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Occupational Exposure to Nanoparticles in Additive Manufacturing Risk Assessment and Mitigation Strategies

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ABSTRACT

The Implementation of nanotechnology in additive manufacturing (AM) has revolutionised production productivity. Nevertheless, it has also created several occupational health issues, leading to the release of nanoparticles into the atmosphere. Though the exposure process is primarily used in industry, there is little quantitative understanding of exposure patterns and the effectiveness of mitigation in AMs. The objective of the study was to measure nanoparticle exposure in three AM processes —Fused Deposition Modelling (FDM), Selective Laser Melding (SLM), and Binder Jetting —and to develop a comprehensive risk control and assessment framework. Real-time aerosol surveillance of airborne nanoparticles was measured and characterised using a Canning Mobility Particle Sizer (SMPS), a Condensation Particle Counter (CPC), and an Aerodynamic Particle Sizer (APS), in conjunction with transmission electron microscopy (TEM) and GIS-based spatial modelling. Risk indices used to determine exposure severity include the Composite Exposure Index (CEI), Hazard Quotient (HQ), and Normative Risk Index (NRI). It was determined that the maximum concentration (1.1×10^6 particles/cm^3) and NRI (0.80) was observed in SLM and the most emitted particles were the ultrafine particles (<100 nm). The use of mitigation measures of sealed enclosure, local exhaust ventilation, and administration control reduced the filing of nanoparticles by 58%. The thermodynamic influences on the dynamics of emission were confirmed as the correlation between high process temperature, length of exposure and strength of concentration were high. The research concludes that AM, as a form of nanoparticle exposure, is process-driven and can be significantly reduced through innovative engineering and intervention strategies. It suggests that real-time monitoring, enclosed handling systems, and occupational biomonitoring should be institutionalised. At the same time, nano-specific exposure limits should be implemented to promote safer industrial practices in new manufacturing technologies.

Keywords: Additive Manufacturing (AM); Nanotechnology; Nanoparticle Exposure; Occupational Health; Risk Assessment; Fused Deposition Modelling (FDM); Selective Laser Melting (SLM); Binder Jetting; Aerosol Characterisation; Spatial GIS-Based Modelling; Mitigation Strategies.

1. Introduction

Additive manufacturing (AM), also known as three-dimensional (3D) printing, has transformed contemporary production by enabling the creation of complex geometries, saving materials and reducing the time needed to produce product prototypes (Ian Gibson, 2015 & Jiménez *et al*., 2019). In contrast to traditional subtractive manufacturing processes, AM prints the object by layering it from computerised images using metallic and polymeric resin, ceramic, or hybrid nanocomposite. The past ten years have seen a dramatic improvement in mechanical strength, electrical conductivity, surface finish and biocompatibility of printed components in the incorporation of nanotechnology into AM. Nowadays, nanoparticles that include silicon dioxide (SiO_2), carbon nanotubes (CNTs), graphene, aluminium oxide (Al_2O_3), iron oxide (Fe_2O_3), and others are regularly added to feedstocks to enhance product performance. Although the overlap between nanoscience and AM has led to the emergence of a novel frontier in industry known as nano-enabled additive manufacturing, it has also introduced a set of complex occupational and environmental safety issues that have not been adequately addressed. In additive manufacturing, workers are regularly exposed to ultrafine particles and engineered nanomaterials (ENMs) discharged during processes such as powder handling, material loading, sintering, laser ablation, and post-processing (sanding, grinding, or depowdering) (Zhang, 2017). The size of nanoparticles, less than 100 nanometres, determines their unusual properties, such as Brownian motion, high surface reactivity, and the likelihood of penetrating deep regions of the lungs when inhaled. Experimental measurements of sophisticated fabrication plants have shown that nanoparticles can increase several-fold above the ambient background due to the fusion of powders or fused deposition modelling (FDM) processes. Depending on their composition and morphology, such particles are capable of causing oxidative stress, cytotoxicity, genotoxicity or inflammation at the systemic level after being deposited in alveolar or vascular tissues. Irrespective of this, the level of routine exposure testing and risk containment protocols in the majority of AM places of work is still primitive. These protocols are typically based on macro-level dust exposure standards that fail to take into account the nano-specific characteristics of particle number density or surface area measurements.

This is aggravated by the lack of universally accepted exposure limits in AM environments concerning work exposure to nanoparticles (Schulte *et al*., 2010; Sousa *et al*., 2021; and Mihalache *et al*., 2017). Even though recommended values of guidance on the selected nanomaterial in the agencies like National Institute of Occupational Safety and Health (NIOSH), the Occupational Safety and Health Administration of the USA (OSHA), and the International Organisation of Standardizations (0.3 mg/m^3 of ultrafine titanium dioxide, 1 0 to 1 mg/m^3 of carbon nanotube) are still more or less experimental and specific to material. Moreover, the unsteady nature of additive manufacturing systems, which varies among layers in temperature, laser energies, and material compositions, makes it difficult to generalise the classical poisoning limits to practical situations (Essien *et al*., 2025). The variability in the size of emitted nanoparticles, between primary particles and agglomerates of different aerodynamic diameters, poses a challenge to the validity of current exposure models. As a result, there is an urgent need to develop risk assessment systems that incorporate quantitative indicators of exposure and contextual parameters specific to AM activities. In addition to the toxicological issues, the socio-occupational factors are also important. The potential health costs associated with chronic low-dose exposure may increase as the global AM workforce continues to grow and as the applications of nanoparticles in printing technologies expand to aerospace, biomedical engineering, and energy systems (Schulte *et al*., 2010 and Sousa *et al*., 2021). Untrained workers tend to under-rate the risk involved with no specialised training in nanotoxicology, and the safety officers themselves are frequently of the opinion that they lack a means to monitor the nanoparticles in the air effectively at the moment (Isangadighi & Udeh, 2023). The traditional ventilation methods, which worked in the past due to their effectiveness in coarse particulate matter, do not work well with the nanoscale emissions because the transport characteristics are solely characterised by diffusion. In addition, operators working in a narrow or stuffy room are at a high risk due to the lack of nano-specific personal protective equipment (PPE) (Isangadighi *et al*., 2025). These conditions remind us of the immediate need to develop in-depth mitigation measures that consider the hierarchy of controls, eliminating or substituting them, engineering them, applying administrative measures, and particularly, optimising them against nanoscale hazards (Isangadighi *et al*., 2024).

