparticle or microplastic exposure	Extend existing Sialkot biomonitoring infrastructure to nanoparticle and microfiber biomarkers
No study pairs exposure biomarkers with validated psychological instruments	Cannot separate a nanomaterial-attributable effect from psychosocial job strain	Cross-sectional biomarker-linked psychological assessment, with a mandatory endocrine covariate panel (cortisol, reproductive hormones) given the pathways' non-independence
Exposure-assessment methodology remains immature	Mass vs. surface area vs. particle count as the relevant dose metric is still unresolved	Multi-metric, task-level exposure characterization; surface area as the primary dose metric, mass and particle count as secondary measures

Gap	Why it matters	Proposed design element
Mechanistic evidence is almost entirely animal-only, high-dose	Limits translational confidence to real-world human exposure levels	Mediation analysis of biomarkers; longitudinal follow-up; community-level sampling

Note. NP equals nanoparticle.

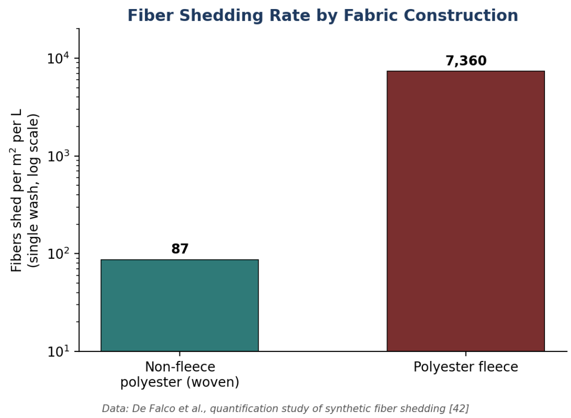

Figure 1

Polyester Fleece Shedding Rates

Polyester fleece sheds approximately 85 times more fiber per wash than woven polyester under comparable conditions.

Adapted from "Quantifying Shedding of Synthetic Fibers From Textiles," by B. M. Carney Almroth et al., 2018, Environmental Science and Pollution Research, 25, p. 1195 (https://doi.org/10.1007/s11356-017-0528-7). Copyright 2018 by the authors.

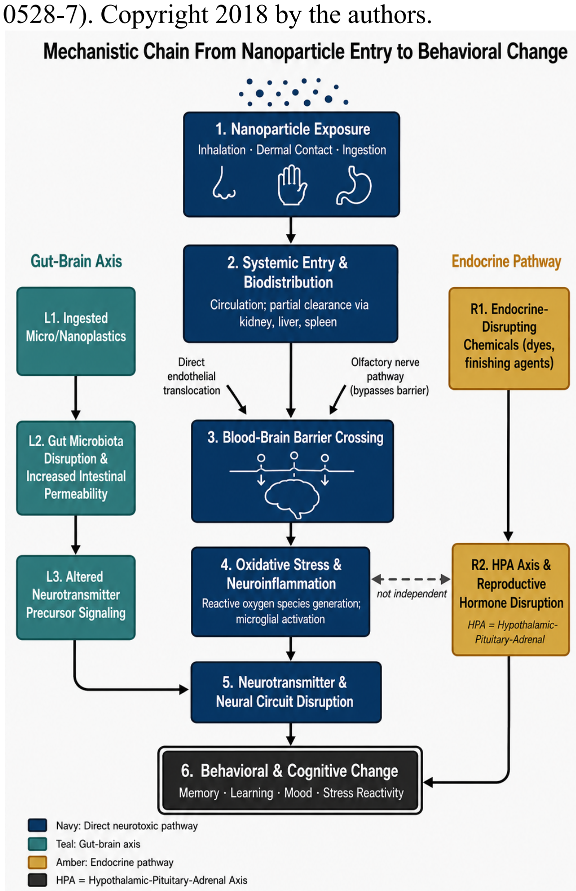

Figure 2

Mechanistic Chain From Nanoparticle Entry to Behavioral Change

The mechanistic chain that recurs across nanoparticle types: entry, biodistribution, blood-brain barrier crossing, oxidative stress and neuroinflammation, and downstream behavioral change, with parallel gut-brain and endocrine branches feeding into the same endpoint.

From the authors.

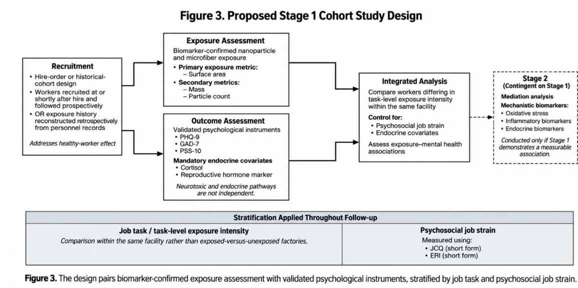

Figure 3

Proposed Stage 1 Cohort Study Design

The design pairs biomarker-confirmed exposure assessment with validated psychological instruments, stratified by job task and psychosocial job strain.

From the authors.