

OCCUPATIONAL RISK EXPOSURE IN AUTOMOTIVE COATINGS SMALL AND MEDIUM ENTERPRISES: ENVIRONMENTAL CONTROLS IN THE EU AND USA CONTEXT

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Background: Occupational exposure in automotive coatings manufacturing remains a major industrial health concern due to volatile organic compounds (VOCs), isocyanates, and mixed solvent aerosols generated during spraying, mixing, curing, and cleaning operations. Exposure conditions are particularly variable in small and medium-sized enterprises (SMEs), where limited engineering controls, insufficient ventilation performance, and inconsistent occupational hygiene implementation contribute to unstable indoor environmental conditions and elevated worker health risks across different regulatory systems. **Objectives:** This review aims to develop an integrated systems-based interpretation of occupational exposure in automotive coatings SMEs by comparatively evaluating exposure pathways, engineering control effectiveness, and occupational risk governance across the European Union, the United States, and Ukraine. **Methods:** A narrative critical review was conducted using peer-reviewed literature, occupational hygiene studies, environmental exposure investigations, and regulatory documents retrieved from Scopus, Web of Science, EU-OSHA, OSHA, and Ukrainian legislative and technical sources published between 2000 and 2025. The review focused on occupational exposure to VOCs and isocyanates in automotive coatings environments, with SMEs serving as the primary analytical context due to their known limitations in exposure monitoring and engineering control implementation. A structured comparative synthesis was applied to examine relationships between exposure dynamics, ventilation and engineering control performance, and regulatory implementation capacity across jurisdictions. The analysis integrated evidence from exposure science, indoor environmental engineering, and occupational risk governance to identify system-level determinants of exposure variability and implementation gaps in SME-dominated industrial settings. **Results:** The analysis demonstrates that occupational exposure in automotive coatings facilities is governed not only by chemical hazard properties, but by the interaction between regulatory implementation, engineering control effectiveness, ventilation stability, and organizational capacity within SMEs. Across all examined jurisdictions, measured exposure conditions frequently diverged from formal occupational exposure limits, particularly during high-emission operations such as spray-painting, solvent mixing, and cleaning processes. The review identifies SMEs as structural amplifiers of exposure variability due to insufficient local exhaust ventilation, inconsistent maintenance of engineering systems, and limited occupational hygiene infrastructure. A novel typology of SME exposure-control environments was developed, consisting of controlled-stable, compliance-driven, fragmented-control, and reactive SMEs. Comparative synthesis further identified three distinct occupational exposure governance paradigms: preventive and engineering-oriented (EU), compliance-oriented (USA), and transitional hybrid (Ukraine). The findings additionally indicate that conventional time-weighted exposure metrics insufficiently capture episodic peak exposures relevant to respiratory sensitization risks associated with isocyanates. **Conclusion:** This review proposes a systems-oriented conceptual framework for interpreting occupational exposure variability in automotive coatings SMEs by integrating regulatory governance, engineering controls, and indoor environmental dynamics. The findings demonstrate that effective occupational risk reduction depends more strongly on implementation capacity and ventilation performance than on formal regulatory compliance alone.

Keywords: occupational exposure; automotive coatings; SMEs; VOCs; isocyanates; indoor air quality; ventilation; peak exposure; exposure variability; industrial hygiene.

INTRODUCTION

Automotive coatings manufacturing is a chemically intensive industrial sector characterized by the use of complex formulations designed to provide corrosion resistance, durability, and aesthetic properties to vehicle surfaces (Sparer et al., 2004; Moura et al., 2024). During production and application processes, workers are exposed to a range of hazardous substances, including volatile organic compounds (VOCs), isocyanates, and solvent-based mixtures, which present significant occupational risk exposure, primarily through inhalation and dermal routes (Liu et al., 2009; Xiao et al., 2024; Moura et al., 2024). These risks are strongly dependent on workplace environmental conditions, including ventilation efficiency and the effectiveness of engineering control systems. Indoor air quality (IAQ) in automotive coatings facilities is a critical determinant of occupational exposure, particularly in SMEs where engineering controls and ventilation systems are often insufficiently implemented.

Among the most critical hazards in this sector are isocyanates, widely used in polyurethane coatings due to their performance advantages. Occupational exposure to isocyanates has been consistently associated with respiratory sensitization and

occupational asthma, which can develop even at low exposure levels and may persist after exposure cessation (Coureau et al., 2021; Word et al., 2022; Sabbioni & Pugh, 2022). In parallel, VOCs such as toluene and xylene contribute to acute and chronic health effects, including neurotoxicity and respiratory irritation, particularly in environments where exposure controls are insufficient or ventilation is inadequate (Alonso-Perarnau et al., 2022; Liao et al., 2022; Dehghan Haghighi et al., 2022).

Despite technological advances in coating formulations, including the introduction of waterborne and low-VOC systems, occupational risk exposure remains significant, particularly in small and medium-sized enterprises (SMEs), where the implementation of engineering controls, exposure monitoring systems, and occupational hygiene infrastructure may be limited or inconsistently applied (Belosi et al., 2023; Badea et al., 2024). SMEs constitute a major share of the automotive coatings and refinishing sector, especially in transitional economies, where risk mitigation practices often depend on variable application of environmental controls rather than systematic exposure management. This contributes to persistent disparities in workplace exposure conditions and overall risk reduction effectiveness (Mølgaard et al., 2015; Keer et al., 2018).

From an occupational risk management perspective, environmental control strategies are influenced by differing regulatory approaches across jurisdictions. The European Union applies a preventive, risk-based framework supported by continuously updated exposure limit values, reflecting advances in exposure science and hazard assessment, while the United States relies on enforceable permissible exposure limits established by the Occupational Safety and Health Administration (OSHA) (OSHA, 1970; CEU, 1998; Schneider et al., 2022). These differences affect how environmental and engineering controls are implemented in practice and shape workplace exposure reduction strategies in occupational settings.