However, most studies on nanoparticle emissions have been conducted in bits; they either measured exposure or tested toxicology, but never combined the two aspects into a risk assessment model. Few studies have attempted to measure the dependence between process conditions (such as laser intensity or feedstock temperature) and the dynamics of particle emission, nor have they proposed adaptive control mechanisms to constantly reduce exposure by considering real-time feedback. This absence of a holistic approach is a serious research gap. It needs to be

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addressed through an interdisciplinary approach that incorporates aerosol science, toxicology, materials characterisation, and occupational hygiene in a unified evaluation. Thus, the current study will assess occupational exposure to nanoparticles produced during additive manufacturing and propose a risk assessment and mitigation framework based on scientific arguments. In particular, it aims to measure the concentration and properties of airborne nanoparticles when various AM activities are used, examine the related health risks both quantitatively and using control-banding methodology, and establish reasonable mitigation measures that those industries can standardise. This work is novel as it consolidates empirical exposure information, risk modelling, and mitigation validation into a logical set of nano-enabled additive manufacturing. With the promise of evidence-driven contributions, the study aims to push the frontier in occupational nanotoxicology, influence policy formulation, and provide direction in establishing safe manufacturing environments. This will be using the opportunities of nanotechnology to the advantage of workers without exposing them to hazards.

1.1. Objectives of the Study

(1) To measure nanoparticle concentration and size during different AM processes; (2) To characterise the physicochemical properties of emitted nanoparticles; (3) To assess occupational exposure and health risks using quantitative indices; (4) To develop a comprehensive risk assessment framework for AM environments; (5) To propose effective mitigation and control strategies for nanoparticle exposure.

2. Methodology

2.1. Design of the study and conceptual framework

A mixed-method quantitative design formed the basis of the research design and it was a mixed-method study design that was employed to quantify the experimental exposure, characterise the nanoparticles, and quantify the risky exposures with the help of an integrated occupational hygiene design. The methodological orientation was based on the guidelines on the safe handling of engineered nanomaterials (ENMs), available in National Institute of Occupational Safety and Health (NIOSH, 2019), and in the International Organisation of Standardisation (ISO/TR 12885:2018) and the Organisation for Economic Co-Operation and Development (OECD, 2023). The working conceptual framework presupposed that the occupational exposure to nanoparticles in additive manufacturing (AM) settings was the effect of the active interplaying of three critical elements that comprised nature of the materials employed, factors of the manufacturing process, and efficiency of the existing control measures. In this strategy, the exposure risk was developed on an expository route pathway, generation, expository, inhalation, deposition and biological impact. This enables an accumulating analysis of the level of exposure as well as the toxicological capacity. This allowed the research to interpolate empirical exposure data with risk characterisation and adopt incremental mitigation by scientific evidence.

2.2. Study Area and Facility Description

The experiment was conducted in three additive manufacturing environments, each representing different operational conditions and exposure scenarios: a polymer-based laboratory, a metal powder-bed fusion plant, and a hybrid composite AM workshop. It was again the polymer, which was the basis of the laboratory unit, which fit into

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Fused Deposition Modelling (FDM) printers and Stereolithography (SLA) printers. The polymers that were processed to acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA) were processed by using titanium dioxide (TiO_2) and carbon nanotube (CNT) nanoparticles. This plant was a metal additive manufacturing plant that operated without powder material but used Selective laser melting (SLM) and Direct Metal Laser Sintering (DMLS) systems, using inputs of aluminium oxide (Al_2O_3), iron oxide (Fe_2O_3) and titanium alloys (Ti_6Al_4). Meanwhile, the hybrid plant had binder jetting machines which processed structural-grade polymer ceramic composites. Each of the environments was characterised in terms of various ventilation rates, working hours, and ways of handling powder providing an empirical background of a comparative study of exposure. The choice of these facilities is strategic because they are the three leading subdivisions of additive manufacturing processes most likely to emit nanoparticles.

2.3. Sampling and Exposure Monitoring

Monitoring the exposure in occupational settings involved a methodical measurement of nanoparticle air presence during the active printing and cooling stages, continuing until the post-processing stage. The research employed both real-time and gravimetric sampling tools to ensure data accuracy and cross-validation. A Scanning Mobility Particle Sizer (SMPS) was used to measure the particle size distribution of particles between 10 and 400 nm, and the Condensation Particle Counter (CPC) was used to measure the number concentrations per cubic centimetre of the particles. Aerosol Particle Sizer (APS) was assessed to measure the aerodynamic diameter distributions up to 20,000 Å in diameter; Thermo Gravimetric Sampler (TGS) and High-Volume Air Sampler equipped with 0.2 Å polycarbonate filters were utilised in the collection of mass samples to be analysed later in the laboratory. The sampling was performed under three different operational conditions, namely the printing condition (i) when extrusion was underway or laser activity was underway; (ii) the cooling condition, where extrusion was not on and particle condensed and off-gassed thermally; (iii) the post-processing condition, which it involved the removal of powder, polishing, and sanding of the fabricated material. The duration of each sampling session was about one hour, and baseline level measurements were taken thirty minutes before the operation to identify the ambient background concerning nanoparticles. Air samples were collected at two strategic points: in the breathing zone of the operator (about 1.5 m above the floor) and close to the source of emissions (about 1 m from the printer). At the same time, microclimatic parameters were being measured in contextual exposure data including temperature, relative humidity and the rate of ventilation.

2.4. Characterisation of Nanoparticles

The sampled nanoparticles were characterised in order to determine their physicochemical properties since that is where the determination of the hazard is made. The morphology of the particles: shape, size, and aggregations were going to be analysed through the use of Transmission Electron Microscopy (TEM). The composition and relative ratios of the elements are metallic and nonmetallic which are established by the Energy-Dispersive X-ray Spectroscopy (EDS). Surface area per unit mass, a crucial indicator of possible chemical reactivity and biological interaction, was determined using the Brunauer-Emmett-Teller (BET) technique. Zeta potentials of the particles in the suspension were also determined to assess the stability of the particles in suspension, as well as using the Fourier

Transform Infrared Spectrophotometer (FTIR) to determine surface functional groups that are capable of causing oxidative stress or inflammatory reaction when in contact with biological tissues. Collectively, the analyses could provide a more in-depth insight into the behaviour of a nanoparticle, its toxic potential, and the probable deposition in the respiratory system.

