

PAPER • OPEN ACCESS

Safe by process design (SbPD) strategies based on proper measures to mitigate nanoparticle exposure in industrial settings

To cite this article: Carlos Fito-López *et al* 2024 *J. Phys.: Conf. Ser.* **2695** 012004

View the [article online](#) for updates and enhancements.



PRIME
PACIFIC RIM MEETING
ON ELECTROCHEMICAL
AND SOLID STATE SCIENCE

HONOLULU, HI
Oct 6–11, 2024

Abstract submission deadline:
April 12, 2024

Learn more and submit!

Joint Meeting of

The Electrochemical Society
•
The Electrochemical Society of Japan
•
Korea Electrochemical Society

Safe by process design (SbPD) strategies based on proper measures to mitigate nanoparticle exposure in industrial settings

Carlos Fito-López ^{1*}, Jorge Salvador Hermosilla¹, Veronica Vela Vela¹, Elena Barbero Colmenar¹, Oscar Andreu Sánchez².

¹ITENE, Technological Institute of Packaging, Transport and Logistics, 46001 Valencia, Spain; carlos.fito@itene.com;

²Department of Vegetal Biology, Faculty of Pharmacy, University of València, C/ Vicent Andrés Estellés, s/n, 46100 Valencia, Spain; oscar.andreu@uv.es

* Correspondence: carlos.fito@itene.es (C.F-L) Tel.: +34-647521544 (C.F.-L.) and oscar.andreu@uv.es (O.A.S)

Abstract. Due to its potential to develop new added value products, a staggering number of nanoparticles (NPs) is already available on the market. Moreover, this increase is expected to continue in the future. However, there is a lack of knowledge on the level of exposure to nanoparticles, and the information related to possible adverse health effects is scarce. Furthermore, there is very little studies concerning the effect of risk management measures (RMMs) on the levels of exposure to nanoparticles at workplaces, compared to the number of exposure situations that can be distinguished.

This study focuses on 5 case studies covering different types of materials, assessing the effectiveness of targeted mitigation strategies applied during the production process. Customized mitigation measures were applied in each industrial scenario to minimize exposure levels. The effects on the particle concentration levels using source enclosure, partial or full, combined with local exhaust ventilation systems (LEVs), was evaluated to generate new knowledge to support the definition of informed safe by process design approaches when dealing with NPs. This study demonstrates that technological advancements can significantly reduce work-related exposures. The findings underscore the importance of tailored mitigation measures due to the diverse range of potential sources and activities in industrial scenarios.



1. Introduction

Nanotechnology, with its remarkable potential for innovation and advancement across various industries, brings forth new materials, processes, and applications. Nanotechnologies have gained significant traction across various sectors such as construction, transportation, energy, and healthcare, finding applications in industrial processes and consumer products [1], [2]. While there is optimism surrounding the potential technological advancements and economic growth facilitated by manufactured nanomaterials (NMs), concerns have been mounting regarding their potential risks to human health and the environment. It is crucial to acknowledge and address these concerns, ensuring the safe and responsible development, and utilization of NMs. [3].

In the last 20 years, it has been made progress in this regard, for instance by manufacturing and using less hazardous NMs or carrying out synthesis processes that make use of safer and more sustainable materials and chemicals [4]. However, some questions about the safety and sustainability of nanotechnology applications in consumer and industrial products remain unanswered, and they become even more difficult when addressing new generations of nanomaterials [5], [6].

Risk management and governance of advanced nanomaterials (also known as smart materials) have drawn the attention of regulatory authorities and scientists. Many of these materials are used in products for biomedical, cosmetic, agriculture, structural, and electronic applications, and they are expected to extend their use in other sectors [7]. Therefore, it is vital to encourage the creation of novel, sustainable, and advanced NMs. A potential path forward to doing this is the Safe Innovation Approach (SIA) for nanomaterials, which merge Safe-by-Design strategies (SbD) in industrial settings with Regulatory Preparedness (RP) [8].

According to the definition adopted under the Horizon 2020 project NanoReg2 [7] SbD is defined as "a process with the goal of identifying, estimating, and reducing uncertainties and risks for humans and the environment along the entire value chain, from an early stage of the innovation process"[8] . This definition can be supported by three main pillars: (i) safe by material design (SbM), involving finding less hazardous NMs as well as nano-enabled products (NEPs); (ii) safer use of products and end-of-life considerations, which includes assessing risks throughout the product's lifecycle in order to optimize acceptable uses and (iii) safe by process design (SbPD), aiming to enhance the control of industrial processes throughout the manufacturing chain. The final goal is to develop processes that eliminate or reduce the release of NMs into the workplace and the surrounding environment.