In Ukraine, occupational safety legislation is currently undergoing harmonization with EU directives, including the adoption of chemical safety regulations aligned with REACH and GHS principles; however, implementation and enforcement remain uneven, particularly in SME-dominated sectors where institutional oversight and technical capacity are limited (Verkhovna Rada of Ukraine, 2022; Ecolitic, 2025). As a result, discrepancies may persist between formal regulatory alignment and actual effectiveness of occupational risk control measures in industrial environments.

Despite increasing attention to chemical safety harmonization, particularly in transitional regulatory systems such as Ukraine, there remains limited integrated evidence comparing how regulatory structures translate into real-world exposure control effectiveness in SME-dominated industrial contexts. Existing studies tend to focus either on toxicological hazards or on national regulatory frameworks in isolation, lacking a unified comparative analysis of exposure pathways, control effectiveness, and enforcement translation.

This review addresses this gap by synthesizing evidence on occupational exposure to VOCs and isocyanates in automotive coatings SMEs, focusing on (i) exposure pathways, (ii) effectiveness of environmental and engineering controls, and (iii) regulatory implementation across the EU, USA, and Ukraine. It is hypothesized that, despite formal harmonization efforts with EU chemical safety legislation, significant gaps persist in Ukraine between regulatory alignment and the actual effectiveness of occupational risk control measures, particularly for isocyanates and volatile organic compounds in SME environments.

METHODOLOGY

This narrative critical review synthesizes peer-reviewed literature, industrial hygiene studies, and regulatory documents retrieved from Scopus, Web of Science, and institutional databases (including EU-OSHA and OSHA). The analysis covers publications from 2000 to 2025 to capture both established evidence and recent developments in exposure assessment and control technologies. The review critically evaluates occupational exposure research and regulatory frameworks related to automotive coatings manufacturing, with a specific emphasis on small and medium-sized enterprises (SMEs) as the primary industrial context due to their distinctive limitations in occupational hygiene infrastructure and exposure control implementation. A narrative review design was selected due to the heterogeneity of available evidence, which includes exposure assessment studies, industrial hygiene investigations, and regulatory frameworks that differ in methodological design, measurement approaches, and reporting structures.

The literature base includes peer-reviewed scientific publications, occupational exposure and environmental monitoring studies, and institutional technical reports issued by international and national bodies, including the European

Agency for Safety and Health at Work and the Occupational Safety and Health Administration, as well as relevant Ukrainian legislative and technical documents related to chemical safety and occupational risk management. The selection of sources was guided by thematic relevance to (i) occupational exposure to hazardous substances in automotive coatings processes, particularly VOCs and isocyanates, (ii) environmental and engineering control measures for exposure reduction, and (iii) regulatory exposure limit frameworks and their influence on workplace risk conditions in SME environments.

A structured comparative narrative synthesis was applied to examine similarities and differences in occupational risk exposure patterns and control strategies across the European Union, the United States, and Ukraine. The analysis focuses on how regulatory frameworks translate into practical environmental control measures, including engineering controls (e.g., ventilation systems and containment technologies), administrative controls, and personal protective equipment, with SMEs serving as the primary analytical context due to their known limitations in occupational hygiene infrastructure and exposure monitoring capacity.

The synthesis is qualitative in nature and emphasizes thematic interpretation of occupational risk exposure patterns, environmental control effectiveness, and implementation gaps rather than quantitative aggregation or meta-analysis. Particular attention is given to the relationship between formal exposure limit systems and their practical effectiveness in reducing real-world occupational risk exposure in industrial settings, especially within SME-dominated segments of the automotive coatings sector.

Although a narrative review design was applied, source selection and synthesis were guided by thematic relevance to exposure pathways, control effectiveness, and regulatory implementation, ensuring consistency in cross-study comparison and reducing selection bias.

OCCUPATIONAL RISK EXPOSURE AND ENVIRONMENTAL CONTROL FRAMEWORKS IN AUTOMOTIVE COATINGS (EU, USA, UKRAINE)

Occupational risk in automotive coatings manufacturing emerges from the interaction between chemical emission intensity, indoor environmental control efficiency, and the regulatory capacity to translate exposure standards into effective workplace practice. Across jurisdictions, this interaction is strongly modified by organizational scale, with small and medium-sized enterprises (SMEs) demonstrating greater exposure variability due to limited engineering controls (Halbach et al., 2023; Sivilka et al., 2014), insufficient occupational hygiene infrastructure (Lee et al., 2024; Badea et al., 2024), and weak exposure monitoring capacity (Halbach et al., 2023; Floeder et al., 2025). Consequently, occupational exposure in SMEs is influenced not only by chemical use itself, but also by reduced ability to maintain stable indoor environmental conditions and consistent control performance.

This issue is particularly significant in automotive coatings operations, where volatile organic compounds (VOCs) and isocyanates constitute dominant airborne contaminants. Their occupational relevance extends beyond conventional toxicological thresholds because exposure conditions are characterized by intermittent peak emissions, transient concentration spikes, and confined indoor microenvironments. Under such conditions, exposure outcomes are governed by the combined effects of ventilation efficiency, evaporation kinetics, spray aerosol formation, and worker proximity to emission sources. These mechanisms are directly associated with respiratory sensitization, occupational asthma, and neurotoxic

effects under both acute and chronic exposure scenarios (Rother et al., 2021; Reindl et al., 2026). Isocyanates are of particular concern because sensitization may develop even at relatively low exposure levels, after which subsequent reactions can be triggered by minimal exposures, indicating limitations of purely threshold-based occupational risk models (Reindl et al., 2026).