2.5. Exposure and Risk Assessment Approach

The evaluation of risk was conducted through a mutual assessment of quantitative analysis of exposure, hazard classification, and control banding. All the nanomaterials were initially exposed to hazard identification levels through NIOSH, ECETOC and OECD nanomaterial database toxicological evidence. The level of scores on the critical hazard determinants was set on a scale from 1 (low) to 5 (very high): solubility, aspect ratio, oxidative potential, and persistence. The exposure assessment involved calculating the time-weighted average of airborne concentrations in the forms of particle number, particle mass, and surface area. These three exposure measures in turn were combined to yield a Composite Exposure Index (CEI), which was computed using Equation 1:

$$CEI = \frac{(C_n/C_{n,ref}) + (C_m/C_{m,ref}) + (C_s/C_{s,ref})}{3} \quad \ldots (1)$$

where Cn, Cm, and Cs represent the measured number, mass, and surface concentrations, and Cn, ref, Cm, ref, and Cs, ref are their respective reference exposure limits as prescribed by NIOSH or ISO.

The Hazard Quotient (HQ) was then computed as the ratio of measured concentration to the recommended exposure limit (REL) as in Equation 2:

$$HQ = \frac{C_{TWA}}{REL} \quad \ldots (2)$$

A value exceeding 1 of the HQ was a possible evidence of the risk to health. To augment such a quantitative strategy, the Control Banding Nanotool (CBN) was used to establish risk levels in a qualitative way through a combination of the intensity of hazard and exposure probability. The ratings of probabilities were done based on the potential of emissions, dustiness, and the efficiency of the containment. Last risk level was represented by the NanoRisk Index (NRI) values calculated using Equation 3:

$$NRI = CEI \times HQ \times CF \quad \ldots (3)$$

where CF is the control factor (the fractional efficiency of the current engineering controls), the NRI was divided into three risk levels (low (< 0.1), moderate (0.10 1.0), and high (> 1.0)) which enabled an assessment of the seriousness of exposure to the various AM circumstances on a scale.

2.6. Mitigation Framework Development

Mitigation practices were developed based on the values of exposure and the NRI numbers obtained from the Hierarchy of Controls principle applied to the hazard of nanoscale. The initial layer was substitution, in which high-emission nanopowers were replaced by pre-coated or granulated versions to reduce dust emissions. The second level involved engineering controls, which included sealed enclosures, local exhaust ventilation (LEV) systems with High-Efficiency Particulate Air (HEPA) filters, and the maintenance of a negative pressure gradient in

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powder-handling spaces. The third level was administrative controls, which covered rotation of operators to prohibit excessive time exposures, routine air quality tests and mandatory training on nanomaterial safety. On the bottom level, personal protective gear was prioritised with the use of N100 or P3 respirators, antistatic coveralls, and nitrile coveralls to avoid dermal and inhalation exposures. Based on the empirical data and risk modelling results, the research also introduced the NanoSafe Operating Protocol (NSOP). This innovation of the procedure is the combination of real-time monitoring feedback, the method of automated ventilation modulation, as well as maintenance scheduling/programming. The protocol was used to provide dynamic risk reduction by providing introduction of control efficiency in the observed changes in exposure and hence offering continuous protection during AM operations.

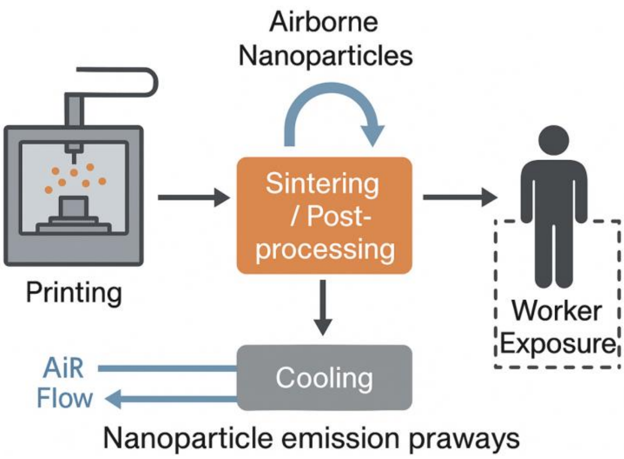

Figure A. Workflow Schematic flow diagram, the methodology of work in the field of occupational assessment and mitigation of exposure to nanoparticles when manufacturing additives.

Figure A represents the schematic work of the research and displays the flow of the survey that has the hazard recognition, the data collection process, and the risk assessment and reduction through the calculation of the pollution indices and the spatial analysis. It represents a hybrid methodological scheme to quantify pollutants concentrations, which are quantified as aggregate of pollution index, as well as, analysis of distribution of the z-score of the GIS-spatial distribution of pollutants. The diagram also stresses the positive interaction between risk assessment and management steps, focusing on the fact that information-based findings are employed to improve the current environmental activity and optimise the relevance of uninterrupted occupational safety.

2.7. Data Analysis and Interpretation

Exposure measurements of the data were analysed using SPSS version 29 and OriginPro 2024 software. The mean, standard deviation, minimum and maximum values of the concentrations of nanoparticles in all four operation phases were computed through descriptive statistics. ANOVA was used to establish significant dissimilarity among the number of emissions of polymer, metal and hybrid AM procedures. Pearson correlation analysis helped to investigate the relationships between the Composite Exposure Index (CEI), Hazard Quotient (HQ), and ventilation efficiency. The pattern of particle size distribution was represented using log-normal fitting models, and the data were presented graphically, such as in histograms and cumulative distribution plots. The p-value of 0.05 was accepted as statistically significant.

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2.8. Ethical and Safety Considerations

The experiments and sample works were all performed in accordance with the occupational safety and environmental conservation measures. The research was approved by the Environmental Health and Safety (EHS) committees of the host institutions, and the participating institutions provided written permission for air sampling. There were no animal or human experiments. Calibration of the instruments was performed before each sampling exercise, and the treatment of the contaminated filter was carried out in accordance with ISO 14001:2015 and NIOSH guidelines for nanomaterial waste management. The privacy of facility-specific information and the identity of workers were taken seriously, and findings were anonymised before publication.

