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REVIEW ARTICLE

Associated Health Risks of Nanomaterials in the Paints and Coatings Industry: Exposure Pathways and Assessment Approaches

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ABSTRACT

The rapid integration of engineered nanomaterials into paints and coatings has substantially improved product performance. However, this technological advancement introduces significant and incompletely characterized occupational health risks for workers in this industry engaged with nanomaterial synthesis, formulation, spray application, sanding, and maintenance operations. This review critically evaluates the occupational health risks associated with nanomaterial exposure in the paints and coatings industry, their exposure pathways, adverse health effects, and the current state of risk assessment frameworks. Inhalation is identified as the dominant occupational exposure route, with spray application and powder handling generating the highest near-field airborne nanoparticle concentrations, in some cases exceeding recommended occupational exposure limits, and dermal contact represents a secondary pathway. The state of exposure risk assessment in the industry and comparison of the existing frameworks reveal no validation against empirical exposure data from the paints and coatings environment, the absence of harmonized occupational exposure limits for most engineered nanomaterials, and the persistent inconsistencies across the control banding tools most widely used in practice. This review identifies three priority research directions for the field: 1. Establishing health-based occupational exposure limits for the nanomaterials most commonly used in coatings, 2. Resolving the aerosol metric debate to enable cross-study comparability of exposure data, and 3. Developing and validating quantitative risk models specifically calibrated to the aerosol dynamics and mixture exposure conditions of industrial coating operations.

Keywords: Engineered nanomaterials; Occupational exposure; Paints and coatings; Spray coating; Control banding; Exposure assessment; Occupational hygiene

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1. Introduction

Nanomaterials are materials with at least one dimension between 1 and 100 nm. These materials exhibit physical and chemical properties that differ from their bulk counterparts [1]. In the paints and coatings industry, such materials are widely used as advanced pigments and fillers to improve mechanical performance and surface functionality [2]. These applications enable the development of multipurpose coatings with enhanced chemical resistance, erosion and abrasion resistance, ultraviolet protection, and antifouling properties [2–4].

The paint and coating industry specifically utilizes various nanomaterials, including nano-silica, nano-titanium, and nano-silver, which pose biological effects through multiple exposure routes, including inhalation, though their successful integration requires careful attention to dispersion and stabilization mechanisms [4]. The industry represents high-risk environments for nanomaterial exposure due to several factors. Processes like spraying are associated with the release of large numbers of predominantly small-sized particles, creating significant exposure potential [5]. Although ventilation systems can reduce airborne particle concentrations, studies show that this protection is often transient, with measurable nanoparticle concentrations detected in both near-field and far-field workplace areas during spray coating [6,7]. In addition, emissions of nanoparticles through local exhaust ventilation systems indicate the potential for broader workplace and environmental release [6].

Despite the increasing incorporation of nanomaterials into paints and coatings, gaps remain in the efficient understanding and management of their occupational health, exposure pathways, and risks under real industrial operating conditions. Existing nanomaterial risk assessment tools used in this industry are primarily qualitative, relying on control banding approaches that lack comprehensive exposure data and operational conditions such as mass, temperature, humidity, and exposure duration [8]. Furthermore, the limited availability of industrial-scale validation data limits the accuracy and applicability of current models, reducing their effectiveness for guiding workplace safety practices and regulatory decision-making. Engineered nanomaterials have also been associated with potential respiratory and dermal health effects in occupational settings, which has increased interest in understanding exposure pathways and improving workplace risk assessment approaches.

This review aims to critically evaluate the current state of nanomaterial risk assessment in the paints and coatings industry, emphasizing occupational health, exposure pathways, and assessment approaches. It synthesizes current literature on nanomaterial exposure pathways and risk assessment approaches in paint and coating operations, drawing on peer-reviewed studies from occupational hygiene, nanotoxicology, and industrial coating research. This work emphasizes the need for future research to improve the industrial relevance of nanomaterial risk management frameworks for occupational health and regulatory practices.

2. Points of Nanomaterials Incorporation in Paints and Coatings Operations

The incorporation of nanomaterials into paints and coatings can occur at several stages throughout the manufacturing and application processes, each impacting the final properties and performance of the nanocomposite material [9]. This strategic integration is essential to leverage the unique chemical, mechanical, thermal, surface, and photophysical properties that nanomaterials impart at the nanoscale [10]. The primary objective is to enhance functionalities such as wear resistance, corrosion protection, UV resistance, self-cleaning, and antimicrobial activity [11–13].

