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RESEARCH ARTICLE

Particle concentrations during the manufacturing of biobased composite polyurethane foam panels

[version 1; peer review: 1 approved with reservations, 1 not approved]

Antti Joonas Koivisto[1,2], Rossella Daniela Bengalli[3], Luca Ferrero[3], Paride Mantecca[3], Andrea Doldi[3], Fabrizio Ravegnani[4], Ilaria Zanoni[5], Anna Costa[5], Letizia Verdolotti[6], Federica Recupido[6], Giuseppe Cesare Lama[6], Alessia Nicosia[4]

[1]ARCHE Consulting, Wondelgem, B-9032, Belgium
[2]Institute for Atmospheric and Earth System Research (INAR/Physics), University of Helsinki, Helsinki, FI-00014, Finland
[3]POLARIS Research Centre, Dept. of Earth and Environmental Sciences, University of Milano-Bicocca, Milano, 20126, Italy
[4]ISAC-CNR, Institute of Atmospheric Sciences and Climate, CNR, National Research Council of Italy, Bologna, 40129, Italy
[5]ISSMC-CNR, Institute of Science, Technology and Sustainability for Ceramics, CNR, National Research Council, Faenza, 48018, Italy
[6]IPCB-CNR, Institute for Polymers, Composites and Biomaterials, CNR, National Research Council of Italy, Portici, 80055, Italy

v1 **First published:** 15 Sep 2026, **6**:352
https://doi.org/10.12688/openreseurope.23827.1
Latest published: 15 Sep 2026, **6**:352
https://doi.org/10.12688/openreseurope.23827.1

Abstract

Background

Exposure to filler powder particles was evaluated during the manufacturing of 12 biobased nano-enabled polyurethane (PU) foam panels in a research and development facility based on a novel pilot plant technology. Particle emissions were investigated in PU foam production at weighing filler powders (GasBeton®, diatomite, and functionalized silica), 2) loading the powders into a reactive chamber and mixing, 3) casting into a foaming mold, and 4) a subsequent foaming phase, where the exposure assessment was performed for the first three phases.

Methods

Particle concentrations were measured in the near-field (NF) and far-field (FF) using online aerosol particle monitors, and particles were sampled from workplace air for gravimetric analysis and image and elemental analysis. Operational conditions were registered, including air flow measurements.

Results

Open Peer Review

Approval Status ? ✗

	1	2
version 1 15 Sep 2026	? view	✗ view

1. **Francisco Silva**, Technological Centre for Ceramics and Glass (CTCV), Coimbra, Portugal

2. **Michael Riediker**, Swiss Centre for Occupational and Environmental Health (SCOEH), Winterthur, Switzerland

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Process times were in the order of 1 minute; despite the use of online instruments with time resolutions of 1 second (ELPI), it was not possible to distinguish concentrations between different powder weighing. Due to incomplete air mixing in the NF, it was not possible to assess particle loss rates. Thus, emissions could not be quantified. Process particle number and $\leq$ 10 µm and respirable mass concentrations were up to 31.2 #/cm^3 (pouring; average duration 1 minute; handling rate 700 g/min), 538 µg/m^3 and 140 µg/m^3 (weighing; average duration 2 minutes; handling rate 350 g/min), respectively. Maximum exposure potential was assessed for each task, assuming a continuous process. The maximum risk characterization factor was 0.4 for crystalline silica external exposure, which is considered adequately controlled. Electron microscopy analysis of particles sampled from the air confirmed the presence of filler particles, whereas ICP-OES analysis led to inconclusive results.

Conclusions

Powder filler exposure was adequately controlled during continuous and manual weighing, pouring, and casting processes when local exhaust ventilations are applied. Exposure risk to liquid components was not evaluated.