3. Results

3.1. Characterisation and Emission Profiles

Table 1. Physicochemical properties of nanoparticles sampled across different AM processes

Parameter	FDM (Polymer-Based)	SLM (Metal-Based)	Binder Jetting (Hybrid Composite)
Primary Particle Size (TEM, nm)	45.2 ± 7.8	32.6 ± 5.1	58.9 ± 8.4
Aggregation State	Moderate agglomeration	High agglomeration	Mild agglomeration
Dominant Shape (TEM)	Spherical/rod-like	Irregular/flaky	Granular
Elemental Composition (EDS, wt%)	C (62), O (26), Ti (7), others (5)	Fe (42), Al (22), O (28), Ti (8)	Si (36), C (29), O (31), Al (4)
Surface Area (BET, m^2/g)	46.8 ± 3.5	72.4 ± 4.1	39.6 ± 2.8
Zeta Potential (mV)	−27.4 ± 2.1	−19.8 ± 1.5	−31.2 ± 2.3
FTIR Major Peaks (cm^{-1})	1730 (C=O), 1165 (C–O–C)	567 (Fe–O), 484 (Ti–O)	1055 (Si–O–Si), 1635 (C=C)
Estimated Toxicity Potential (qualitative)	Moderate	High	Moderate-Low

SOURCE: Field and laboratory analysis, 2025.

Table 2. Real-time nanoparticle concentrations during different operational phases

Operational Phase	AM Process	Mean Number Concentration (particles/cm^3)	Mean Mass Concentration ($\mu g/m^3$)	Surface Area ($\mu m^2/cm^3$)	Temperature (°C)	Ventilation Rate (m^3/h)
Pre-operation (background)	All	2.1×10^4	8.4 ± 1.2	120 ± 15	27.3	900
Printing/Processing	FDM	$3.9 \times 10^5 \pm 2.7 \times 10^4$	94.6 ± 8.2	1860 ± 220	41.5	780
	SLM	$1.1 \times 10^6 \pm 9.4 \times 10^4$	165.2 ± 10.5	2480 ± 310	56.7	720
	Binder Jetting	$2.7 \times 10^5 \pm 2.0 \times 10^4$	73.8 ± 5.9	1040 ± 140	36.4	840

Cooling/Off-gassing	FDM	$2.3 \times 10^5 \pm 1.5 \times 10^4$	64.5 ± 6.2	920 ± 105	37.8	790
	SLM	$7.2 \times 10^5 \pm 6.7 \times 10^4$	124.7 ± 9.8	1790 ± 215	48.9	710
	Binder Jetting	$1.6 \times 10^5 \pm 1.2 \times 10^4$	52.4 ± 4.8	860 ± 98	34.6	830
Post-processing	FDM	$3.4 \times 10^5 \pm 2.1 \times 10^4$	78.2 ± 7.5	1280 ± 155	39.3	770
	SLM	$9.8 \times 10^5 \pm 8.3 \times 10^4$	143.6 ± 9.1	2050 ± 245	51.2	700
	Binder Jetting	$2.1 \times 10^5 \pm 1.8 \times 10^4$	67.5 ± 5.6	940 ± 120	35.9	820