2.1. Formulation, Mixing, and Dispersion Stages

Nano-paint production typically involves two main stages: the preparation of an intermediate product with a linear molecular structure, followed by its conversion into a final spatial configuration [8]. In practice, this involves dispersing nanoparticles, typically in the size range of 1–100 nm, into base coat paints using techniques such as ultrasonication and magnetic stirring [14,15]. These high-energy dispersion processes are designed to achieve uniform nanoparticle distribution and prevent agglomeration, which is critical for product quality.

Several factors influence nanoparticle behavior during formulation, including particle size, shape, concentration, and distribution within the coating matrix. Chemical and physical stabilization strategies are therefore required to maintain dispersion stability throughout processing and storage. The selection of appropriate surface modifications is dependent on the resin system or solvent environment, such as acrylic, urethane, epoxy, or alkyd formulations [9]. Mixing and dispersion stages represent critical points where mechanical agitation, high shear forces, and open or partially enclosed systems may increase the likelihood of nanoparticle release into the workplace atmosphere if engineering controls are inadequate.

2.2. Application and Finishing Processes (Spraying, Sanding, Curing)

Paint formulations containing nanomaterials are applied using a range of conventional coating methods, including brush coating, roller coating, air spray coating, and airless spray coating. Each application technique involves distinct operating conditions that influence aerosol generation, particle dispersion, and worker exposure. Spray coating processes, particularly air and airless spray painting, are recognized as high-energy operations capable of generating fine aerosols containing nanoscale particles, resulting in elevated inhalation exposure potential in the near-field of operators. Empirical evidence has shown that during airless spray application of nano-enabled coatings, airborne concentrations of nano-titanium dioxide may exceed recommended occupational exposure limits, highlighting the importance of effective ventilation and appropriate personal protective equipment by the National Institute for Occupational Safety and Health (NIOSH) [16].

Following application, finishing processes such as curing, drying, sanding, and surface preparation may further affect nanoparticle release and redistribution. The thickness and uniformity of coating layers are constrained by the particle size of fillers and pigments, which can influence deposition efficiency, overspray behavior, and subsequent surface finishing requirements. Mechanical actions such as sanding and abrasion of coated surfaces can resuspend deposited nanoparticles, generating secondary dust clouds and extending exposure beyond the initial application stage.

3. Occupational Exposure Pathways

Workers involved in producing nanomaterials or using nanomaterials in manufacturing plants are likely to have earlier and higher exposure to manufactured/engineered nanomaterials than the general population. This is because both the volume handled and the probability of the effluence of 'free' nanoparticles from the handled volume are much higher during a production process than at any other stage in nanomaterials and nanotechnology-enabled products [17]. Unlike controlled laboratory environments, industrial facilities operate under dynamic conditions characterized by intermittent containment, varying ventilation effectiveness, and frequent worker–process interactions, all of which can contribute to unintended nanoparticle release. Among the potential exposure routes, inhalation represents the dominant pathway in most coating operations, while dermal contact and inadvertent ingestion may occur under specific handling practices and hygiene conditions.

Empirical studies have documented significant exposure potential during key painting and coating processes. [16] reported that airless spray application of nano-enabled paints containing titanium dioxide generated airborne concentrations that may exceed recommended occupational exposure limits, whereas sanding activities generally resulted in lower exposure levels, particularly when local exhaust ventilation was effectively applied. Similarly, Bellagamba et al. [6] identified the release of graphene nanoplatelets during spray deposition of graphene-based polymer coatings, with exposure risks concentrated in the near-field of operators within restricted work areas. At a broader scale, Bekker, et al. [18] estimated that approximately 3,000 workers in the Netherlands may be occupationally exposed to manufactured nanomaterials during the production or application of nano-enabled products, with the paint industry identified as one of the contributing sectors. Figure 1 schematically summarizes occupational exposure pathways relevant to paints and coatings operations involving engineered nanomaterials.