SbPD emerges as a vital approach that emphasizes the integration of safety considerations into the design and development of industrial processes and systems. Its primary goal is to identify and eliminate or minimize hazards and risks early in the design phase of the process, rather than relying on downstream control measures or protective equipment.

When it comes to reducing exposure to metal oxides and carbon-based nanoparticles, several strategies can be applied within the framework of SbPD. One of the primary strategies is *substitution*, which involves replacing hazardous materials with safer alternatives whenever possible [9]. This approach requires a thorough assessment of the toxicity profiles of different materials and the exploration of alternative processes that can achieve similar outcomes without relying on hazardous substances. By selecting and using safer materials, the potential for harm and exposure can be significantly reduced.

Engineering controls play a vital role in minimizing exposure risks. These controls encompass various measures, such as the use of containment systems, local exhaust ventilation, and other engineering techniques, to limit the release or spread of metal oxides and nanoparticles in the workplace

[10]. Implementing effective engineering controls ensures that exposure to these substances is minimized, providing a safer working environment for employees.

Process optimization is another crucial strategy within SbPD. By designing and optimizing processes, it is possible to reduce the formation or release of hazardous nanoparticles. This may involve adjusting reaction conditions, such as temperature and pressure, or incorporating additives that can inhibit or prevent the formation of hazardous particles. Through careful process design, the potential for exposure to metal oxides and carbon-based nanoparticles can be minimized, enhancing overall safety[11].

Enclosed systems and automation are valuable considerations to reduce exposure risks. Implementing closed systems and automated processes limits human interaction with hazardous materials, thereby reducing the likelihood of accidental exposure [12]. By minimizing direct contact and human involvement, the potential for exposure to nanoparticles is further diminished.

While the emphasis in SbPD is on eliminating or reducing hazards at the source, *personal protective equipment* (PPE) remains an important aspect of ensuring worker safety. Properly selected and used PPE, such as respirators, gloves, or protective clothing, can provide an additional layer of protection when combined with other control measures[13]. However, PPE should be considered as a supplementary measure, with a primary focus on hazard elimination or reduction through process design.

Overall, it is essential to note that the application of these strategies should be tailored to the specific characteristics of the processes, the nanoparticles involved, and the applicable regulations and standards. Different industries and applications may have unique considerations, and a comprehensive risk assessment should be conducted to identify the most suitable strategies for reducing exposure.

By incorporating the principles of Safe by Process Design, the inherent risks associated with metal oxides and carbon-based nanoparticles [14], [15] can be effectively managed throughout the lifecycle of a process. This integration leads to safer working environments, reduced occupational hazards, and a more sustainable approach to nanotechnology. As nanotechnology continues to advance, SbPD serves as a crucial framework for ensuring the safe development and implementation of nanomaterials and processes.

In this manuscript, we applied these “by design” principles to demonstrate and validate the utility of the implementation of suitable risk management measures. In particular, we demonstrate the efficacy of reducing nanoparticles’ exposure in an industrial environment due to the installation of a local exhaust ventilation (LEV) systems. For this purpose, we conducted several case studies, covering the production processes of different nanomaterials, such as metal oxide nanoparticles and carbon-based nanomaterial, and nano-enabled products (NEPs). For the different case studies, the exposure to these nanomaterials was monitored under different operative conditions, analysing whether the use of a LEV system has an effect on the levels of nanoparticles in the workplace.

2. Methodology

The methodology used in the framework of this study follows the sampling procedures defined in the NEAT (Nanoparticles Emission Assessment Technique), which consists of a step-by-step approach widely used for this type of studies. A first study (Tier 1) focuses on the identification of emission sources, as well as a first face-to-face visit to gather information on background level and variations in particle number concentration during the relevant activities. The Tier 2 assessment comprises an in-depth study of the type and levels of particles released during the selected tasks and operations at the workplace.

It should be noted that assessments are made at Level 2 “Tier 2” when a release of NPs is expected to occur, based on information gathered during the previous visit and questionnaires developed to obtain information of possible release patterns. Several types of measurements are made at this Level: first, the background level (BG) is measured. The background gives a general idea of the number of particles in suspension that are in the environment, and its analysis concludes whether they are all due to the activity of the company or are also due to natural causes, nearby works, forklift engines or machinery among other causes. The background is generally measured when there is no activity in progress or the activity level is low. Real-time and offline instruments are used for measurement and analysis, including SEM, TEM, EDX, XRD, and various particle counters.

The methodology emphasizes the importance of measuring the background particle concentration to establish a reference value for deciding when monitoring of human exposure is necessary. This reference value is not an Occupational Exposure Limit (OEL) but serves as pragmatic guidance. To provide a realistic comparison, the average values of fine ($> 2.5 \mu\text{m}$) and ultrafine ($< 100 \text{ nm}$) particle concentrations are presented for both indoor and outdoor environments.