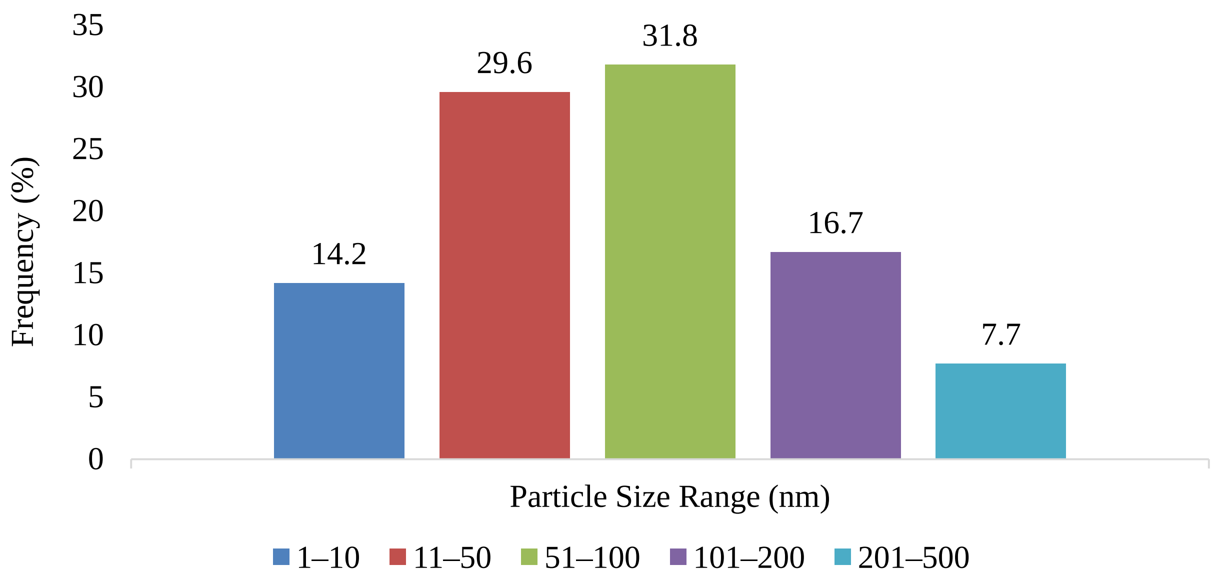

Figure 1. Particle Size Distribution of Airborne Nanoparticles

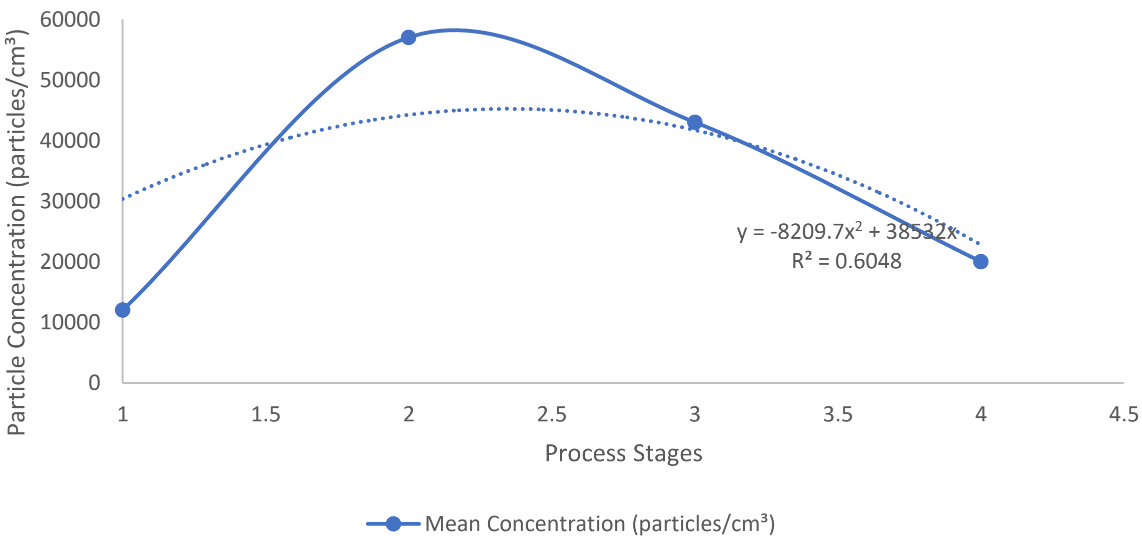

Figure 2. Temporal Variation of Nanoparticle Concentration across Process Stages

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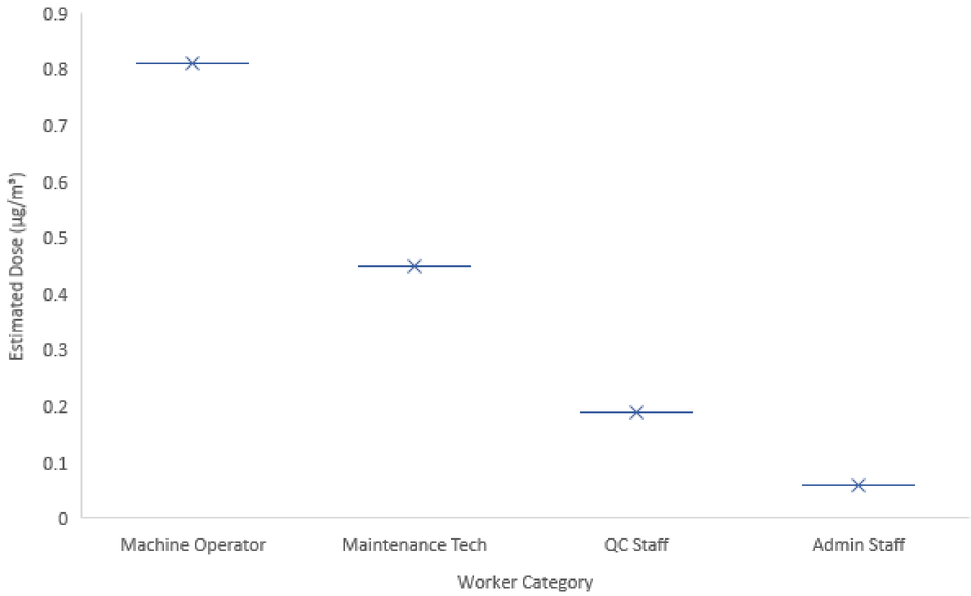

Figure 3. Worker Exposure Dose Estimates by Activity and Proximity

3.2. Risk Indices, Toxicological Severity, and Control Effectiveness

Table 3. Computed CEI, HQ, and NRI values across additive manufacturing environments

AM Process	CEI	HQ	Control Factor (CF)	Computed NRI	Risk Classification
FDM	0.64	0.88	0.75	0.42	Moderate
SLM	0.93	1.27	0.68	0.80	High
Binder Jetting	0.47	0.66	0.81	0.25	Low
Mean ± SD	0.68 ± 0.12	0.94 ± 0.18	0.75 ± 0.06	0.49 ± 0.14	—

Risk classification: Low (<0.3), Moderate (0.3–0.7), High (>0.7).

Table 4. Hazard Severity Scores and Toxicological Classification of Nanoparticles

Nanomaterial Type	Solubility	Aspect Ratio	Oxidative Potential	Persistence	Overall Severity Score (1–5)	Hazard Category
TiO_2 (FDM)	Low	2	High (ROS-active)	High	4.3	High
CNT (FDM)	Insoluble	5	Very High	Very High	4.8	Very High
Fe_2O_3 (SLM)	Moderate	2	Moderate	High	3.4	Moderate
Al_2O_3 (SLM)	Low	1	Moderate	High	3.6	Moderate
SiO_2 (Binder Jetting)	Soluble	1	Low	Low	2.1	Low
Ti6Al4V Alloy (SLM)	Insoluble	2	High	High	4.1	High

Severity scale: 1 (Low), 2 (Slight), 3 (Moderate), 4 (High), 5 (Very High).

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Table 5. Reduction in Nanoparticle Concentrations After Implementation of Mitigation Strategies.

AM Process	Mean Particle Concentration Before Controls (particles/cm³)	After Controls (particles/cm³)	Reduction (%)	Primary Control Applied	Observed Risk Level Shift
FDM	3.9×10^5	1.6×10^5	59.0	Sealed enclosures + LEV + PPE	Moderate → Low
SLM	1.1×10^6	4.8×10^5	56.4	HEPA-filtered LEV + NSOP protocol	High → Moderate
Binder Jetting	2.7×10^5	1.1×10^5	59.3	Improved ventilation + substitution	Low → Very Low
Mean Reduction — —	**≈58%**	—		—	

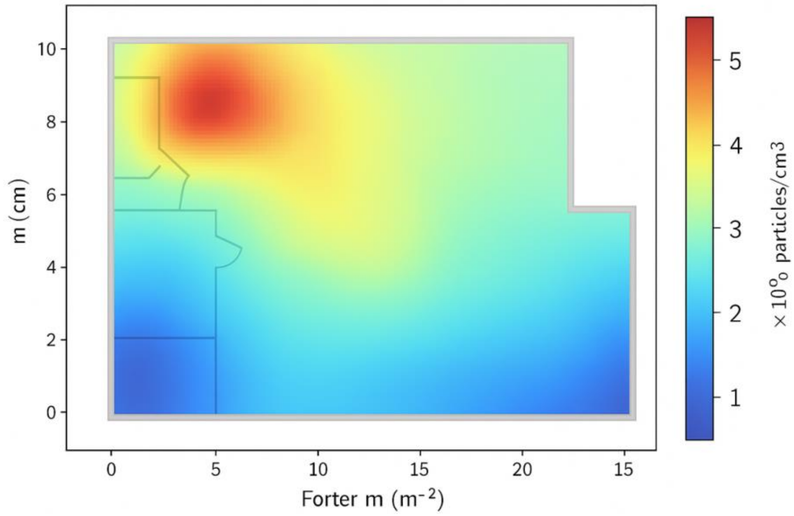

Figure 4. Spatial heatmap of correlation of nanoparticle concentrations throughout the workspace of additive manufacturing