Comparative regulatory frameworks

Although the European Union, the United States, and Ukraine employ different occupational safety architectures, all systems attempt to address the same fundamental challenge: controlling chemically complex indoor environments characterized by variable emission profiles and task-specific exposure peaks (Anhäuser et al., 2024; Hahn et al., 2024; Martins et al., 2025). Consequently, regulatory effectiveness depends not only on formal exposure limits, but also on the practical ability to sustain stable environmental control conditions within real production settings.

In the European Union, occupational risk management is structured around a preventive and hierarchy-based framework emphasizing hazard anticipation, substitution, and engineering controls through Directive 89/391/EEC and Directive 98/24/EC. Continuous revision of exposure limits and risk assessment approaches enables stronger integration of emerging toxicological evidence into occupational practice. Empirical evidence suggests that this preventive orientation contributes to more consistent implementation of technical controls and comparatively lower exposure levels in highly regulated industrial environments (EU, 1989; CEU, 1998).

By contrast, the United States applies a compliance-oriented regulatory model based on enforceable Permissible Exposure Limits (PELs) under the Occupational Safety and Health Act. While this system provides legal enforceability, many exposure limits remain partially disconnected from current toxicological understanding of coating-related chemicals and mixed solvent exposures. As a result, regulatory compliance does not necessarily correspond to optimal exposure prevention under contemporary production conditions (Schneider et al., 2022; Schenk et al., 2024; NIOSH, 2026).

Ukraine represents a transitional regulatory system undergoing gradual harmonization with EU chemical safety principles, including GHS classification and REACH-aligned approaches. However, convergence at the legislative level has not yet produced equivalent convergence in implementation capacity. Persistent limitations in exposure monitoring, engineering control deployment, and institutional enforcement remain particularly evident in SME-dominated sectors, where compliance often functions as an administrative requirement rather than as a fully operational exposure reduction system (Schenk et al., 2015; Badea et al., 2024; EcoPolitic, 2025).

Cross-jurisdictional synthesis

Taken together, the comparative evidence indicates that occupational exposure outcomes are determined less by formal regulatory architecture alone than by the interaction between regulatory design, environmental control performance, and organizational implementation capacity (Table 1). These regulatory differences produce varying capacities to stabilize workplace exposure conditions and reduce airborne contaminant variability across jurisdictions (Tynkkynen et al., 2015; Schenk & Johanson, 2019; Schenk et al., 2008; Högberg & Järnberg, 2023; Clean Air for Ukraine, 2020; EEAS, 2024).

Despite structural differences between regulatory systems, SMEs consistently remain the most vulnerable operational environments due to reduced technical and organizational capacity for maintaining effective exposure controls. This suggests that organizational scale functions as a critical mediator between formal regulation and actual indoor environmental exposure conditions (Sankaran et al., 2023; Badea et al., 2024; De Raevé et al., 2024; Gržinić et al., 2025).

Key occupational risk and implementation gaps

The integrated evidence identifies three interconnected structural gaps that persist across regulatory systems.

First, an enforcement–implementation gap exists between formal occupational safety requirements and the practical ability to maintain stable exposure control conditions. Variability in inspection intensity, occupational hygiene expertise, and monitoring infrastructure directly influences the effectiveness of engineering and administrative controls (MacEachen et al., 2016; Schubert et al., 2026). Recent evidence further indicates that limitations in inspectorate capacity, including staffing shortages and incomplete inspection coverage, can substantially reduce the effectiveness of enforcement systems in practice (Controller and Auditor General, 2025).

Second, an exposure assessment gap remains evident where occupational exposure limits are insufficiently adapted to complex short-term emission conditions. Conventional time-weighted exposure metrics may underestimate episodic peak exposures associated with spraying, solvent evaporation, and cleaning processes, particularly for sensitizing agents such as isocyanates (Coureau et al., 2021; Smith, 2022; Sabic et al., 2024).

Third, a systemic SME capacity gap acts as a cross-cutting determinant of occupational risk. SMEs consistently demonstrate lower adoption of engineering controls and greater reliance on administrative measures and personal protective equipment, which are inherently more dependent on behavioural compliance and therefore less stable as long-term exposure mitigation strategies. Collectively, these interacting gaps indicate that occupational risk in automotive coatings manufacturing should be understood as an emergent property of coupled regulatory, technical, and indoor environmental systems rather than as a consequence of isolated workplace factors.

OCCUPATIONAL EXPOSURE AND INDOOR ENVIRONMENTAL CONDITIONS IN AUTOMOTIVE COATINGS FACILITIES

Automotive coatings facilities represent complex indoor occupational environments in which exposure conditions are determined by the interaction between chemical emission sources, process characteristics, and environmental control performance (Moura et al., 2023; Moura et al., 2024). Major exposure agents of concern in this context include volatile organic compounds (VOCs), isocyanates, and complex mixtures of solvent-based aerosols, all of which may be generated during routine industrial and occupational processes such as spraying, mixing, curing, and cleaning operations. Because these activities occur in semi-confined indoor settings with variable ventilation efficiency, airborne contaminant concentrations exhibit pronounced temporal and spatial variability, particularly in small and medium-sized enterprises (SMEs) where engineering controls and exposure monitoring systems are often limited or inconsistently maintained (Hahn et al., 2021; Moura et al., 2024).