2.1. Particle exposure scenarios

The exposure scenarios were evaluated within different industrial facilities in the framework of the projects SbD4Nano (GA 862195) and LIFE NanoRISK (LIFE12 ENV/ES/00017). The main objective of SbD4nano project is to develop a decision-making tool for the automatic generation of a Safe-by-Design performance index calculated on the basis of the combination of severity, exposure, cost and product performance scores derived by means of tailored designed cost-benefit and product performance analysis algorithms, and existing and new predictive toxicology and exposure estimation models. To support the development of the abovementioned decision making tool, a number of experimental studies were conducted to generate knowledge on the reduction of the exposure potential through the implementation of risk management measures (RMMs). For its part, the objective of the LIFE nanoRISK project was to minimise environmental, health and safety (EHS) risks from exposure to engineered nanomaterials (ENMs). The aim was to improve our understanding of the risks associated with their release into the environment by the polymer nanocomposite industry, and identify prevention and protection measures.

Table 1 includes the exposure scenarios reported in this study.

Table 1. Particle exposure scenarios and applied mitigation measures.

Case study	Activity-Source	Material	Scale of facility	Engineering controls (EC) Mitigation measure	Personal Protection Equipment (PPE)*
A	Synthesis	SiC@TiO ₂	Industrial – Pilot plant	Engineering controls: LEV & partial/full enclosure	Filtering half mask with inhalation valves (P3) & Nitrile gloves
B1	Disgregating	Graphene Oxide	Industrial – Pilot plant	Engineering controls: LEV & partial enclosure	Filtering full mask (P3) & Nitrile gloves
B2	Cleaning	Graphene Oxide	Industrial – Pilot plant	Engineering controls: LEV & partial enclosure	Filtering full mask (P3) & Nitrile gloves
C	Extrusion of PMMA containing TiO ₂	TiO ₂	Industrial – Pilot plant	Engineering controls: LEV & partial enclosure	Filtering full mask (P3) & Nitrile gloves
D	Extrusion of TPE containing graphene	Graphene	Industrial – Pilot plant	Engineering controls: LEV & partial enclosure	Filtering full mask (P3) & Nitrile gloves

**EC have priority over PPE. If the concentrations of the process after implementing EC are still over the recommended exposure limit, PPE must be implemented.* 2.2. Mitigation strategies implemented and assessed

All the data provided in the table were collected in real industrial operating conditions. These conditions encompass various aspects such as production scale (ranging from kilograms to tons), facility surface area (ranging from tens to thousands of square meters), and the number of workers (ranging from two to hundreds).

The effectiveness of the mitigation measures was quantitatively determined; however, it is important to acknowledge certain practical limitations. Specifically, there were instances where different mitigation measures overlapped within certain scenarios. For example, in the facilities, both local exhaust ventilation (LEV) and partial source enclosure were simultaneously employed. Additionally, there is a potential influence from external sources due to inadequate isolation of the studied area B, which should be taken into consideration.

2.2. Particle monitoring instrumentation

In order to assess workplace exposure, particle number concentration and particle diameter were monitored using state of the art instrumentation, as outlined in Table 2. The monitoring devices utilized in this study were capable of measuring particle diameters ranging from 10 nanometers to 1 micrometer.

Table 2. Instrumentation used for particle monitoring.

Instruments	Size range (nm)	Data recorded	Sampling locations
Condensation Particle Counter (CPC, TSI 3007)	4-1000	Total particle number concentration ($\#/cm^3$)	Emission source Worker area
Apex Air Sampling Pump (Casella pump)	< 2500 nm	-	Emission source Worker area

Particle number concentrations were measured at different locations depending on the scenario, including the emission source, the worker area, or the breathing zone. The inlets of the devices located in the near field (NF) were approximately at a height of 1.4 ± 0.2 m and ~ 0.5 m from the worker. When possible, the exposure was assessed by measuring directly in the personal breathing zone (PBZ) of an individual, defined as a 30 cm hemisphere around mouth and nose (EN, 2012). Flexible Tygon® tubes were attached to the inlets of the instruments to achieve the worker's breathing zone. The far field (FF) devices were placed from 6 to 12 m.

The instrument suite defined previously was complemented with several filter-based air samples (37-mm open-faced cassettes) collected during the sampling campaign for morphological and compositional data of airborne and settled particles respectively. These air samples were collected from the breathing zone (BZ; personal sampler) at the stationary NF locations using a polycarbonate filter mounted in an open cowl sampling head at flow rate of 3.5 l min⁻¹ maintained by APEX (Casella CEL) personal sampling pumps.

At the stationary FF locations, the filter samplers were mounted at 1.40 m height on tripod. The filters collected were further analysed by Scanning Electron Microscopy/Energy Dispersive X-ray Spectroscopy (SEM/EDXS) to obtain relevant morphological and compositional data.