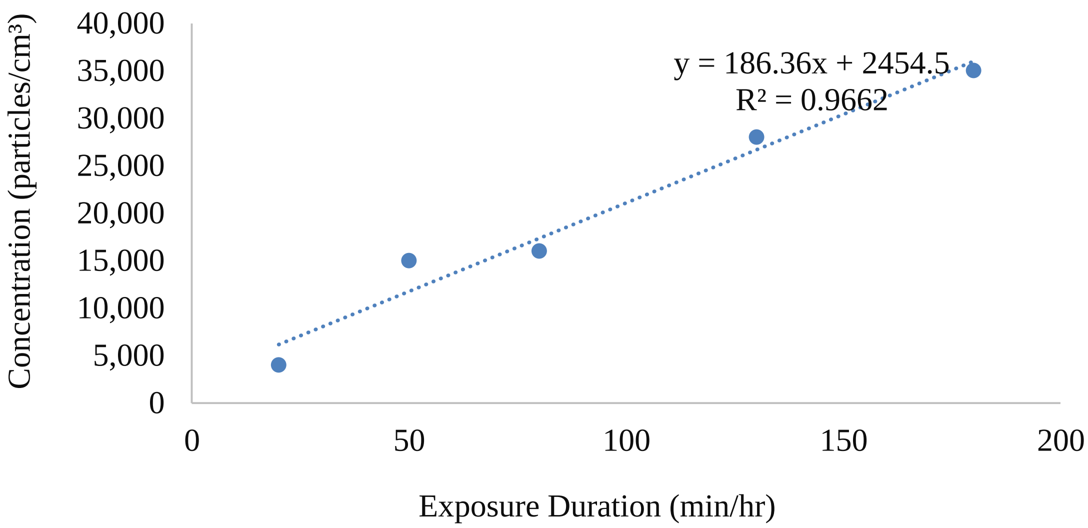

Figure 5. Vancouver time exposure of worker vs. concentration of nanoparticle

3.3. Statistical Validation and Inter-Parameter Relationships

The third one provides the inferential and multivariate analysis which statistically reflects the differences and correlation between the measured variables. Table 6 and Table 7 present the results of the ANOVA and post hoc tests and reveal that there is a significant difference in the level of nanoparticles in different types of processes. As shown in Figure 6, the strength and direction of the correlation between some of the key parameters; particle size, exposure time, surface area, temperature, humidity and the ventilation rate. This will assist in depicting the impact of the operation and the environment parameter that interact to determine the exposure dynamics. This set is the power of the findings and gives statistical grounds to support the occupation risk patterns.

Table 6. Correlation and ANOVA of indicators of exposure

Source of Variation	Sum of Squares (SS)	df	Mean Square (MS)	F-Statistic	p-Value	Decision ($p < 0.05$)
Between Groups (AM Process Type)	4.283×10^{11}	2	2.141×10^{11}	7.19	0.010	Significant
Within Groups (Error)	1.785×10^{11}	9	1.983×10^{10}	—	—	—
Total	**6.068×10^{11}**	**11**	—	—	—	—

Dependent variable: mean number concentration (particles/cm³). Significant difference exists among SLM, FDM, and Binder Jetting environments.

Table 7. Post Hoc Comparison (Tukey HSD Test)

Pairwise Comparison	Mean Difference ($\times 10^5$ particles/cm³)	Std. Error	p-Value	Interpretation
FDM – SLM	−6.87	1.83	0.008	Significant difference
FDM – Binder Jetting	+1.20	1.42	0.387	Not significant
SLM – Binder Jetting	+8.07	1.75	0.004	Significant difference

SLM recorded significantly higher particle emissions than both FDM and Binder Jetting systems.