Table 1. Comparative occupational risk and chemical exposure control frameworks: Ukraine vs EU vs USA

Criterion	Ukraine	European Union	United States
Core OSH legal framework	Labour protection law (No. 2694-XII, 1992)	Framework Directive 89/391/EEC establishing employer responsibility for occupational safety and prevention	Occupational Safety and Health Act (1970), establishing federal OSH requirements enforced by OSHA
Regulatory approach	Hybrid framework combining general OSH legislation with subordinate regulations; fragmented implementation structure	Integrated preventive framework based on risk hierarchy and employer responsibility	Predominantly compliance-based system with enforceable federal standards
Chemical regulation system	Law No. 2804-IX (2022); transitional alignment with EU REACH/CLP system	REACH and CLP regulations governing registration, evaluation, authorisation, and restriction of chemicals	Toxic Substances Control Act (TSCA), regulating chemicals with comparatively narrower scope
Chemical registration system	Mandatory registration of substances under emerging REACH-aligned framework	Comprehensive registration and evaluation system under REACH covering manufactured and imported substances	Inventory-based registration system under TSCA with reduced data requirements compared to REACH
Classification and labelling (GHS)	Gradual implementation of GHS-aligned classification system under chemical safety legislation	Fully harmonised classification and labelling system under CLP Regulation	GHS implemented via OSHA Hazard Communication Standard
Occupational exposure limits (OELs)	OELs partially based on legacy hygienic standards; ongoing revision process	Regularly updated health-based OELs informed by scientific risk assessment	Permissible Exposure Limits (PELs), many of which are outdated and infrequently revised
Risk management approach	Predominantly compliance-oriented system with emphasis on formal documentation	Preventive hierarchy-based system prioritising substitution and engineering controls	Mixed compliance–enforcement system with strong inspection-based enforcement
Employer obligations	Mandatory training, information provision, medical surveillance, and workplace safety duties	Legal obligation to prevent risks through technical and organisational measures and worker training	General Duty Clause requiring employers to maintain a workplace free from recognized hazards
Implementation and enforcement	Developing institutional capacity with ongoing enforcement and coordination challenges	Strong enforcement via EU-OSHA and national competent authorities	Dual federal–state enforcement system under OSHA
Current regulatory trends	Ongoing harmonisation with EU REACH/CLP and GHS frameworks	Continuous updating of chemical risk governance, including carcinogens and reprotoxic substances	Incremental updates focused on enforcement rather than systemic regulatory reform

Note: Based on EU Directive 89/391/EEC, REACH Regulation (EC) No 1907/2006, CLP Regulation (EC) No 1272/2008, OSHA (1970), TSCA, and Ukrainian laws No. 2694-XII and No. 2804-IX (2022)

From an exposure science perspective, occupational risk in automotive coatings environments cannot be interpreted solely through the intrinsic toxicological properties of individual chemicals. Exposure outcomes are additionally shaped by emission intensity, aerosol formation, ventilation efficiency, and worker proximity to active emission zones. Consequently, these facilities operate as dynamic indoor exposure systems in which short-term concentration peaks may contribute disproportionately to cumulative occupational health risk (Virji & Kurth, 2021; Hahn et al., 2021).

Hazardous exposure pathways in automotive coatings environments

Occupational exposure occurs through multiple interconnected pathways, including inhalation of airborne contaminants, dermal absorption from liquid coating formulations, and secondary contact with contaminated indoor surfaces. These pathways become particularly significant during spray-painting and paint-

mixing operations, where atomization processes increase aerosol dispersion and worker contact with reactive chemical species (Schäferhenrich et al., 2023; Sabic et al., 2024).

Among the identified contaminants, isocyanates used in polyurethane-based coatings represent the most critical respiratory hazard because of their established association with occupational asthma and respiratory sensitization (Gomez-Lopez et al., 2021; Coureau et al., 2021). Toxicological and epidemiological evidence indicates that sensitization may develop even at relatively low exposure levels and may persist after exposure cessation, suggesting that threshold-based exposure concepts may incompletely characterize long-term respiratory risk (Coureau et al., 2021). Field investigations further demonstrate that spraying operations frequently generate short-duration peak exposures exceeding time-weighted average conditions, emphasizing the importance of episodic exposure events in overall risk characterization (Pronk et al., 2007).

VOCs, including toluene, xylene, and ethylbenzene, constitute an additional major exposure category associated with respiratory irritation, neurotoxicity, and systemic toxic effects (Saeedi et al., 2024). Their indoor concentration profiles are strongly influenced by evaporation kinetics, ventilation performance, and spatial confinement (D'Amico et al., 2020; Park et al., 2026). Monitoring studies consistently report elevated VOC concentrations in poorly ventilated workshops, particularly in SMEs lacking effective local exhaust ventilation systems or enclosed spray environments (Mølgaard et al., 2015).

Indoor environmental quality (IEQ) in automotive coatings facilities is therefore closely dependent on engineering control performance and process configuration. Ventilation design, airflow distribution, containment efficiency, and process layout collectively influence contaminant dispersion and pollutant persistence within indoor air. In SMEs, insufficient investment

in ventilation infrastructure and process enclosure contributes to unstable exposure conditions characterized by uncontrolled concentration peaks during spraying, cleaning, and solvent-handling operations (Keer et al., 2018; Xiao et al., 2024).

Taken together, the available evidence indicates that automotive coatings facilities function as direct interfaces between occupational exposure processes and indoor environmental contamination dynamics. Across studies, SMEs consistently demonstrate greater exposure variability and lower control stability, indicating that organizational capacity is a major determinant of workplace environmental risk conditions (Song & Chun, 2021; Chun et al., 2021; Wang et al., 2023).

To compare regulatory variability in occupational exposure thresholds for major hazardous substances used in automotive coatings operations, occupational exposure limits (OELs) across jurisdictions are summarized in Table 2.