Summary exposure estimates were determined as arithmetic mean, maximum and minimum number concentrations by exposure scenario (ES).

2.3. Exposure assessment and Risk Characterization Ratio

Currently, there are no specific occupational exposure levels or international regulations on the exposure to ENMs at work, being subjected to the general regulations for the protection on workers from the risk of chemical agents. Despite this situation, there are some initiatives and methodologies that can be used to determine the potential risk on human health of the exposure to ENMs. The approaches implemented within this study include:

1. **Comparison with the background (BG) concentration:** when background concentrations remain stable during the measurement period, the exposure levels in the particle breathing zone are

considered statistically significant if the mean particle concentration measured is higher than the BG concentration plus 3 times the standard deviation ($3 \cdot \sigma_{BG}$) of the average BG concentration. The exposure can be considered significant based on the formula below:

$$\frac{\text{Particle concentration}}{3 \cdot \sigma_{BG}} > 1$$

2. **Comparison with recommended exposure levels (RELs):** several initiatives have define recommended benchmark for ENMs based on specific characteristics, including the Nano Reference Values (NRVs) accepted in the Netherlands. Under this approach, worker exposures to ENMs must maintained below the RELs.

Group Description	Nano reference values (SER, 2012)
Rigid, biopersistent nanofibers (aspect ratio larger than or equal to 3:1) for which effects similar to those of asbestos cannot be excluded	0.01 fibers/cm³ (10,000 fibers/m ³)
Biopersistent, granular nanomaterial in the range of 1 and 100 nm and a density of >6000 kg/m ³	20,000 particles/cm³
Biopersistent, granular nanomaterial in the range of 1 and 100 nm and a density of < 6000 kg/m ³	40,000 particles/cm³
Non-biopersistent, granular ENMs in the range of 1 and 100 nm	Use OEL for the non-nano form

Measurements were taken before the operations involving the use of NPs to establish the background levels (BG). Comparison of background levels with measured concentrations (taken when the process is in operation) is carried out to identify any increases in the levels. Any enhanced concentration levels are then assigned to emission sources or activities using the activity/time log.

3. Results and discussion

The results and observations in each cases study conducted are described below:

3.1. Case study A. Synthesis of SiC@TiO₂

Case study A covers the synthesis of SiC@TiO₂ (silicon carbide/titanium oxide) nanoparticles to be incorporated into the formulation of antistick coatings used in baking trays for industrial ovens representing a promising way to avoid recurrent greasy or flour coatings when alimentary products are cooked.

Figure 1 depicts the exposure levels and particle behaviour during the production of SiC@TiO₂, which comprises the functionalization of silicon carbide particles with TiO₂.

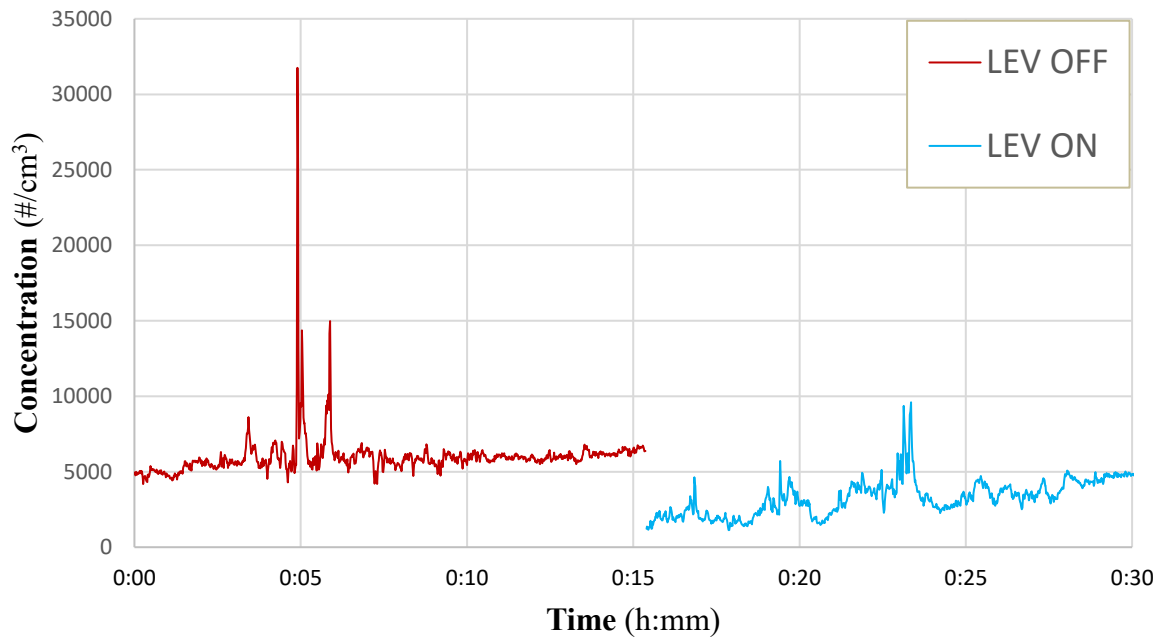


Figure 1: Measurements taken by a CPC 3007 where the local exhaust ventilation was used or not during the nanopaint NM synthesis. The measurements were corrected by subtracting background data taken before any activity in the industrial pilot plant.