3.1. Inhalation Exposure during Spraying and Mixing

Inhalation exposure is the primary occupational hazard during nanomaterial handling in paints and coatings operations, particularly during high-energy processes such as spray application, powder handling, and mixing. These activities generate airborne nanoparticles that can remain suspended in the workplace atmosphere, resulting in elevated near-field exposure. During powder handling and mixing, near-field particle number concentrations have been reported to exceed far-field levels by 1,000 – 40,000 cm^{-3}, with personal

PM_1 exposures ranging from 0.156 to 0.839 mg m^{-3} [19]. Empirical studies have demonstrated that spray application methods strongly influence inhalation exposure levels. Park et al. [20] reported that propellant-based spray systems generated substantially higher nanoparticle number concentrations (approximately 1,466 – 5,565 particles/cm^3) compared to pump sprays, leading to increased inhalation exposure potential. Bellagamba et al. [6] identified the release of graphene nanoplatelets during spray deposition of graphene-based polymer coatings, with exposure levels highest in restricted near-field areas. Although the use of ventilated hoods significantly reduced airborne concentrations, measurable particle levels persisted during active spraying. Cooper et al. [21] similarly reported that spray application of zinc oxide nanoparticle wood sealants generated airborne nanoparticle concentrations above background levels, with local exhaust ventilation achieving reductions of up to 92%. Despite these reductions, residual exposure remained during spraying activities.

Quantitative exposure assessments have also reported measurable mass-based concentrations during spray application of nano-enabled coatings. Koivisto et al. [22] estimated 8-hour time-weighted average exposures of up to 171 µg/m^3 for titanium dioxide nanoparticles under worst-case spray-coating scenarios, with detectable exposures also reported for silver nanoparticle-containing coatings. These findings validate that inhalation exposure during spraying of nanomaterials can approach or exceed benchmark values, particularly when ventilation is inadequate or process conditions are poorly controlled. While engineering controls like local exhaust ventilation consistently reduce airborne nanoparticle concentrations across different coating applications, the exposure is not fully eliminated.

3.2. Dermal and Ingestion Pathways

Although inhalation is established as the dominant exposure route to nanomaterials in paints and coatings operations, dermal contact and ingestion can be seen as important secondary pathways that may contribute to overall occupational exposure to nanomaterials. Human exposure to Engineered Nanomaterials (ENMs) has been shown to occur through multiple routes, including dermal and ingestion pathways alongside inhalation and, in some contexts, ocular exposure, depending on material form and use conditions [23]. In industrial coating environments, these non-inhalation pathways are most associated with manual handling activities, surface contamination, and non-routine tasks rather than airborne release alone.

[24] indicate that dermal exposure can occur even when inhalation exposure is unlikely, particularly when ENMs are present in liquid formulations or suspensions. In paints and coatings operations, such scenarios arise during formulation handling, equipment cleaning, maintenance, and spray application, where workers may come in direct contact with nanomaterial-containing liquids, residues, or settled dust. The likelihood of dermal exposure is strongly influenced by the physical form of the nanomaterial, the applied process, and operational conditions, with manual tasks such as cleaning, maintenance, and spraying consistently associated with increased exposure potential [24].

On the other hand, ingestion exposure in occupational settings is usually indirect and occurs via hand-to-mouth transfer after coming in contact with contaminated surfaces, tools, or personal protective equipment. While ingestion is generally considered less significant than inhalation and dermal contact in terms of dose, its occurrence reflects deficiencies in workplace hygiene and contamination control.

Understanding dermal and ingestion exposure pathways is further complicated by nanomaterial transformation in biological environments. Although these processes are not fully understood in occupational settings, they highlight the complexity of exposure assessment and reinforce the importance of comprehensive characterization across multiple exposure pathways. Figure 1 illustrates the key process stages and the relative mechanisms through which workers may be exposed to nanomaterials through inhalation, dermal contact, and incidental ingestion as occupational exposure pathways in nano-enabled paints and coatings operations.