Table 2. Comparative occupational exposure limits (OELs) for key substances in automotive coatings: Ukraine vs European Union vs United States

Substance	Ukraine	European Union	United States
HDI (hexamethylene diisocyanate)	No harmonised OEL (regulatory gap / limited coverage)	0.034 mg/m ³ (TWA, NCO-equivalent fraction)	0.035 mg/m ³ (ceiling limit, OSHA PEL)
TDI (toluene diisocyanate)	0.05 mg/m ³ (approx.) (legacy hygienic standard)	0.005 ppm (0.036 mg/m ³ (approx.), indicative OEL)	0.02 ppm (0.14 mg/m ³ (approx.), ceiling limit, OSHA PEL)
MDI (methylene diphenyl diisocyanate)	Outdated / inconsistently applied exposure limits	0.005 ppm (indicative OEL)	0.02 ppm (ceiling limit, OSHA PEL)
Toluene	50 mg/m ³ (approx.) (legacy hygienic standard)	50 ppm (192 mg/m ³ (approx.), EU OEL framework value)	200 ppm (OSHA PEL, TWA)
Xylene	50 mg/m ³ (approx.) (legacy hygienic standard)	50 ppm (221 mg/m ³ (approx.), EU OEL framework value)	100 ppm (OSHA PEL, TWA)
Total VOCs	No unified collective exposure limit	No aggregate OEL (substance-specific regulation under REACH framework)	No unified PEL for total VOC exposure

Note: Occupational exposure limits (OELs) differ across jurisdictions not only in numerical values but also in underlying regulatory concepts, including time-weighted averages (TWA), ceiling limits, indicative health-based values, and legacy hygienic standards. Consequently, the table is intended to illustrate regulatory heterogeneity and framework variability rather than strict numerical equivalence. Conversion between ppm and mg/m³ depends on substance-specific molecular weight and standard conditions (25°C, 1 atm), and differences in converted values reflect chemical-specific parameters rather than inconsistencies in reported data

The data presented in Table 2 demonstrate substantial heterogeneity in occupational exposure limit frameworks across the European Union, United States, and Ukraine, reflecting differences in precautionary principles, toxicological interpretation, and occupational risk governance strategies.

Analysis of occupational exposure limit discrepancies

A major regulatory divergence concerns isocyanates (HDI, TDI, and MDI), which represent critical sensitizing agents in automotive coatings environments. Within the European Union, comparatively lower OEL values reflect a preventive risk management approach based on evidence that respiratory sensitization may occur even at very low exposure levels without a clearly identifiable safe threshold (Rother & Schlüter, 2021; EPRS, 2023; CEU, 2024). Accordingly, the EU framework prioritizes exposure minimization rather than strict reliance on compliance thresholds alone.

By contrast, the United States OSHA system is primarily structured around enforceable permissible exposure limits (PELs), several of which remain derived from historical toxicological assumptions and have not been comprehensively revised to reflect current understanding of chronic low-dose exposure and sensitization mechanisms. As a result, formal

regulatory compliance may not necessarily correspond to effective prevention of adverse health outcomes in contemporary coatings environments (Hargitai et al., 2024; Park, 2025).

Ukraine represents a transitional regulatory framework undergoing harmonization with EU-aligned chemical safety legislation, including REACH and GHS principles. However, implementation gaps remain evident in exposure limit revision processes, monitoring infrastructure, and technical enforcement capacity, particularly for substances such as HDI and mixed solvent systems (KFT Chemieservice, 2024; EBA, 2025; Semenova, 2025).

From a systems perspective, these differences can be interpreted as three distinct occupational exposure governance paradigms: preventive (EU), compliance-oriented (USA), and transitional hybrid (Ukraine). Nevertheless, the practical effectiveness of each system remains strongly mediated by workplace-level implementation capacity. Across all jurisdictions, small and medium-sized enterprises (SMEs) tend to exacerbate existing regulatory limitations, as weaker implementation of engineering control measures, combined with insufficient exposure assessment and monitoring

practices, reduces their capacity to maintain consistently stable indoor environmental conditions and effectively manage occupational exposure variability.

To complement the regulatory comparison, occupational health outcomes associated with isocyanate- and solvent-exposed spray-painting workers are summarized in Table 3.

Table 3. Occupational health outcomes in isocyanate- and solvent-exposed spray painting workers

Agent	Health outcome	Reported prevalence / risk estimate	Study population	Source
Isocyanates (mixed PPI/TDI)	Occupational asthma (OA)	11.8% confirmed OA cases	Paint shop workers (n=51)	Séguin et al., 1987
Isocyanates (HDI oligomers)	Asthma-like respiratory symptoms	Significant exposure–response relationship (no pooled prevalence reported)	Spray painters (n=581)	Pronk et al., 2007
Isocyanates (TDI, historical exposure)	Occupational asthma incidence	5–6% annual incidence under historical exposure conditions	Industrial manufacturing workers	Derived from Pronk et al., 2007 and historical industrial TDI cohort data
Isocyanates (TDI, exposure control)	Reduced occupational asthma incidence	<1% incidence following exposure reduction below exposure limits	Foam production workers	Derived from Pronk et al., 2007 and historical industrial TDI cohort data
Isocyanates (poorly controlled spray operations)	Asthma symptom prevalence	Up to 41% reported symptom prevalence	End-user spray painting industry	Pronk et al., 2007 (literature synthesis)
VOCs (solvent exposure)	Respiratory symptoms (wheeze, rhinitis)	Wheeze: 8.6% vs 3.6%; rhinitis: 33.1% vs 19.1% (exposed vs controls)	Exposed workers vs control group	Sari-Minodier et al., 2009
Mixed exposure (isocyanates)	Occupational asthma prevalence	3.0% OA prevalence	Cross-sectional worker cohort (n=366)	An et al., 2013

Note: Variability reflects heterogeneity in study design, exposure assessment methods, and outcome definitions

Occupational health outcomes associated with exposure conditions

The evidence summarized in Table 3 demonstrates a clear relationship between exposure intensity, engineering control performance, and the prevalence of respiratory and neurological health effects among spray-painting workers. Importantly, measured indoor contaminant concentrations frequently diverge from formal occupational exposure limits, particularly in SMEs where ventilation performance and exposure control systems are inconsistent (Mølgaard et al., 2015; Bennett et al., 2016).