Table 3: Impact of the use of LEVs during the nanocoating synthesis.

	BG	LEV OFF	LEV ON	Reduction
statistics	#/cm ³	#/cm ³	#/cm ³	%
Mean	8815,6	14788,3	10735,4	<u>27,41%</u>
Minimum	7804	12998	8320	-
Maximum	10264	40568	18416	<u>54,60%</u>
RSD (*)	3,7%	9,6%	15,4%	-

(*) RSD: Relative standard deviation

3.2. Case study B1. Synthesis of Graphene through Microwave Assisted processes

The case study B consists in the disintegration of graphite into graphene oxide nanoplatelets through Microwave Assisted Liquid Exfoliation. This scenario belongs to a process which high purity graphene nanoparticles are produced. Within this process, graphite was converted to graphene using various solvents with the help of microwave energy in order to exfoliate the graphite to graphene. Figure 2 shows the operative conditions in the company.



Figure 2: LEV (fume hood) used for the MW-assisted exfoliation of graphite to graphene.

Figure 3 shows the evolution of the concentration of the nanoparticles released during the process. The figure clearly shows how the ventilation drastically reduces the concentration levels.

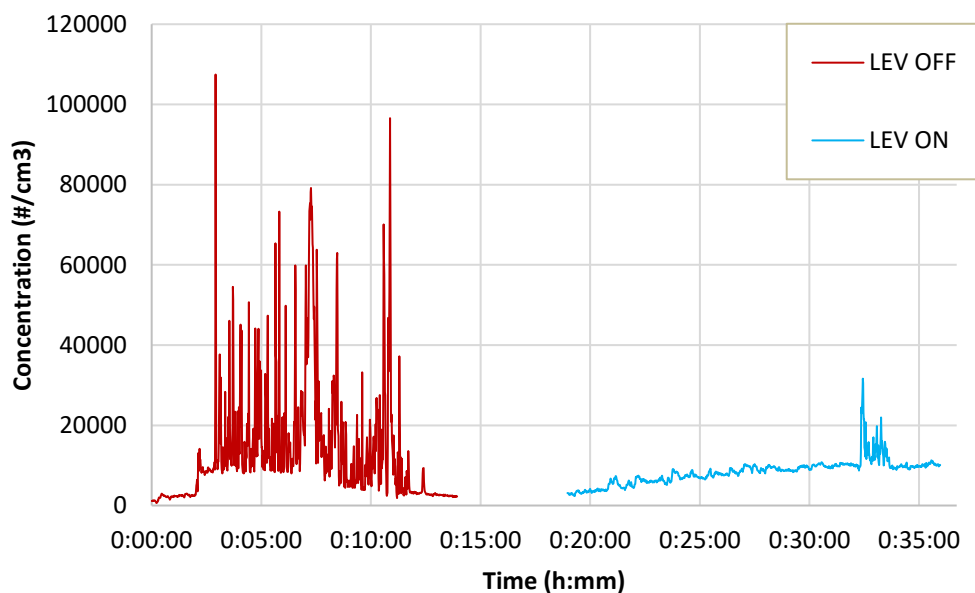


Figure 3: Measurements taken by a CPC 3007 where the local exhaust ventilation was used or not during the Graphite exfoliation.

Table 4: Impact of the use of LEVs during the graphene production

	BG	LEV OFF	LEV ON	Reduction
Statistics	#/cm ³	#/cm ³	#/cm ³	%
Mean	7890,4	21086,4	16252,9	<u>22,92%</u>
Minimum	5226	8513	10252	-
Maximum	9817	115346	39524	<u>65,73%</u>
RSD	8,1%	70,6%	19,2%	-

(*)RSD: Relative standard deviation

3.3. Case study B2. Cleaning operations after the synthesis of Graphene through Microwave Assisted processes

The following picture depicts the evolution of the concentration levels of NPs during the cleaning operations. A series of concentration spikes were observed by the CPC near-field instrument during cleaning operations, with particularly elevated concentrations during the dry cleaning operations.