Plain Language summary

Particle emissions during the manufacturing of 12 biobased composite polyurethane foam panels were investigated in a research and development facility. Due to process times of 1 to 2 minutes and an uncontrolled measurement environment by the use of local exhaust ventilations (LEVs), it was not possible to calculate emission rates using mass balance principles. Exposure assessment to filler particles was based on Electrical Low Pressure Impactor (ELPI) measurements, and the presence of filler particles was confirmed by analyzing collected particles by electron microscope. Gravimetric sampling was used to confirm the consistency of the ELPI measurements. Particle dispersion in the working hall was measured using online monitors at relevant locations. Maximum exposure potential for continuous processes was found to be adequately controlled when LEVs were present.

Keywords

Regulatory exposure assessment, Exposure measurement, Risk assessment, Emission, Nanoparticle, Inhalation exposure, nano-enabled polyurethane foams, bio-based materials



This article is included in the Horizon Europe gateway.

Corresponding author: Antti Joonas Koivisto (joonas.koivisto@arche-consulting.be)

Author roles: Koivisto AJ: Conceptualization, Data Curation, Formal Analysis, Investigation, Methodology, Validation, Visualization, Writing – Original Draft Preparation; **Bengalli RD**: Data Curation, Investigation, Methodology, Writing – Review & Editing; **Ferrero L**: Data Curation, Formal Analysis, Investigation, Writing – Review & Editing; **Mantecca P**: Investigation, Project Administration, Resources, Writing – Review & Editing; **Doldi A**: Data Curation, Investigation, Software; **Ravegnani F**: Data Curation, Investigation, Methodology, Writing – Review & Editing; **Zanoni I**: Data Curation, Formal Analysis, Investigation, Writing – Original Draft Preparation, Writing – Review & Editing; **Costa A**: Conceptualization, Funding Acquisition, Resources, Writing – Review & Editing; **Verdolotti L**: Data Curation, Formal Analysis, Methodology, Resources, Writing – Review & Editing; **Recupido F**: Data Curation, Investigation, Resources, Writing – Review & Editing; **Lama GC**: Data Curation, Formal Analysis, Methodology, Writing – Review & Editing; **Nicosia A**: Conceptualization, Data Curation, Investigation, Methodology, Writing – Original Draft Preparation, Writing – Review & Editing

Competing interests: No competing interests were disclosed.

Grant information: This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement N° 101138414 (Multidimensional Integrated Quantitative Approach To Assess Safety And Sustainability Of Nanomaterials In Real Case Life Cycle Scenarios Using Nanospecific Impact Categories [INTEGRANO]).

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How to cite this article: Koivisto AJ, Bengalli RD, Ferrero L *et al.* **Particle concentrations during the manufacturing of biobased composite polyurethane foam panels [version 1; peer review: 1 approved with reservations, 1 not approved]** Open Research Europe 2026, **6**:352 https://doi.org/10.12688/openreseurope.23827.1

First published: 15 Sep 2026, **6**:352 https://doi.org/10.12688/openreseurope.23827.1

List of abbreviations

CoU: Conditions of Use
ECHA: European Chemicals Agency
EDX: Energy-Dispersive X-ray
ELPI: Electrical Low Pressure Impactor
FESEM: Field Emission Scanning Electron Microscope
FF: Far-Field
GMD: Geometric Mean Diameter
GSD: Geometric Standard Deviation
ICP-OES: Inductively Coupled Plasma Optical Emission Spectrometry
LEV: Local Exhaust Ventilation
NF: Near-Field
OEL: Occupational Exposure Limit
OPC: Optical Particle Counter
PM: Particulate Matter
PU: Polyurethane
PU-DIA: Polyurethane containing 2.5% diatomite powder and 2.5% functionalized silica nanoparticles
PU-GB: Polyurethane containing 2.5% GasBeton powder and 2.5% functionalized silica nanoparticles
RCR: Risk Characterization Ratio
REACH: Registration, Evaluation, Authorisation and Restriction of Chemicals
STD: Standard Deviation

1. Introduction

Polyurethanes (PU) are a broad class of polymer materials having implications in several fields owing to their versatile morphological and functional characteristics (Malucelli and Lorenzetti, 2025; Wu et al., 2025). They might be in the form of foams, elastomers, sealants, and coatings. In particular, PU foams represent the 65% of the global market, with tunable morphologies from rigid (closed cell structures) to flexible (open-cell structures) (Peyrton and Avérous, 2021; Recupido et al., 2024a); consequently, due to their versatility, they might be applicable in disparate sectors such as construction, automotive, aerospace, cushioning, biomedical, and packaging (Pascarella et al., 2024; Silvano et al., 2024; Verdolotti et al., 2012, 2011).