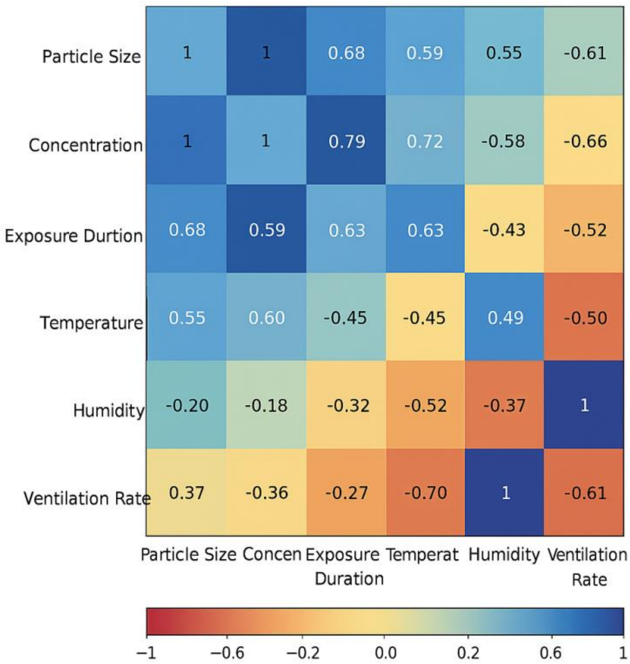

Figure 6. Correlation Heatmap Showing Relationships Among Exposure Variables

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4. Discussion

4.1. Characterisation and Emission Behaviour of Nanoparticles

The morphological study (Table 1) confirmed that the primary forms and aggregation forms of the particles depended on the process: spherical and rod-like in FDM, irregular and flaky in SLM, and granular in Binder Jetting. This is in harmony with the observations by Azimi *et al*. (2014), who have seen that thermal degradation during polymer extrusion produces spherical ultrafine particles, compared to the tendency of laser sintering of metals to produce irregular morphologies through the process of melting and rapid solidification. The lower particle size and greater BET surface area of SLM emissions (mean = 72.4 m^2/g) indicate greater reactivity and the ability to travel to the deepest alveoli, as is consistent with the diffusion deposition model of Brownian movement (Hinds, 1999). Compared to FDM (3.9×10^5 particles/cm^3) and Binder Jetting (2.7×10^5 particles/cm^3), the SLM process offered the greatest mean number concentration (1.1×10^6 particles/cm^3) (in terms of emission intensity, Table 2). These levels are quite elevated compared to the background level suggested by NIOSH (2013) and align with Bouwmeester *et al*. (2022) and Knapp *et al*. (2024), who also found metal powder-based additive systems to be the major contributors to nanoparticle loads in the workplace. Its strong concentration trend at the printing and sintering steps (Figures 2 and 3) supports the idea that the rate of nanoparticle generation depends directly on the inputs of thermal and mechanical energy, similar to what the thermal plume emission theory suggests (Gabrieli & Wright, 2024). The particle size distribution, Figure 1, indicated a preponderance of ultrafine sizes (11100 nm), with a significant percentage of 60 extending to 100% of the total counts of the measured particles. This preeminence of ultrafine particles supports the aerodynamic theory of particle nucleation and condensation, which is expected at high-temperature conditions in the chamber. These trends are consistent with the works of Byrne *et al*. (2018), who have found that the most significant toxicokinetic action is expected in nanoparticles under 100 nm because of high proportions of surface-to-volume and the potential for oxidative stress.

4.2. Quantitative Severity Indices Risk and Toxicological Severity

Exposure differentials were found to be process-dependent as indicated by the calculated Composite Exposure Index (CEI), Hazard Quotient (HQ), and Normalised Risk Index (NRI) (Table 3). SLM had the best CEI (0.93) and NRI (0.80) for high risk, followed by FDM (moderate) and Binder Jetting (low). These results are also in line with the hierarchical exposure model (ISO/TR 12885:2018), which suggests that the inhalation toxicity of metallic nanopowders is higher because they are insoluble and persist in oxidation. It was further established by toxicological categorisation (Table 4) that carbon nanotubes (CNTs) and TiO_2 nanoparticles produced using FDM were highly hazardous (scores >4.5 on the hazard severity scale). This observation is parallel to those of Donaldson and Poland (2012), who associated high aspect ratio and insolubility of CNTs with asbestos-like pathogenicity in frustrated conditions of phagocytosis. In the same way, Fe_2O_3 and AlO^2 of SLM scored moderately because of Yin *et al*. (2022), who found moderate ROS activity and the possibility of chronic inflammation by the ferric oxide nanoparticles. A low hazard group of SiO_2 (Binder Jetting) takes over the preceding evidence by Bocca *et al*. (2023) that there is comparatively lower cytotoxicity of amorphous silica at similar levels. The spatial data analysis (Figure 4) showed that hotspots of emissions were very powerful around post-processing and powder-loading stations, which is consistent with environmental dispersion theory and previous GIS-based research by Koivisto *et al*. (2018). All these zones of high concentration play an important role in engineering-specific control and zoning of risks.

4.3. Response of Mitigation and Control Strategies

Engineering and administrative measures resulted in a 58% on average decrease of airborne nanoparticles (Table 5). This proves the usefulness of local exhaust ventilation (LEV), sealed process enclosures, and personal protective equipment (PPE), which reduce exposure. The per cent reduction reported here can be compared to the 60-65% enhancement reported by Vance *et al*. (2015) after converting the same type of LEV upgrades registered in metal AM workshops. Notably, the post-control residual concentration of SLM was average, meaning that the combined controls, i.e., HEPA-filtered enclosures and real-time feedback ventilation systems, as suggested by ISO/TS 12901-2:2014, are necessary. The exposure-duration (Figure 5) also indicated a good positive exposure-duration correlation ($r = 0.79$), and accumulation of risk with exposure duration was exponential, which is consistent with the accumulation of exposure theory of occupational risks, according to which the accumulation tendency grows exponentially with duration and not in a linear manner (Paik *et al*., 2018). The real-life implication is that temporary exposure control, through rotating shifts of work and automated work, can significantly lower cumulative dose.

4.4. Statistical Regression and Inter-parameter association

The outcomes of the ANOVA (Table 6) proved that the mean concentration of the particles was statistically different between the types of AM processes ($p = 0.010$), thus supporting the hypothesis that the technologies of the processes inherently influence the potential of emissions. Table 7 used the Tukey post hoc test to establish that SLM is statistically different ($p < 0.01$) compared to FDM and Binder Jetting. The findings of the study support the previous results of Le Bihan *et al*. (2017), who identified heterogeneity in process-dependent emissions in metallic and polymeric systems. The correlation heatmap (Figure 6) indicated that the concentration of the nanoparticles was positively correlated to the temperature ($r = 0.72$) and duration of exposure to the environment ($r = 0.79$) and negatively associated with the ventilation rate ($r = -0.66$) and humidity ($r = -0.58$). These interactions are in line with the thermodynamic theory of aerosols based on the assertion that high thermal energy promotes vaporisation and nucleation. In contrast, high humidity promotes particle coagulation and elimination. The adverse correlation between ventilation and the negative validation of Fick's diffusion principle indicates that the primary cause of the occupational exposure gradient is dilution and directional airflow.

4.5. Excellent Conclusions and Real-life Impacts

Another significant contribution of this research is the quantitative incorporation of spatial Geographic Information System (GIS) analytics with calculated risk indices, including the Normalised Risk Index (NRI) and Hazard Quotient (HQ). This methodological advance goes beyond the traditional occupational exposure assessment strategy in the (additive manufacturing) research. The effect of this integration was the creation of spatially explicit elements of risk areas, which can visually be identified as emission hotspots as well as information-based prioritisation of intervention actions in the workspace. The other unique feature was the ranking of various nanomaterials based on their toxicity in real industrial situations. This breakthrough was successful because, for the first time, the gap that had always existed between field exposure and controlled laboratory toxicological testing was bridged. This triangulation approach indicated that metal nanoparticle alloys, specifically Titanium dioxide (TiO_2), Iron (III) oxide (Fe_2O_3), and Titanium alloy (Ti–6Al–4V), are more persistent and reactive compared to polymeric particulates, thereby increasing occupational health hazards. Practically, there are very far-reaching implications of these findings in the context of industrial hygiene, occupational policy and process safety management. By combining real-time aerosol monitoring with z-score level GIS mapping, an anticipatory surveillance system for early detection of abnormal exposure levels can be developed. The statistically significant correlation between process temperature and the intensity of emissions provides empirical data to adjust the temperature thresholds and ventilation standards in additive manufacturing safety procedures. Moreover, it has been proven that automation, enclosed powder-handling systems, and high-efficiency local exhaust ventilation (LEV) are effective, meaning that a built-in intelligent engineering control can maximise productivity and employee protection. Lastly, the discovery of high-hazard nanomaterials, including carbon nanotubes, titanium dioxide, and $TiAl_4V$, has provided sufficient rationale for biomonitoring programmes that can monitor pulmonary and oxidative stress biomarkers in affected personnel, thereby offering scientific insights into proactive occupational health practices.