For isocyanates, field measurements indicate that short-term peak exposures during spraying operations may exceed regulatory limits even when time-weighted average values remain formally compliant. This finding highlights an important limitation of averaging-based exposure assessment approaches in dynamic indoor environments characterized by episodic aerosol generation (Flack et al., 2012).

Similarly, VOC concentrations exhibit substantial temporal variability depending on process stage, ventilation efficiency, and enclosure conditions. Episodic concentration exceedances are most frequently observed during spraying and cleaning operations, where rapid solvent evaporation and inadequate airflow management contribute to transient accumulation of airborne contaminants (Mølgaard et al., 2015; Sabic et al., 2024).

Control effectiveness and implementation limitations

Although occupational risk management formally follows the hierarchy of controls, practical effectiveness remains strongly dependent on organizational and technical capacity, particularly within SMEs (de Rouw et al., 2021). Substitution with low-VOC or waterborne coating systems represents the

most effective long-term exposure reduction strategy because it directly reduces emission generation at the source. However, implementation is frequently constrained by economic limitations, coating performance requirements, and technological compatibility (Keer et al., 2018; Hōrak, 2020).

Engineering controls, including local exhaust ventilation systems and enclosed spray booths, remain the primary mechanisms for reducing airborne contaminant concentrations and may reduce exposures by more than 90% under optimized operating conditions (Liu et al., 2021). Nevertheless, their effectiveness depends on maintenance quality, airflow stability, and process integration, all of which are frequently inconsistent in SME environments.

Administrative controls are widely implemented but often remain procedural rather than functionally integrated into exposure prevention systems, limiting their effectiveness under variable production conditions (Ohlander et al., 2020; Basso et al., 2020). Personal protective equipment (PPE), although extensively used, represents the least stable layer of protection because its effectiveness depends on worker compliance, correct equipment selection, and maintenance practices (Heederik & Preller, 2006; Bello et al., 2008; Ceballos et al., 2014).

Overall, the evidence indicates that SMEs exhibit a persistent implementation gap between formal occupational safety requirements and actual exposure control performance, primarily due to limited engineering infrastructure, insufficient occupational hygiene capacity, and weak exposure monitoring systems (Masi et al., 2014; Tejamaya et al., 2021). Consequently, indoor environmental conditions in automotive coatings facilities should be understood as dynamic emission systems governed more strongly by ventilation performance and process-related emission intensity than by regulatory compliance status alone.

INTEGRATED DISCUSSION: EXPOSURE PATTERNS, REGULATORY TRENDS AND RISK CONTROL GAPS

The integrated evidence from exposure assessment studies, occupational hygiene research, and comparative regulatory analysis indicates that occupational risk in automotive coatings manufacturing is governed not only by chemical hazard profiles or formal exposure limits, but by the interaction between regulatory implementation, indoor environmental conditions, and engineering control performance. This interaction is particularly critical in small and medium-sized enterprises (SMEs), where limited technical infrastructure and reduced occupational hygiene capacity contribute to increased variability in airborne concentrations of volatile organic compounds (VOCs) and isocyanates (Pronk et al., 2006; Moura et al., 2024; IRSST, 2025).

Regulatory diversity and exposure–control misalignment

Despite substantial differences in occupational safety frameworks across the European Union, the United States, and Ukraine, a consistent discrepancy remains between formal occupational exposure limits (OELs) and measured indoor exposure conditions in automotive coatings environments. The European Union applies a preventive and science-oriented regulatory approach based on periodic revision of exposure limit values, resulting in comparatively stronger alignment with current toxicological evidence, particularly for respiratory sensitizers such as isocyanates (Jones, 2024; CEU, 2024).

By contrast, the United States OSHA framework relies on enforceable Permissible Exposure Limits (PELs), several of which remain derived from legacy toxicological datasets and therefore show limited responsiveness to contemporary exposure science. Ukraine represents a transitional regulatory system in which formal harmonization with EU chemical safety legislation is progressing; however, implementation capacity, exposure monitoring infrastructure, and enforcement consistency remain uneven, especially in SME-dominated industrial sectors.

Although international frameworks such as REACH and GHS have promoted regulatory convergence, harmonization of formal standards has not resulted in equivalent convergence in practical exposure control. Across all jurisdictions, measured exposure conditions continue to be strongly influenced by local implementation capacity and engineering control effectiveness rather than by regulatory alignment alone. These cross-regional differences in regulatory structure and implementation are summarized in Figure 1, which illustrates the regulatory–implementation mismatch across the EU, United States, and Ukraine.