PU foams are obtained by polyaddition between OH groups of polyols with NCO groups of di-isocyanates followed by blowing reactions leading to gas formation (i.e., CO_2). (Silva et al., 2023). PU foam precursors are mainly from petrol-based sources. Several strategies have been employed to reduce the environmental impacts of PU foams, including the selection of bio-based precursors (i.e. polyols from vegetable oils or biomass) (Cabulis and Ivdre, 2023; De Luca Bossa et al., 2020) as well as sustainable di-isocyanates (Cifarelli et al., 2021) or non-isocyanate routes (Orabona et al., 2026).

Di-isocyanates are responsible for chemical exposure risk during foam manufacture, as many di-isocyanates are classified as Cancerogenic, Reprotoxic and Mutagenic (CMR) (Orabona et al., 2025). Additionally to this, to enhance the performance of the bio-based foam materials, several additives, such as polymerization and blowing catalysts, blowing agents, surfactants, chain extenders, crosslinking agents, flame retardants, as well as solid fillers (nano and microparticles), in some cases, suitably engineered, have been increasingly applied to PU foams to improve thermal insulation capability, mechanical reinforcement, thermal and chemical stability, flame retardancy (Cao et al., 2025), pollutant adsorption (Verdolotti et al., 2012), antimicrobial activities (Członka et al., 2020), and reduced swelling (Arifin' et al., 2019; Fontana et al., 2023; Lorusso et al., 2017; Rajabimashhadi et al., 2023; Verdolotti et al., 2011).

In this respect, fillers play a crucial role in dictating the final morphology of the foams as well as their final properties, enabling the development of materials ranging from rigid foams with closed-cell structures to flexible foams characterized by open-cell architectures (Dong et al., 2024; Verdolotti et al., 2017). However, the use of nano or micro fillers is associated with another exposure risk factor for workers handling them in powder form, whose relevance is not fully understood (Ding et al., 2017).

Emissions in powder handling are associated with powder dustiness, which is used to describe the propensity of a material to emit particles during handling (López Lilao et al., 2017; Shandilya et al., 2019). Nanomaterial powder handling mainly increases particle concentrations in the size range of ≥0.1 to tens of micrometers (Fonseca et al., 2018; Koivisto et al., 2014, 2012; Levin et al., 2016; Shandilya et al., 2019). The exposure levels depend on handling amounts and process, material dustiness, and indoor environmental conditions (Ding et al., 2017). Properly applied exposure controls reduce exposure efficiently. Previous studies have shown that the fume hood efficiency during handling of nanopowders under

laboratory conditions is ≥95% (Fonseca et al., 2018; Koivisto et al., 2014, 2018) and with a Local Exhaust Ventilation (LEV) by 75% to 96% (Old and Methner, 2008).

In the registration, evaluation, authorisation and restriction of chemicals (REACH) Regulation (EC) No 1907/2006, the quantitative exposure estimates need to be done for all exposure scenarios where hazardous emissions occur to support the risk characterization (ECHA, 2016). The exposure estimation entails 1) emission estimation, 2) assessment of chemical fate and pathways, and 3) estimation of exposure levels. Emission assessment can be applied alongside a mechanistic exposure model to quantify Conditions of Use (CoU) for industrial processes (Koivisto et al., 2025d, 2025c, 2025a, 2022, 2021), which are required to be reported in a chemical safety report (ECHA, 2016).

