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PERSPECTIVE

Risk assessment of occupational exposure to engineered and incidental nanomaterials: differences and challenges

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Abstract Occupational settings are increasingly dealing with nanomaterials, leading to significant concerns about health risks. Nanomaterials in occupational settings can be categorized as engineered and incidental nanomaterials. Projections indicate that more than eight million individuals across the globe will be exposed to engineered nanomaterials as part of their occupational activities, by the year 2029 and assessing the associated risks presents challenges to occupational health experts. Incidental nanomaterials exhibit inherent distinctions from their engineered counterparts, which exert a discernible influence on the outcomes of risk assessments. Notably, a pivotal distinction resides in the controlled nature of the manufacturing process for engineered nanomaterials, which enables meticulous regulation of their size, morphology, quantity, and chemical composition. Conversely, incidental nanomaterials do not benefit from such control, leading to inherent variability in these attributes. Distinguishing risk assessment procedures for incidental and engineered nanomaterials is crucial due to the different processes that generate them, leading to differences in parameters needed for risk assessment. Incidental nanomaterial risk assessments face unknown parameters, emphasizing the need for distinct methodologies.

Keywords Risk assessment · Nanomaterials · Nano-objects · Control banding · Metal 3D printing

Introduction

Activities related to nanomaterials have gained prominence as a paramount concern in occupational settings. Projections based on statistical data indicate that, by the year 2029, nearly 8 million individuals across the globe will find themselves exposed to engineered nanomaterials as part of their occupational activities [1, 2]. Naturally, if exposure to incidental nanomaterials is also considered, this number will be much larger. An extensive body of research has unveiled the potential health risks attributed to such exposure, encompassing detrimental outcomes like oxidative stress, tissue accumulation, and respiratory ailments [3, 4]. Furthermore, empirical findings have confirmed that the extent of occupational exposure to nanomaterials is indeed substantial [5–7]. Consequently, occupational health experts have refocused their attention on these working environments, prioritizing strategies for risk reduction arising from occupational exposure to nanomaterials.

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Different activities involved with nanomaterials

Occupational processes entailing engineered nanomaterials encompass a diverse array of activities, varying in scale from large industrial operations to medium-sized enterprises and small-scale applications [8]. It is imperative to emphasize the occupational hazards posed within laboratory environments dedicated to engineered nanomaterial research, where exposure risks are salient concerns demanding meticulous assessment and mitigation [9]. Moreover, it is crucial to acknowledge activities that may not inherently involve the intentional production or utilization of nanomaterials but result in the inadvertent generation of nanomaterial byproducts [10]. Within this context, engineered or manufactured nanomaterials denote those that are meticulously designed and fabricated for specific applications. In contrast, incidental nanomaterials encompass those that emerge as unintentional byproducts during various processes, such as welding, metalworking, and metal 3D printing [11]. This classification serves to differentiate between nanomaterials intentionally created for purposes and those arising serendipitously during different industrial activities.

Risk assessment of activities involving nanomaterials

The quantitative assessment of risks associated with activities involving nanomaterials confronts a series of inherent limitations, contributing to its subdued prevalence. Among the foremost constraints are the absence of agreed upon occupational exposure limits (despite the fact that some organizations [12] and researchers [13] have proposed such limits for some engineered nanomaterials), non-standardized and non-agreed sampling procedures, uncertainties about the consequences of exposure (especially long-term exposures) to nanomaterials, the elevated cost implications, and sporadic unavailability of requisite equipment, among other pertinent considerations [14]. Nevertheless, some organizations have proposed methods for sampling and other quantitative investigations of engineered nanomaterials [15, 16]. Consequently, semi-quantitative and qualitative methodologies for risk assessment have garnered increased traction in the evaluation of nanomaterial-related activities. This transition has yielded a spectrum of methodologies, with prominent options encompassing Monte Carlo simulations, Bayesian techniques, tiered approach [17], multi-criteria decision-making approaches, decision tree analyses, and control banding (CB) [18]. Upon meticulous scrutiny and juxtaposition of these methodologies, it becomes apparent that CB-based approaches, which officially gained prominence in 2008 with the introduction of the Nanotool method, confer a plethora of advantages while bearing fewer drawbacks [19–21]. In the wake of this recognition, several CB-based methods have surfaced, with notable examples being ANSES, Nanosafer, Guidance, ISO/TS12901-2, Stoffenmanager Nano, and Precautionary Matrix, representing a significant evolution in risk assessment strategies tailored for activities involving engineered nanomaterials [22].