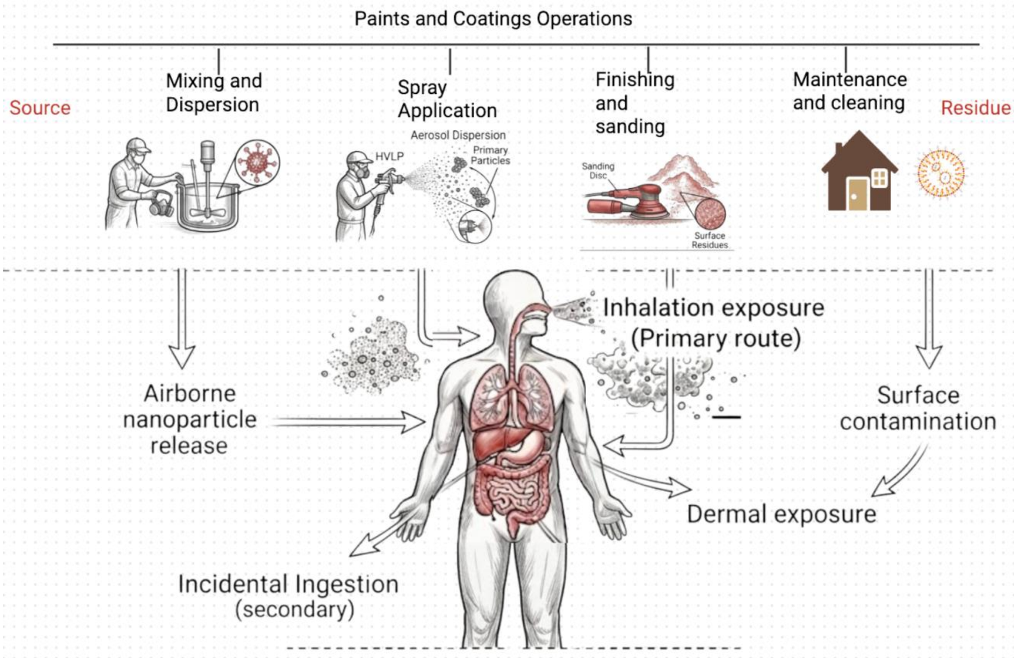

Figure 1. Common occupational exposure pathways to nanomaterials in paints and coatings operations. Key process stages and associated release mechanisms.

An overview of tasks and activities related to the use of nanomaterials in the industries, along with the potential hazards associated with each process or task, is summarized in Table 1, according to Malaysia's DOSH guidelines [25].

Table 1. Potential Hazards According to the Process or Task [25].

S/N	Process/Task	Work activities	Descriptions	Exposure to Nanomaterials
	Downstream processing	Bag/container emptying	Workers manually open and emptying bags of solid materials	Nanoparticles (dry powder) in high concentration
		Small-scale weighing	Handling of nanomaterials/nanoparticles during scooping, pouring, and dumping activities	Nanoparticles in high concentration
		Machining of products	Machining of parts that containing nanomaterials (e.g., sawing, polishing, grinding)	Nanoparticles
	Product packaging	Small-scale weighing/handling	Handling of nanomaterials/nanoparticles for quality assurance/control sample	Nanoparticles
		Large-scale weighing/handling	Large-scale powder packing, process loading, and tray dryer loading	Nanoparticles in high concentration
		Product packaging	Powder product is commonly discharged into a bulk tote or drum before packaging	Nanoparticles (dry powder) in high concentration
	Maintenance	Facility equipment cleaning	When cleaning dust collection systems used to capture nanoparticles, such as performing fan maintenance.	Liquid or solid that contains nanomaterials
		Air filter changeout	Removal of dirty air filter from a ventilation unit	
		Spill clean-up	Cleaning up spills	Liquid or solid that contains nanomaterials

4. Adverse Health Effects of Occupational Exposure to Nanomaterials

The adverse health effects associated with engineered nanomaterial exposure are strongly influenced by exposure route, particle characteristics, dose, and duration. In industrial paints and coatings operations, these effects are most relevant when exposure occurs repeatedly under insufficiently controlled process conditions, rather than as a result of isolated or incidental contact. This review is limited to respiratory and dermal effects, which correspond to the primary and secondary occupational exposure routes in coating operations. However, ingestions, often resulting from poor hygiene practices in the workplace, may also occur and could lead to gastrointestinal absorption and systemic bioaccumulation, raising concerns about potential long-term toxicity[26].

4.1. Respiratory Effects

The respiratory tract represents the primary entry route for inhaled nanoparticles in occupational settings, with deposition governed by multiple physical mechanisms that depend largely on particle size and airflow characteristics. Penetration and deposition within the airways occur through gravitational sedimentation, inertial impaction, interception, diffusion, and electrostatic interactions, with diffusion playing a dominant role for nanoparticles due to their small size and high thermal mobility [27]. Deposition patterns are further influenced by airway geometry, breathing rate, and breathing mode (nasal versus oral), all of which may vary during coating-related activities. Once deposited in the respiratory tract, nanoparticles may undergo aggregation or agglomeration, increasing their effective aerodynamic diameter from the nanoscale to the microscale and altering deposition and clearance behavior [27]. In paints and coatings operations, workers are typically exposed to mixed aerosols rather than isolated primary nanoparticles, and these dynamic transformations complicate exposure assessment and interpretation of respiratory risks under real industrial conditions.