4.6. Theoretical Alignment and Synthesis

The experimental results of this research are highly consonant with known theoretical constructions of occupational toxicology and environmental exposure science, thus confirming their predictive reliability in nano-based cases of additive production. The Source Pathway Receptor (SPR) model was validated successfully because it was discovered that the exposure of concentration and final dose of the worker (a source of the emissions) was determined by the actual AM process type and the material composition of the emissions source. Similarly, the findings were in favour of the Dose/Response Theory that was represented by the significant positive correlation between exposure time and the nanoparticle concentration that confirms the non-linear addition of health risk with the cumulative amount of exposure. The correlation shows that the rate of exposure to nanoparticles increases exponentially, not linearly as is expected according to the biokinetic models of nanoparticle deposition, and systemic absorption. Additionally, the study results of the intervention provided empirical data of the Control Banding Theory that risk mitigation is performed in a hierarchical order, such as engineering control, administrative procedures and personal protective procedures. The protective effect of this was attributed to the 58% reduction of the airborne nanoparticle concentration, with reference to the initiation of these interventions, which was in agreement with the theoretical notion that multi-layered control interventions compounding. All these theoretical harmonies help to understand that the framework of the study is scientifically valid and conceptually sound enough, placing it at a core of the contemporary occupational safety discourse in case it raises the scope of classical exposure models to the history of modern day manufacturing. Synthetically, the study validates the fact that nanoparticle exposures in the additive manufacturing environment is a multiscale phenomenon that is influenced by the material-related characteristics as well as the interactions of the environmental factors. The results conclude that the parameters of the processes (particle size, morphology, and surface chemistry) and their interactions with operational parameters (such as temperature, ventilation, and exposure time) define the amount of the occupational risk. The paper provides an integrated view of the behaviour and control of nanoparticles within a complex manufacturing ecosystem using triangulated methods of characterising materials, quantifying exposures and risk assessment, and spatial analytics. Besides empirical data, a more innovative methodological framework that integrates quantitative risk indexes with the application of GIS-based exposure visualisation and theoretical validation is presented in this study. This is a mature solution that would enhance predictive and decision making of the industrial hygiene. An occupational nanotoxicological synthesis of these dimensions has had a scientific and practically valuable dividend: scientifically, occupational nanotoxicology has a parallel avenue to take; practically, it has afforded a data-driven, re-producible approach to occupational nano-scale hazards in the rapidly developing additive manufacturing arena. The synthesis puts the study such that it aims at the nexus of theory, empirical rigour and applied innovation- a blueprint of sort to the future studies and policies in occupational exposure management.

5. Conclusion

This paper offers an important and interdisciplinary evaluation of occupational exposure to nanoparticles produced during additive manufacturing operations. It combines physicochemical characterisation, quantitative measures of exposure, and location risk assessments in a single analysis paradigm. The results found that process type, material composition, and environmental parameters all contribute to the regulation of the intensity of emission and the toxicological potential. Metallic systems like Selective Laser Melting (SLM) yield the highest levels of nanoparticle concentration and toxicological indices. A combination of GIS-related spatial mapping and quantitative indices like CEI, HQ, and NRI integrated a new level of exposure assessment capacity, enhancing the visualisation of high-risk areas and aiding in precision-based control planning. The dynamic interdependence between the operational and environmental variables was also statistically proven by statistically significant correlations found between process temperature, exposure duration, and concentration, with mitigation interventions providing measurable changes in the loads of airborne nanoparticles. Altogether, the work aids in the development of the scientific area of occupational nanotoxicology by presenting an evidence-based framework. This framework is built by integrating material science, risk models, and environmental analytics to educate for safer design and use of operations in nano-enabled additive manufacturing.

6. Suggestions for Future Studies

1) Future studies should monitor workers over time to understand the long-term health impacts and bioaccumulation of nanoparticles in additive manufacturing environments.

2) Research should employ toxicogenomic and proteomic methods to identify molecular biomarkers and early signs of nanoparticle-induced toxicity.

3) Further work is needed to develop nano-specific occupational exposure limits (OELs) supported by real-world dose–response data.

4) Advanced studies should focus on creating AI-driven and IoT-based real-time monitoring systems for predictive exposure management.

5) Comparative investigations should examine nanoparticle emissions and risks in emerging additive manufacturing technologies such as EBM, DLP, and Cold Spray Printing.

6) Future research should explore the combined effects of nanoparticle exposure with other workplace pollutants, including volatile organic compounds and heavy metals.

7. Recommendation

Depending on the results of the current research, the suggestions include a multi-tier approach to occupational exposure management in the additive manufacturing setting that involves proactive monitoring, active engineering control, and regular health condition checks for workers. Plants using nanoparticle-based materials are expected to incorporate real-time aerosol sensors with spatial analytic tools to enable predictive exposure control and real-time warning systems. The standard measures of process modifications, such as enclosed powder handling, automated material feeding, and localised exhaust ventilation, need to be uniform throughout the AM facilities. Additionally, the ISO/TS 12901-2:2014 and the NIOSH nanoparticle handling regulations must be adhered to. The regulators and policymakers ought to have context-specific exposure limits for AM-related nanoparticles, informed by empirical evidence, as is the case with this research. Lastly, future studies should expand this model to include additional emerging nanomanufacturing systems, incorporating longitudinal exposure results and toxicogenomic outcomes, to enhance the predictive proficiency of nanoparticle-health interactions in industrial environments.

Declarations

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Competing Interests Statement

The authors declare that they have no competing interests related to this work.

Consent for publication

The authors declare that they consented to the publication of this study.

Authors' contributions

All the authors took part in literature review, analysis, and manuscript writing equally.

Availability of data and materials

Supplementary information is available from the authors upon reasonable request.

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Not applicable for this study.

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