Engineered nanomaterials vs. incidental nanomaterials

The existing frameworks primarily pertain to risk assessment within the domain of engineered nanomaterials. All CB-based methods discussed earlier have been meticulously crafted and tailored for the purpose of evaluating engineered nanomaterials [23]. Nevertheless, certain studies have ventured to extend these methodologies to appraise the risks associated with incidental nanomaterials [24]. However, it is imperative to acknowledge that incidental nanomaterials show inherent distinctions from their engineered counterparts, which exert a discernible influence on the outcomes of risk assessments. Notably, a pivotal distinction exists in the controlled nature of the manufacturing process for engineered nanomaterials, which enables meticulous regulation of their size, morphology, quantity, and chemical composition. Conversely, incidental nanomaterials do not benefit from such control, leading to inherent variability in these attributes [25]. Furthermore, a critical disparity arises in the level of awareness among individuals who encounter these materials. In the case of engineered nanomaterials, personnel, be they workers or researchers, possess comprehensive awareness of the presence of nanomaterials, along with precise knowledge about the specific materials involved in their tasks. This awareness is notably less assured in the context of incidental nanomaterials, with a significant proportion of employees remaining unaware of the generation of nanomaterials during numerous industrial processes [26].

Discussion

Control banding (CB)-based methods share a common structural framework and underlying principles, despite variations in the parameters that determine the risk [14]. In essence, these methods utilize the attributes of nanomaterials (and, in some methods, the properties of the parent material) to establish severity scores, while characteristics of the work environment, specific tasks or activities, and exposure variables are employed to derive probability scores [9]. It is important to note that the nature, quantity, and scoring methodology of these parameters associated with severity and probability scores may differ depending on the specific CB method in use. Once the severity and probability scores are ascertained, they are integrated within a risk level matrix to determine the overall risk level. Subsequently, based on the assessed risk level, recommendations for measures and general controls are provided to mitigate and manage the associated risks effectively [23].

These methodologies have found extensive application in assessing the risk associated with activities involving engineered nanomaterials. They have been deployed across a spectrum of contexts, ranging from a diverse array of occupational endeavors [23] to meticulously controlled laboratory settings [27]. A notable aspect of their utilization is the concurrent application and comparative analysis of these methods, an approach that has unveiled their respective merits and demerits to a considerable extent. In the case of the Nanotool method, a specific study has delved into its validation, accentuating the meticulous nature of the evaluation process. This validation endeavor entailed a rigorous comparison between the risk assessments conducted via the Nanotool method and the outcomes derived from quantitative measurements executed using innovative instrumentation. The noteworthy result of this investigation was the discernment of a robust correlation between these two approaches [28].

In a recently published review, Omari Shekaftik et al. reviewed all the studies conducted on the risk assessment of activities involving nanomaterials using control banding approach [29]. Among twenty-three studies included in their analysis, eighteen of them focused on activities involving engineered nanomaterials. The Nanotool method was the most frequently employed, utilized in twenty of these studies, with twelve studies exclusively employing this approach. These investigations encompassed diverse workplace settings, including engineered nanomaterial production, consumption, and research environments, yielding a wide spectrum of risk assessment outcomes. These ranged from activities associated with low risk [30, 31] to those linked with very high risk [32]. In contrast, only five studies specifically targeted the risk assessment of activities involving incidental nanomaterials. Notably, in all these studies, the Nanotool method was consistently used. Despite variations in the nature of the work activities under scrutiny, which encompassed welding, electronic waste management, and metal 3D printing, the risk assessment results across all five studies demonstrated strikingly similar outcomes, predominantly falling within risk levels RL3 and RL2 [33].

The principal challenge encountered when applying CB-based methodologies to evaluate activities involving incidental nanomaterials pertains to the pervasive uncertainty surrounding specific input data. In these methodologies, data pertaining to nanomaterial characteristics, encompassing factors such as size, shape, solubility, and toxicity, exert a significant influence on the determination of severity scores [34]. Concurrently, data related to task execution, including the type and method of task performance, as well as the prevailing environmental conditions (e.g., the quantity of nanomaterial produced), significantly contribute to the calculation of exposure scores. However, a notable dearth of comprehensive data characterizes incidental nanomaterials, rendering these methods predominantly designed for the systematic assessment of activities involving engineered nanomaterials, rather than incidental instances [35].

Although the Nanotool, as any of the other CB tools mentioned, is specifically designed for the risk assessment of engineered nanomaterials, so it is normal that they are not appropriate for the risk assessment of incidental nanomaterials, the Nanotool method distinguishes itself from other CB-based approaches in a significant manner. In this methodology, the intensity score derives from the cumulative scores of fifteen parameters, while the probability score results from the summation of scores from five distinct parameters. These scores are subsequently converted into risk levels within a four-by-four matrix. Notably, the Nanotool method incorporates an "unknown" option for each parameter governing the intensity and probability scores. This feature enables the computation of these scores even when specific parameters are unknown in cases involving incidental nanomaterials. However, this also creates a fundamental problem: the unknown score yields a remarkably high risk level. For example, if the nanoparticle size is indeterminate, selecting the “unknown” option assigns a score of 7.5 points (from a maximum of ten points) to the “diameter of nanomaterials” parameter, contributing to the overall intensity score. Likewise, when the quantity of produced or consumed nanomaterial remains unspecified, opting for the “unknown” designation allocates 18.5 points (from a maximum of 25 points) to the “amount of produced/consumed nanomaterial” parameter, influencing the probability score [36–38].