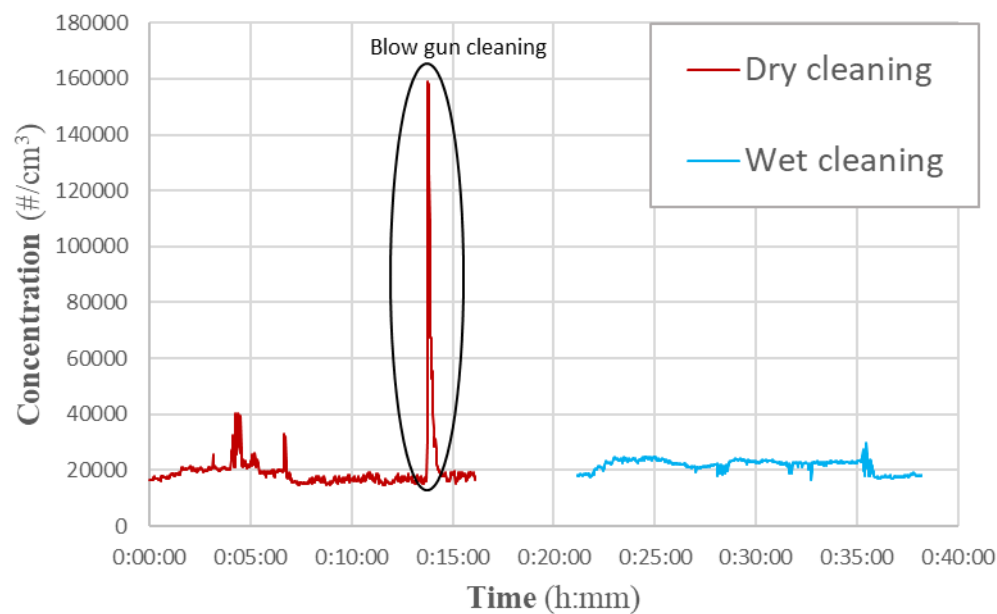
**Figure 4:** Measurements taken by a CPC 3007 during cleaning operations

Table 5: Impact of the use of LEVs during the cleaning operation

	BG	LEV OFF	LEV ON	Reduction
statistics	#/cm ³	#/cm ³	#/cm ³	%
Mean	7890,4	23963,5	21735,0	<u>9,30%</u>
Minimum	5226	17588,4	16397	-
Maximum	9817	190860	29820	<u>84,38%</u>
RSD(*)	8,1%	56,2%	10,0%	-

(*) RSD: Relative standard deviation

3.4. Case study C. Extrusion of PMMA containing nanoTiO₂

The particle number concentration registered in the NF and FF during operation is shown in Figure 5. The dramatic increase from background levels to activity levels (up to 3 orders of magnitude), even without nanoparticles addition, was due to the propensity of PMMA to form airborne dust. Residuum was found deposited even in far field devices. However, no significant difference between blank PMMA and PMMA + TiO₂ nanoparticles was found, which indicates that the dust comes mainly from the PMMA itself. It must be remarked that concentration reaches up to 3.0×10^6 #/cm³. Consequently, devices were reaching their upper limits, causing a higher associated error.

The difference between NF and FF concentrations was very high, up to 2.0×10^6 particles/cm³. In this concrete case, it was recorded a higher concentration in FF, probably as a consequence to vicinity of the cutter to the chosen FF location, where there is high PMMA dust release.

A clear effect of the LEV activation can be derived from figure 5, with a clear reduction on the particle concentration levels.

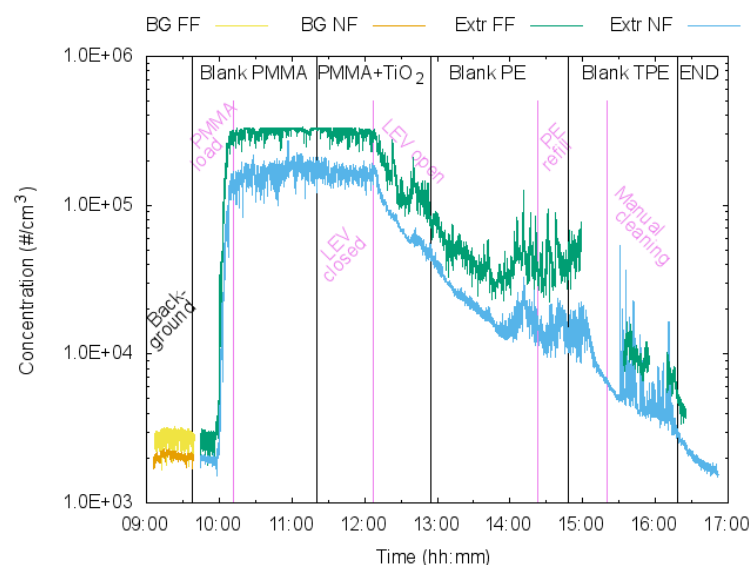


Figure 5: Concentration of particles in the Near and far Fields recorded by the CPC considering variations on the use of LEVs.