DIMENSION	EUROPEAN UNION (EU)	UNITED STATES (US)	UKRAINE
OEL updating frequency	High (science-driven updates)	Low (legacy PELs persist)	Medium–low (partial harmonization)
Enforcement capacity	High	High–medium	Low–medium
SME compliance support	Structured (EU-OSHA programs)	Variable	Limited
Engineering control penetration	High	Medium	Low
Exposure monitoring	Systematic	Partial	Sporadic
Real-world protection effectiveness	High–moderate	Moderate	Low–moderate
	High / Strong (robust system or performance)	Medium / Moderate (partial or uneven implementation)	Low / Weak (significant limitations or gaps)

Figure 1. Regulatory–implementation mismatch matrix across the EU, United States, and Ukraine

Note: The matrix illustrates cross-regional differences in occupational exposure governance, implementation capacity, and practical effectiveness of worker protection measures

SMEs as amplifiers of exposure variability

The findings consistently identify SMEs as a structural modifier of occupational exposure dynamics rather than as an isolated high-risk subgroup. Compared with larger industrial facilities, SMEs more frequently demonstrate limited implementation of local exhaust ventilation systems, inconsistent maintenance practices, and reduced integration of occupational hygiene management (Mølgaard et al., 2015; See et al., 2026).

As illustrated in Figure 2, these constraints create a nonlinear amplification effect in which relatively minor deficiencies in ventilation performance, process enclosure, or operational control produce disproportionate increases in airborne concentrations of VOCs and isocyanates. Consequently, the practical effectiveness of otherwise well-established regulatory frameworks becomes highly dependent on organizational scale and technical implementation capacity.

This effect is particularly important in automotive coatings operations characterized by intermittent high-emission activities such as spraying, solvent mixing, and surface cleaning, where exposure conditions fluctuate rapidly and are strongly affected by ventilation efficiency and spatial confinement (Tischer & Meyer, 2022; Moura et al., 2024).

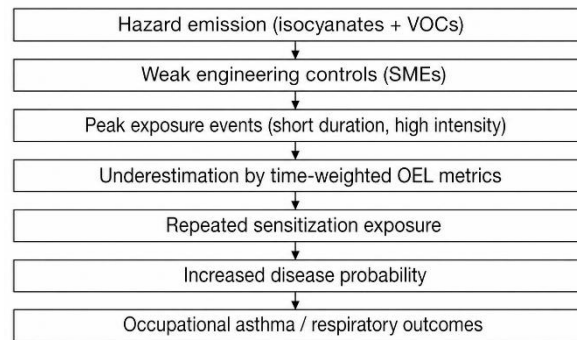


Figure 2. SME risk amplification mechanism

To structure the observed heterogeneity in SME exposure conditions, four SME risk patterns are identified based on the interaction between engineering control capacity, regulatory implementation strength, and exposure dynamics.

Controlled-stable SMEs are characterized by effective engineering controls, systematic monitoring, and stable exposure conditions with limited peak events.

Compliance-driven SMEs operate under formal regulatory compliance, where time-weighted exposure limits are generally met, but short-term peak exposures remain insufficiently controlled.

Fragmented-control SMEs exhibit partial and inconsistent implementation of control measures, resulting in high exposure variability and frequent uncontrolled peaks.

Reactive SMEs represent low-control environments with minimal engineering systems, reliance on personal protective equipment, and exposure conditions dominated by high-intensity episodic emissions.

These patterns represent a continuum of implementation capacity and exposure control effectiveness across SME environments.

Exposure dynamics and indoor environmental implications

Automotive coatings facilities function as dynamic indoor emission systems characterized by episodic peak exposures and substantial temporal variability. Under these conditions, time-

weighted average exposure metrics may insufficiently characterize short-term concentration peaks that are increasingly recognized as critical determinants of respiratory sensitization risk, particularly for isocyanates (Pronk et al., 2007; IRSST, 2025).

Occupational asthma studies further suggest that sensitization may develop at relatively low exposure levels, after which subsequent clinical responses can occur following minimal re-exposure events, highlighting limitations of threshold-based regulatory assumptions (Daniels, 2018; Coureau et al., 2021). VOC exposure profiles are similarly influenced by evaporation kinetics, ventilation effectiveness, aerosol generation, and

workspace confinement, resulting in heterogeneous exposure patterns that are difficult to capture using conventional monitoring strategies, especially within SMEs (Schendel & Rogasch, 2021; Tischer & Roitzsch, 2022).

The interaction between regulatory conditions, technical controls, and operational practices is conceptualized in Figure 3, which presents the integrated Exposure–Control–Health outcome interaction model for SME automotive coatings environments. Within this framework, deficiencies in engineering controls act as key mediators linking workplace environmental conditions with increased occupational exposure variability and adverse health outcomes.

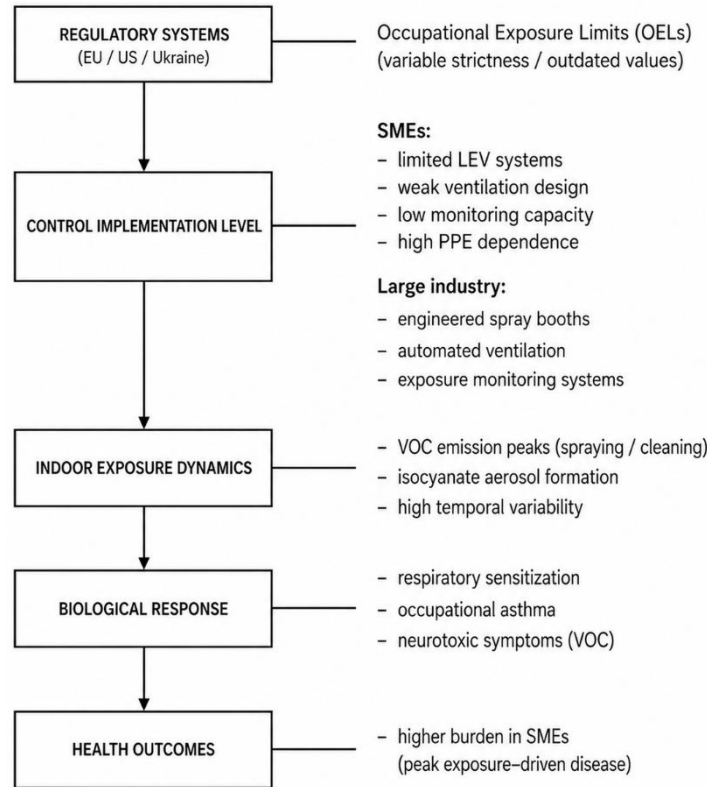


Figure 3. Exposure–Control–Health outcome interaction model in SME automotive coatings environments (conceptual framework diagram)