Respiratory effects are the most consistently reported adverse health outcomes associated with occupational exposure to engineered nanomaterials and are therefore of primary relevance in paints and coatings operations. For example, titanium dioxide (TiO_2) and silica nanoparticles (SiO_2), widely used for UV protection and scratch resistance, have been linked to oxidative stress, lung inflammation, and systemic toxicity [28]. Inhalation exposure during high-energy processes such as spray application, powder handling, and sanding allows airborne nanoparticles to penetrate deep into the respiratory tract, where interactions with pulmonary tissues may occur. Experimental and occupational studies have associated such exposures with inflammatory responses, oxidative stress, fibrosis, and impaired lung function, particularly under conditions of repeated or prolonged exposure [29,30].

A widely proposed mechanism underlying respiratory toxicity is the generation of reactive oxygen species and subsequent oxidant injury, which can initiate inflammatory cascades in the lung, similar to responses observed for ambient ultrafine particles [31]. Metal and metal-oxide nanoparticles commonly used in paints and coatings have been shown to induce pulmonary inflammation and fibrotic changes in experimental studies under high exposure scenarios [1,32]. These responses are influenced by particle size, surface area, surface chemistry, exposure concentration, and duration.

Importantly, translation of experimental findings to occupational settings remains subject to uncertainty. Workers are more frequently exposed to agglomerated or aggregated particles rather than primary nanoparticles, which may modify deposition patterns and biological interactions within the respiratory system[32]. Observed respiratory outcomes are therefore closely linked to process conditions, ventilation effectiveness, and task frequency. As such, respiratory risks in paints and coatings operations should be interpreted within the exposure pathways described earlier, with emphasis on the role of engineering controls and work practices in mitigating inhalation-related health effects.

4.2. Dermal Effects

Dermal contact may occur in paints and coatings operations, arising during liquid formulation handling, spray application, equipment cleaning, and maintenance tasks, as shown in Figure 1. Workers come into direct contact with liquids, residues, or settled surface deposits, but the extent to which dermal exposure poses a risk depends on whether nanoparticles can penetrate the skin barrier and reach viable biological tissue.

The stratum corneum is the primary barrier to nanoparticle penetration, and studies have found confined particles on its surface or the uppermost layers of the stratum corneum, with negligible penetration into dermal tissue under intact skin conditions [33] However, nanoparticles within the range of 45 nm have been found to have a direct channel through hair follicles, even though this area accounts for less than 1 % of the total skin surface, they represent an alternative penetration pathway for some nanomaterials [34].

The primary dermal health concern in coating environments is sensitisation rather than acute irritation, as available evidence suggests minimal irritant effects of nanoparticles on intact human skin [34]. Metal-containing nanoparticles present in antimicrobial and corrosion-resistant coating formulations release ions at the skin surface at higher rates than bulk materials owing to their elevated surface-to-mass ratio, triggering allergic contact dermatitis in sensitized individuals [34,35]. In coating environments where concurrent chemical exposures to solvents and resins are routine, co-exposure to nanoparticles may further potentiate allergic risk beyond single-agent predictions [36].

4.3. Evidence from Occupational Case Studies

Some studies assert that nanomaterials pose minimal risk when they are firmly bound within the paint or coatings matrix, reducing their bioavailability and potential for release during use, thereby minimizing inhalation, skin contact, or environmental exposure [37]. Despite these claims, research on the long-term effects of exposure to these nano-products in both industries remains limited, particularly regarding chronic health impacts on humans, with minimal experimental data available, highlighting a critical knowledge gap [38,39]. Occupational exposure to nanomaterials in the paints and coatings industry has been associated with various health complications, primarily affecting respiratory function and systemic toxicity. Table 2 summarizes reported occupational exposure incidents involving engineered nanomaterials and associated adverse health outcomes. It is important to note that many of the reported findings originate from case reports, accidental high-exposure events, or observational studies in complex workplace environments where concurrent exposure to solvents, volatile organic compounds, welding fumes, pigments, and other airborne contaminants may have contributed to the observed outcomes. Consequently, the reported health effects should not be interpreted as definitive evidence of a direct causal relationship between nanomaterial exposure alone and clinical disease. Likewise, in several studies, the available evidence is limited to biomarkers of exposure or effect, rather than confirmed nanomaterial-induced disease.

Although several reviews have evaluated occupational exposure routes, toxicological mechanisms, and health effects of engineered nanomaterials, systematic reviews focusing specifically on validated human biomarkers of effect remain limited. Current evidence is largely derived from toxicological studies, occupational exposure assessments, and isolated case reports rather than longitudinal epidemiological investigations capable of establishing clear exposure–response relationships. This limitation highlights the continuing uncertainty regarding causality between occupational nanomaterial exposure and clinically significant disease outcomes.