In 2023, Sousa et al. tried to introduce a semi-quantitative approach for the risk assessment of activities associated with incidental nanomaterials in the realm of metal 3D printing industries. Their method was fundamentally grounded in control banding (CB) principles, and it was a fusion of the Stoffenmanager Nano and Nanotool methodologies. The proposed method bore a striking resemblance to the Nanotool approach, with a particularly noteworthy similarity being the inclusion of the “unknown” option to delineate parameters. Notably, the results of the risk assessment closely mirrored those derived from the Nanotool method within two out of the three scrutinized activities [39]. The pervasive issue of “unknowingness” stands as a pivotal challenge in the risk assessment of activities involving incidental nanomaterials. An effective approach for risk assessment in these scenarios needs the capability to address unknown aspects. This entails either obtaining and incorporating these specifics into the risk assessment process or structuring the risk assessment in a manner that obviates the need for such unknown variables. However, it is widely recognized within the research community that certain unknown parameters, such as size, shape, solubility, and quantity, are indispensable for comprehensive risk assessment [40].

The concurrent use of both qualitative methodologies and quantitative equipment has garnered increased attention from researchers in recent years. This integrated approach serves to mitigate overall uncertainty and uphold a precautionary stance in the risk assessment of activities associated with nanomaterials. This approach is particularly pivotal in the context of assessing the risks posed by incidental nanomaterials [41]. Qualitative methods, and notably those based on the control banding (CB) approach, amalgamate quantitative and qualitative inputs alongside modeling (depending on the specific method employed) to yield a qualitative risk assessment outcome [42]. Given that, concerning incidental nanomaterials, several critical nanomaterial properties stay undisclosed, it is prudent to initially find these properties through empirical measurements using proper equipment. Subsequently, the risk assessment process can be complemented by incorporating qualitative methods. This methodological sequence ensures a more comprehensive and right risk evaluation. A good example of the simultaneous use of quantitative and qualitative methods is tiered approach. It is a harmonized approach based on three tiers. Tier 1 is dedicated to the collection of data before any laboratory or field evaluations to effectively determine the potential release and exposure to nanoparticles (qualitative tier). If the analysis in the first phase (tier 1) indicates that there is a possibility of occupational exposure, a more detailed investigation (tier 2) will be conducted on-site. The key aspects of tier 2 include characterizing the workplace environment for airborne nano-objects using instruments and strategies. It involves conducting a basic exposure or release assessment using easy-to-use, portable equipment (semi-quantitative tier). Tier 3 is required if there is still a possibility of significant exposure. Tier 3 is the highest level in the tiered approach for assessing exposure to engineered nano-objects in the workplace. It involves more advanced and comprehensive measurements and analyses compared to tier 2 (quantitative tier) [17].

Conclusion

As elucidated in the preceding sections, for the purpose of assessing the risk associated with activities entailing incidental nanomaterials, the most favorable approach, where feasible, is the employment of sophisticated measurement and analysis equipment. Such instruments furnish the most comprehensive insights into the presence, quantity, and dispersion of these nanomaterials, thereby providing invaluable data for decision-makers. Using semi-quantitative methods and approaches that use quantitative and qualitative methods simultaneously (such as tiered approach) can be the next option. Subsequently, the utilization of a qualitative methodology tailored to accommodate the limited information available about incidental nanomaterials should be the third option. It is worth noting that, as of the composition of this article, a dedicated qualitative method for such nanomaterials was not yet accessible. In this context, the following priority would be the application of certain control banding (CB)-based risk assessment methods, which, to a certain extent, are deemed suitable for this purpose. Examples of such methods include Nanotool and Stoffenmanager Nano.

Author contribution All authors contributed to the study conception and design. Investigation, formal analysis, and methodology were performed by Soqrat Omari Shekaftik. Supervision and visualization were performed by Seyed Jamaledin Shahtaheri. Software and writing—review and editing were performed by Neda Mehrparvar. The original draft of the manuscript was written by Zahra Peivandi. All authors read and approved the final manuscript.

Data Availability No datasets were generated or analysed during the current study.

Compliance with ethical standards

Conflict of interest The authors declare no competing interests.

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