Implications for occupational risk governance

The integrated findings indicate that occupational exposure in automotive coatings manufacturing should be interpreted as an emergent property of interacting regulatory, environmental, and engineering systems rather than as a direct consequence of chemical hazard classification alone. Across all examined regulatory contexts, exposure outcomes were more strongly associated with ventilation performance, implementation consistency, and operational control capacity than with formal regulatory structure itself.

This interaction is further illustrated in Figure 4, which demonstrates the SME-specific exposure–control failure loop, whereby insufficient engineering controls contribute to contaminant accumulation, increased peak exposure events, and reduced effectiveness of occupational risk management measures.

Overall, the evidence suggests that continued regulatory harmonization alone is unlikely to substantially reduce occupational exposure unless accompanied by improved implementation of engineering controls, ventilation performance, and accessible occupational hygiene practices at

the SME level, where exposure variability remains greatest and control systems are most vulnerable to operational deficiencies.

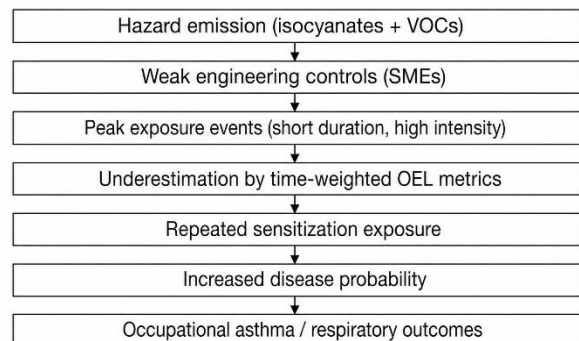


Figure 4. Exposure–control failure loop (SME-specific)

CONCLUSION

This review advances the understanding of occupational exposure in automotive coatings manufacturing by moving beyond a conventional toxicological or regulatory overview toward an integrated systems-based interpretation of

occupational risk in SME environments. Rather than treating exposure as an isolated consequence of hazardous chemical use alone, the study demonstrates that occupational risk emerges from the interaction between regulatory implementation, engineering control performance, and indoor environmental dynamics.

A central scientific contribution of this review is the development of an integrated conceptual risk framework linking exposure variability to three interconnected system-level determinants: (i) regulatory governance structure, (ii) engineering and ventilation control effectiveness, and (iii) organizational implementation capacity within SMEs. Within this framework, automotive coatings facilities are interpreted as dynamic indoor emission systems in which occupational exposure is governed not only by toxicological properties of VOCs and isocyanates, but also by ventilation stability, aerosol generation, spatial confinement, and the ability of enterprises to maintain consistent exposure control conditions.

The review further introduces a novel typology of SME exposure-control environments, identifying four distinct SME risk patterns: controlled-stable SMEs, compliance-driven SMEs, fragmented-control SMEs, and reactive SMEs. This classification provides an original conceptual structure for interpreting heterogeneity in occupational exposure conditions across SME-dominated industrial settings. The proposed typology demonstrates that organizational scale acts as a critical mediator between formal regulatory requirements and actual workplace exposure outcomes. In particular, fragmented-control and reactive SMEs exhibit disproportionately elevated exposure variability due to unstable engineering controls, insufficient ventilation performance, and limited occupational hygiene infrastructure.

Another important contribution of this study is the cross-jurisdictional synthesis of occupational exposure governance across the European Union, the United States, and Ukraine. Unlike conventional comparative reviews focused primarily on legislative description, this analysis evaluates how different regulatory architectures translate into practical exposure-control effectiveness under real industrial conditions. The findings identify three distinct regulatory paradigms: a preventive and engineering-oriented EU model, a compliance-oriented U.S. model relying on enforceable exposure limits, and a transitional Ukrainian model characterized by ongoing harmonization with EU chemical safety frameworks but incomplete implementation capacity. The analysis demonstrates that formal regulatory convergence alone does not guarantee equivalent occupational protection outcomes, particularly within SMEs where technical implementation capacity remains limited.

Across all examined jurisdictions, a persistent exposure-implementation mismatch was identified. Measured

occupational exposure conditions frequently diverge from formal exposure limits, especially during high-emission activities such as spraying, solvent mixing, and cleaning operations. The findings further indicate that conventional time-weighted exposure metrics may insufficiently capture short-term episodic peak exposures that are increasingly recognized as critical determinants of respiratory sensitization risk, particularly for isocyanates.

Overall, this review proposes that occupational risk in automotive coatings manufacturing should be interpreted as an emergent property of coupled regulatory, technical, and environmental systems rather than as a direct function of chemical hazard classification alone. The study therefore contributes a systems-oriented conceptual framework for understanding exposure variability in SME environments and highlights the need to complement regulatory harmonization with improved engineering controls, ventilation performance, and occupational hygiene implementation strategies in SME-dominated sectors.

Author's statements

Contributions

Conceptualization: O.N., S.V.; Formal Analysis: O.N., S.V.; Investigation: O.N., S.V.; Methodology: O.N., S.V.; Project administration: S.V.; Supervision: S.V.; Visualization: O.N.; Writing – original draft: O.N., S.V.; Writing – review & editing: O.N., S.V.

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