Table 2. Previous reported cases of nanomaterials exposure in the paint and coating industry.

S/N	Activity/Process	Adverse health outcomes	Consequence	Evidence	Reference
1	Spraying nickel in a metal arc process	Respiratory distress syndrome	One fatality	High levels of nickel found in urine and kidney; nanoparticles < 25 nm found in alveolar macrophages.	[40]
2	Aluminum welding	Pneumoconiosis	Two fatalities	Aluminum concentration from 8.5 to 11.2 billion particles per cm^3 of lung tissue; most particles ~10 nm.	[41]
3	Polyacrylate spray painting	Shortness of breath, pleural effusion, progressive pulmonary fibrosis	Seven injuries	Silica nanoparticles in alveolar macrophages, epithelial cells, and chest fluid.	[42]
4	Polyester powder painting	Bronchiolitis obliterans organizing pneumonia	One fatality	Titanium dioxide nanoparticles found in pulmonary samples.	[43]
5	Toner from laser printing process	Abdominal pain, weight loss, and diarrhea	One injury	Submesothelial aggregates of carbon nanoparticles (31-67 nm) were found in tissue specimens.	[26]
6	Handling or manufacturing nanomaterials in 340 workplaces	Suspected respiratory occupational disease	Nine injuries	Not specified.	[44]

5. Risk Assessment Approaches in Nano Paint and Coating Operations

Assessing risks associated with nanomaterials remains a complex challenge due to the absence of established occupational exposure limits (OELs). The existing occupational risk assessment approaches for ENMs have evolved from qualitative control banding strategies to more quantitative and model-based frameworks. This section reviews the current state of exposure assessment, the process-specific parameters that drive exposure in coating operations, the screening and control banding tools most widely used in practice, and the quantitative models now emerging for more precise risk estimation.

5.1. Measurement-Based Exposure Assessment

Direct measurement remains the reference standard for occupational exposure characterization in nano-enabled coating operations. The most widely cited structured framework is the OECD Harmonized Tiered Approach (OECD SNN No. 55, 2015), which organizes field assessment into three progressive tiers.

The Nanomaterial Exposure Assessment Technique (NEAT 2.0) provides a structured task-based field assessment protocol integrating both real-time and filter-based sampling, developed by Eastlake et al. [45] as a practical operational tool applicable to nano workplace scenarios. A persistent methodological challenge is the lack of consensus on the appropriate exposure metric for nanomaterials. Belosi et al. [46] directly compared mass concentration, surface area concentration, and particle number concentration as exposure metrics during industrial spray coating processes, demonstrating that these metrics can yield markedly different risk pictures for the same operation. Galey et al. [47] concluded that no harmonized approach has been fully adopted across industrial sectors, and that high levels of metrological expertise are required to implement comprehensive measurement programs, a constraint particularly acute for small and medium-sized enterprises.

5.2. Operating Parameters as Exposure Determinants

A significant limitation of most risk assessment frameworks is their failure to adequately capture the process-specific operating parameters that govern nanoparticle aerosolization, dispersion, and accumulation in industrial scenarios. The physical state of the nanomaterial is the most fundamental determinant of release potential. Free or unbound nanoparticles encountered during powder handling, bag emptying, and certain mixing operations present substantially higher aerosolization risk than nanomaterials embedded within liquid formulations or cured coating matrices [25]. The mass of nanomaterial in use scales directly with airborne concentration potential during high-energy operations such as spraying, grinding, and mixing; larger quantities processed in a given period of time increase the source strength available for dispersion into the worker's breathing zone.

Air exchange rate is a critical mitigating variable, as poor ventilation facilitates nanoparticle accumulation and sustains elevated breathing-zone concentrations, as demonstrated by the significant near-field to far-field concentration differentials measured across multiple coating spray studies [6,16,21]. Halil et al. [8] operationalized these parameters for nanomaterial risk assessment in the paints and coatings context by developing a quantitative classification scheme defining low, medium, and high exposure categories based on measurable thresholds of temperature, humidity, and nanomaterial mass. Their findings showed that nanomaterial mass and elevated temperature consistently produced higher airborne particle release rates, and that the combined influence of multiple parameters was not captured by physicochemical hazard banding alone. This work represents an important step towards process-integrated exposure assessment, establishing that operating parameters must be treated as active input variables rather than contextual background factors in risk models designed for the paints and coatings sector.