3.5. Case study D. Extrusion of TPE containing graphene

In Figure 6, It can be seen that the concentration increases up to 1 order of magnitude when the extrusion process starts. Again, FF is greater than NF. This could be explained as a result of the location selected to measure this parameter was not the adequate.

However, in this particular case, when the ventilation at low flowrate is opened, the concentration increases dramatically (up to 1 order of magnitude), reaching peaks of 9.5×10^4 part/cm³. This is contrary to the effect in previous extrusion, as is contrary to the effect seen afterwards, when a blank polymer (PP) is passed to clean the machine, decreasing the total concentration slowly. The opening of the LEV seems to help the natural tendency to decrease.

This seems to be a particular effect with graphene, in which air flows nearby raise the airborne particles and drives them all around in some sort of turbulence.

During the cleaning process, a great peak was generated, probably because polypropylene is highly electrostatic and it mixes very well with the remaining TPE + graphene. Thus, released particles can be dispersed along the room driven by electrostatic forces.

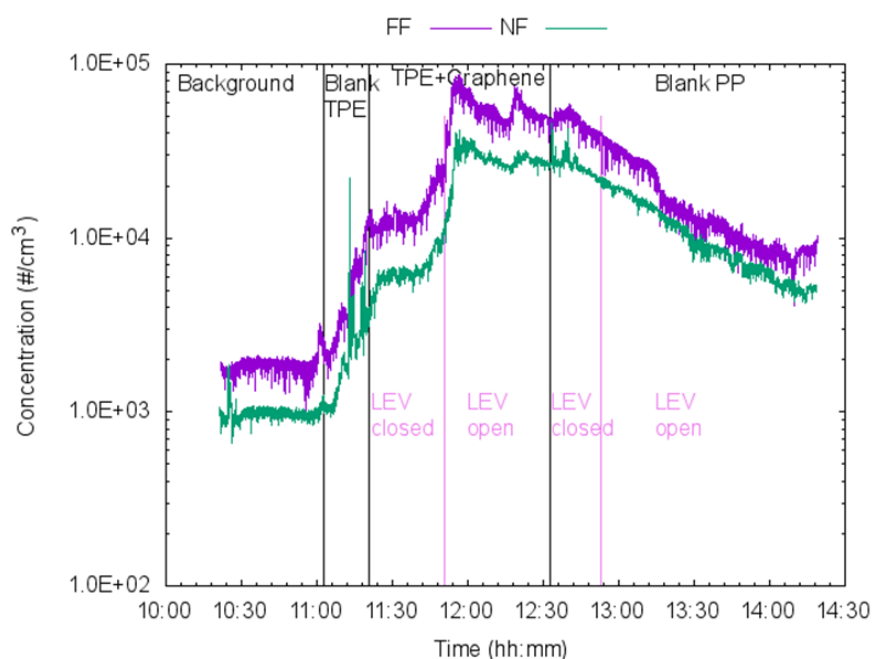


Figure 6: Concentration of particles in the Near and far Fields recorded by the CPC.

4. Conclusions

This work provides an in depth description of the activities conducted to validate the reduction of the exposure to nanoparticles “nano-objects”, and their aggregates and agglomerates (NOAA) in real case studies. The measures evaluated included mainly Laboratory Hoods (partial enclosure), demonstrating that an adequate protection of the human health and the environment when dealing with NPs can be achieved by means of the combination of administrative controls, engineering controls and personal

protective equipment. Notwithstanding, a proper risk evaluation by expertise staff should be conducted to evaluate the risk in the workplace. The following observations were defined in view of the results:

1. The selection of measures shall be conducted according with the measured or estimated exposure, physical state of the nanomaterials (i.e dry forms, dispersed in liquids or embedded into a matrix), as well as release potential of the operations.
2. An average reduction of 50 % was achieved after implemented the measures recommended on the basis of the effectiveness measured in the workplace . A major reduction is achieved in process involving the use of low amounts of NPs. A minor reduction was achieved when dealing with NPs in dry/ powder forms as expected due to a higher dustiness index.

Acknowledgments

The work reported in this paper was funded by the European Horizon H2020 programme SbD4Nano (grant number 862195), and LIFE NanoRISK (LIFE12 ENV/ES/00017).