5.3. Screening Tools: Control Banding and Nano Reference Values

Control Banding (CB) has become the most widely implemented first-line risk management approach in occupational settings, including the paints and coatings industry. CB methods categorize nanomaterials into hazard bands based on physicochemical and toxicological attributes by using particle size, solubility, shape, and toxicity potential, and assign exposure bands based on work practices, process characteristics, and emission potential, with recommended minimum control measures corresponding to each combined risk level[24,48]. Examples include CB Nanotool, Stoffenmanager Nano, NanoSafer, and ISO/TS 12901-2. Their principal advantages are practical applicability under data-scarce conditions, accessibility for non-specialist users, and early-stage risk prioritization capability, particularly valuable for small and medium-sized enterprises without dedicated occupational hygiene resources.

As an interim measure in the absence of OELs, Nano Reference Values (NRVs) developed through an international workshop process and adopted in European occupational hygiene practice provide precautionary 8-hour time-weighted average benchmark values differentiated by nanomaterial hazard category [49]. NRVs are not health-based exposure limits in the regulatory sense but represent an expert-consensus pragmatic intermediate tool that can be applied alongside CB outputs or direct measurements to support practical exposure.

Despite their widespread implementation, comparative studies have consistently identified substantial methodological inconsistencies across CB tools. When applied to the same nanomaterial and process scenario, different tools produce divergent hazard and exposure outputs, reflecting fundamental differences in regulatory purpose, input parameter definitions, hazard-scoring algorithms, and output formats. Liguori et al. [50] concluded that while harmonization of inputs and outputs could support the development of a tiered cross-tool framework, integration of existing CB tools into a unified system is not currently feasible without fundamental restructuring of their underlying methodologies. CB tools typically require detailed physicochemical inputs that are not consistently available for nanomaterials used in commercial paint formulations. In dynamic operations such as spray application, CB tools do not account for real-time operational variability in ventilation, task frequency, or worker proximity to the emission source. This conclusion is especially pertinent for the paints and coatings industry, where exposure conditions are highly variable, and the physicochemical data required by CB tools are frequently incomplete.

5.4. Quantitative Exposure Models for Spray and Mixing Operations

Recognizing the limitations of qualitative CB approaches, quantitative and model-based frameworks have been developed that integrate mechanistic exposure modelling with hazard characterization, enabling probabilistic risk estimates and scenario-specific control guidance suited to the operational realities of coating environments. The most significant recent development in this area is the Nano Exposure Quantifier (NEQ), a mechanistic, tiered quantitative model validated against a dataset of 128 real workplace nanomaterial exposure measurements across multiple industrial sectors [51]. The NEQ estimates airborne manufactured nanomaterial concentrations in particle number units with 95% confidence intervals, incorporating two sub-models of increasing complexity. The Tier 1 NEQ requires minimal input data and is designed for rapid screening, while the Tier 2 NEQ integrates substance emission potential, activity emission potential, and room ventilation parameters for more precise estimation. The NEQ is directly applicable to spray and mixing operations in coating environments, where near-field particle concentrations are strongly dependent on spray parameters and ventilation conditions. A companion tool, the NEQ-SbD [52], integrates a Safe-by-Design module into the NEQ framework, enabling users to prospectively compare the exposure impact of alternative risk management measures, including material substitution, process enclosure, and local exhaust ventilation, and supporting iterative process improvement rather than single-point risk classification.

Halil et al. [8] developed an integrated nanomaterial risk framework combining Bayesian Network (BN) modelling with control banding, incorporating process-specific operating parameters such as nanomaterial mass, ambient temperature, and relative humidity, to improve risk estimation accuracy under variable process conditions. BN models are particularly suited to nanomaterial risk assessment because they can represent probabilistic dependencies between multiple exposure determinants, explicitly propagate uncertainty through the risk estimate, and update model outputs as new workplace measurement data become available, with a capacity for adaptive learning that static CB tools cannot replicate. The probabilistic structure of BN approaches aligns well with the variable and often incompletely characterized exposure environments of industrial spray coating operations.

Machine learning approaches are increasingly being explored as complements to mechanistic models. Ji et al. [53] demonstrated that ML models can accurately predict nanomaterial cytotoxicity from physicochemical descriptors. Timothy and Hussain [54] specifically demonstrated the utility of deep learning for classifying workplace risk levels associated with engineered nanomaterials based on exposure-related variables. While these approaches remain at the research stage for occupational coating applications, they represent a credible trajectory towards adaptive, high-resolution risk characterization that can accommodate the physicochemical diversity and process variability of nano-enabled coating environments. Table 3 summarizes the quantitative and predictive approaches used for nanomaterial exposure risk assessment.