References

- [1] V. K. Yadav *et al.*, “Recent Advances in Synthesis and Degradation of Lignin and Lignin Nanoparticles and Their Emerging Applications in Nanotechnology,” *Materials*, vol. 15, no. 3. MDPI, Feb. 01, 2022. doi: 10.3390/ma15030953.
- [2] S. Modi *et al.*, “Recent trends in fascinating applications of nanotechnology in allied health sciences,” *Crystals (Basel)*, vol. 12, no. 1, Jan. 2022, doi: 10.3390/cryst12010039.
- [3] B. Salieri *et al.*, “Integrative approach in a safe by design context combining risk, life cycle and socio-economic assessment for safer and sustainable nanomaterials,” *NanoImpact*, vol. 23, p. 100335, Jul. 2021, doi: 10.1016/J.IMPACT.2021.100335.
- [4] Y. Lu and S. Ozcan, “Green nanomaterials: On track for a sustainable future,” *Nano Today*, vol. 10, no. 4, pp. 417–420, Aug. 2015, doi: 10.1016/J.NANTOD.2015.04.010.
- [5] K. Grieger *et al.*, “Best practices from nano-risk analysis relevant for other emerging technologies,” *Nat Nanotechnol*, vol. 14, no. 11, pp. 998–1001, 2019, doi: 10.1038/s41565-019-0572-1.
- [6] L. E. Friedersdorf, R. Bjorkland, R. D. Klaper, C. M. Sayes, and M. R. Wiesner, “Fifteen years of nanoEHS research advances science and fosters a vibrant community,” *Nat Nanotechnol*, vol. 14, no. 11, pp. 996–998, 2019, doi: 10.1038/s41565-019-0574-z.
- [7] E. Commission *et al.*, *NANoREG framework for the safety assessment of nanomaterials*. Publications Office of the European Union, 2017. doi: doi/10.2760/245972.
- [8] L. G. Soeteman-Hernandez *et al.*, “Safe innovation approach: Towards an agile system for dealing with innovations,” *Mater Today Commun*, vol. 20, p. 100548, Sep. 2019, doi: 10.1016/J.MTCOMM.2019.100548.
- [9] J. Tickner, M. M. Jacobs, and N. B. Mack, “Alternatives assessment and informed substitution: A global landscape assessment of drivers, methods, policies and needs,” *Sustain Chem Pharm*, vol. 13, p. 100161, Sep. 2019, doi: 10.1016/J.SCP.2019.100161.
- [10] M. A. McDiarmid, J. Schaefer, C. L. Richard, R. E. Chaisson, and B. S. Tepper, “Efficacy of Engineering Controls in Reducing Occupational Exposure to Aerosolized Pentamidine,” *Chest*, vol. 102, no. 6, pp. 1764–1766, Dec. 1992, doi: 10.1378/chest.102.6.1764.
- [11] S. A. Brenner and N. M. Neu-Baker, “Occupational exposure to nanomaterials: Assessing the potential for cutaneous exposure to metal oxide nanoparticles in a semiconductor facility,” *J Chem Health Saf*, vol. 22, no. 4, pp. 10–19, Jul. 2015, doi: 10.1016/j.jchas.2014.11.001.
- [12] S. Soefje, K. Rickabaugh, R. Rajkumar, and K. P. Wall, “Evaluation of Closed-system Transfer Devices in Reducing Potential Risk for Surface Contamination Following Simulated Hazardous-drug Preparation and Compounding,” *Int J Pharm Compd*, vol. 25, no. 6, pp. 515–522, 2021.
- [13] S. Ludy and A. J. Eyre, “Personal Protective Equipment,” *Ciottone’s Disaster Medicine*, pp. 323–329, Jan. 2024, doi: 10.1016/B978-0-323-80932-0.00049-5.
- [14] Y. Morimoto, M. Horie, N. Kobayashi, N. Shinohara, and M. Shimada, “Inhalation Toxicity Assessment of Carbon-Based Nanoparticles,” *Acc Chem Res*, vol. 46, no. 3, pp. 770–781, Mar. 2013, doi: 10.1021/ar200311b.
- [15] A. B. Sengul and E. Asmatulu, “Toxicity of metal and metal oxide nanoparticles: a review,” *Environ Chem Lett*, vol. 18, no. 5, pp. 1659–1683, 2020, doi: 10.1007/s10311-020-01033-6.
- [16] Hodson L, Eastlake A., and O. Cincinnati, “Occupational exposure sampling for engineered nanomaterials. Technical report,” 2022.
- [17] F. Boccuni *et al.*, “Occupational exposure to graphene and silica nanoparticles. Part I: workplace measurements and samplings,” *Nanotoxicology*, vol. 14, no. 9, pp. 1280–1300, Oct. 2020, doi: 10.1080/17435390.2020.1834634.
- [18] OCDE, “STRATEGIES, TECHNIQUES AND SAMPLING PROTOCOLS FOR DETERMINING THE CONCENTRATIONS OF MANUFACTURED NANOMATERIALS

IN AIR AT THE WORKPLACE,” Paris, 2017. Accessed: Jun. 30, 2023. [Online]. Available: [https://one.oecd.org/document/ENV/JM/MONO\(2017\)30/en/pdf](https://one.oecd.org/document/ENV/JM/MONO(2017)30/en/pdf)