Table 3. Quantitative and Predictive Models for Nanomaterial Exposure Assessment.

Model / Framework	Type	Key Inputs	Output	Limitation for Coatings
EQ (Tiers 1 & 2) [55]	Mechanistic (Tiered Approach)	Tier 1: Substance form & activity. Tier 2: + Ventilation rates, room volume, & RMM efficiency.	Quantitative exposure concentration (Particle Number/Mass) with 95% CI.	Dynamic Modeling: Tier 1 is often overly conservative; Tier 2 lacks specific modifiers for solvent-based spray aerosol physics.
NEQ-SbD [56]	Mechanistic + SbD	NEQ inputs + control measure parameters	Comparative exposure impact of RMMs	Prospective tool; requires NEQ as base
	Probabilistic	Mass, temperature, humidity, CB hazard band	Risk probability distribution	Predefined case studies; limited dynamic adaptation
ML/Deep Learning [53,57,58]	Data-driven	Physicochemical descriptors, exposure variables	Toxicity/risk classification	Requires large validated training datasets

5.5. Remaining Gaps in Paint and Coating Exposure Assessment and Future Directions

Despite the breadth of approaches reviewed above, several critical gaps remain unresolved, specifically for nano-enabled paint and coating operations, limiting the accuracy and practical applicability of current risk assessment frameworks in this sector. The absence of internationally harmonized OELs for most engineered nanomaterials is the most fundamental regulatory gap. Without health-based exposure limits, all current frameworks, whether CB tools, NRVs, or quantitative models, operate without a defined risk acceptability threshold, making it impossible to determine definitively whether measured or modelled exposures constitute acceptable or unacceptable risk.

At the measurement level, the unresolved metric debate, mass concentration versus surface area concentration versus particle number concentration, means that exposure assessments conducted with different primary metrics cannot be directly compared across studies or against available benchmark values [59]. This hinders the accumulation of an evidence base that would support sector-specific guidance for painting and coating operations.

At the modelling level, existing quantitative frameworks, including the NEQ, have not been specifically validated on paint and coating spray operations. Their training datasets include diverse industrial processes, but the high aerosol generation rates, complex solvent environments, and mixture exposures characteristic of coating applications may fall outside the conditions on which models were calibrated [55].

At the process level, mixture exposures of workers in coating environments are simultaneously exposed to nanomaterials, coarse spray aerosols, and volatile organic compounds, which are not addressed by any current nanomaterial-specific risk assessment framework. The interaction of these co-exposures in terms of combined toxicity and cumulative risk remains largely uncharacterized [32]. Developing validated parameter thresholds and integrating them into both CB tools and quantitative models represents the most tractable near-term priority for improving the accuracy and industrial relevance of nanomaterial risk assessment in this sector.

6. Conclusion

Our review examined occupational health risks associated with engineered nanomaterial exposure in the paints and coatings industry, covering nanomaterial incorporation into coating processes, occupational exposure pathways, adverse health effects, and risk assessment frameworks. The evidence reveals a sector in which nanomaterial use is extensive, occupational exposure potential is well-documented, and the tools available to assess and manage that exposure remain inadequately calibrated to real industrial conditions. Spray application is the highest-risk operation, generating near-field airborne concentrations that can approach or exceed benchmark values for nano-TiO_2, nano-ZnO, and related materials even when local exhaust ventilation is in operation. Occupational documented case studies of pulmonary fibrosis, bronchiolitis obliterans, and pneumoconiosis among spray painting and powder coating workers confirm that the health consequences of inadequate exposure control in this sector are real and severe. These health effects are strongly determined by physicochemical properties rather than material identity alone, reinforcing the need for material-specific characterization as a foundation of occupational risk management. Risk assessment in this sector is hindered by the absence of harmonized occupational exposure limits, persistent inconsistencies across control banding tools, and the lack of validation of any existing framework against empirical exposure data from coating operations. Quantitative mechanistic models represent the most meaningful advances, incorporating process-specific parameters that qualitative tools neglect. Three research priorities follow: establishing health-based exposure limits for nano-TiO_2, nano-ZnO, nano-SiO_2, and nano-Ag; resolving the aerosol metric debate to enable cross-study comparability; and developing and validating quantitative models specifically calibrated to the exposure conditions of industrial coating operations. Progress on these fronts is a prerequisite for risk assessment frameworks that are both scientifically credible and practically useful for this industry.

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Conflict of interest

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