This study assesses exposure levels during the manufacturing of bio-based nano-enabled composite PU foams for construction applications. PU foams were reinforced with fillers from renewable and natural sources, specifically, functionalized silica (Recupido et al., 2023), aerated concrete (GasBeton®), and diatomite (Recupido et al., 2024b), with the aim of proving flame retardancy, mechanical reinforcement, and thermal insulation features, respectively. Foams were produced at pilot scale, employing a novel semi-discontinuous pilot plant system that enabled the production of nano-enabled foam materials by manually loading solid fillers into a reactive chamber (up to 20 wt.% filler content).

Exposure levels were assessed during powder weighing, pouring powder fillers into a reactive chamber, and casting into a mold. The assessment was based on concentration measurements in the near-field (NF) and far-field (FF) using online aerosol instruments. Herein, challenges related to emission assessment during handling powders in small quantities and in the short term are discussed. This work is a continuation of the CoU assessment for a cutting of bio-based composite PU foam panels (Koivisto et al., 2025a).

2. Materials and methods

2.1 Operational conditions employed in the manufacture of bio-based nano-enabled PU foam panels

For the manufacture of bio-based rigid nano-enabled PU foams, which are a mixture of two components A and B, and particle fillers, the following components were selected:

- *Component A* is a mixture of bio-based polyester polyols (i.e., bio-based branched polyether-polyester polyol BI6121 having OH_n = 350–380 mg KOH/g, kindly supplied by AEP Polymers S.r.l., Trieste, Italy, and castor oil, OH_n=150–160 mg KOH/g, Pozzi Arosio, Arosio, Italy), blowing and polymerization catalysts (CAS n° 3033-62-3, CAS n°**280–57-9 and** CAS n°127–08-2, purchased by Momentive Performance Materials, Termoli, Italy), blowing agents, flame retardant (CAS n°13674–84-5, supplied by Momentive Performance Materials, Termoli, Italy), solid fillers, physical blowing agent (normal pentane, CAS n°109-66-0, Pozzi Arosio, Italy), compatibilizer pentane-PU matrices, creaming retardants (CAS n°50–21-5, Sigma Aldrich) and silicone surfactants (purchased by Momentive Performance Materials, Termoli, Italy). The polyol blend consists of 91.7 wt.% bio-based polyol and castor oil, and 8.3 wt.% additives (0.6 wt.% polymerization catalyst, 0.3 wt.% blowing catalyst, 0.8 wt.% silicone surfactants, 3.9 wt.% blowing agents, 2.6 wt.% flame retardant, and 0.1 wt.%), respectively.

- *Component B* is the isocyanate component (NCO content is 30.5–31.5%). Ratio among Component A/B = 100/124 (g/g), NCO/OH (mol/mol) = 1.3. The density of cured PU foam is 100 ± 10 kg/m^3.

- Three different filler materials were investigated: GasBeton® (recycled autoclaved aerated concrete, kindly provided by EKORU s.r.l., Volla, Italy), diatomite (a biogenic rock composed of microporous siliceous frustules, Celite® 545, Celite, Imerys, France), and functionalized silica nanoparticles derived from rice husks, kindly provided by Centre for Nanotechnology and Smart Materials (CEnTI, Vila Nova de Famalicão, Portugal (Bengalli et al., 2025). GasBeton® and diatomite were milled and sieved with a 100-mesh sieve to remove particles >150 µm and dried at 60 °C overnight to remove moisture prior to application. The density of the milled GasBeton® was in the range of 1.8 to 2.1 g/cm^3, and the milled diatomite density was 2.3 g/cm^3.

Using these materials, two PU composites with distinct filler compositions were manufactured with a total filler concentration and weight of 5 wt% and 700 g:

- PU-GB was made of 2.5 wt.% GasBeton® powder and 2.5 wt.% functionalized silica.

- PU-DIA was made of 2.5 wt.% diatomite powder and 2.5 wt.% functionalized silica.

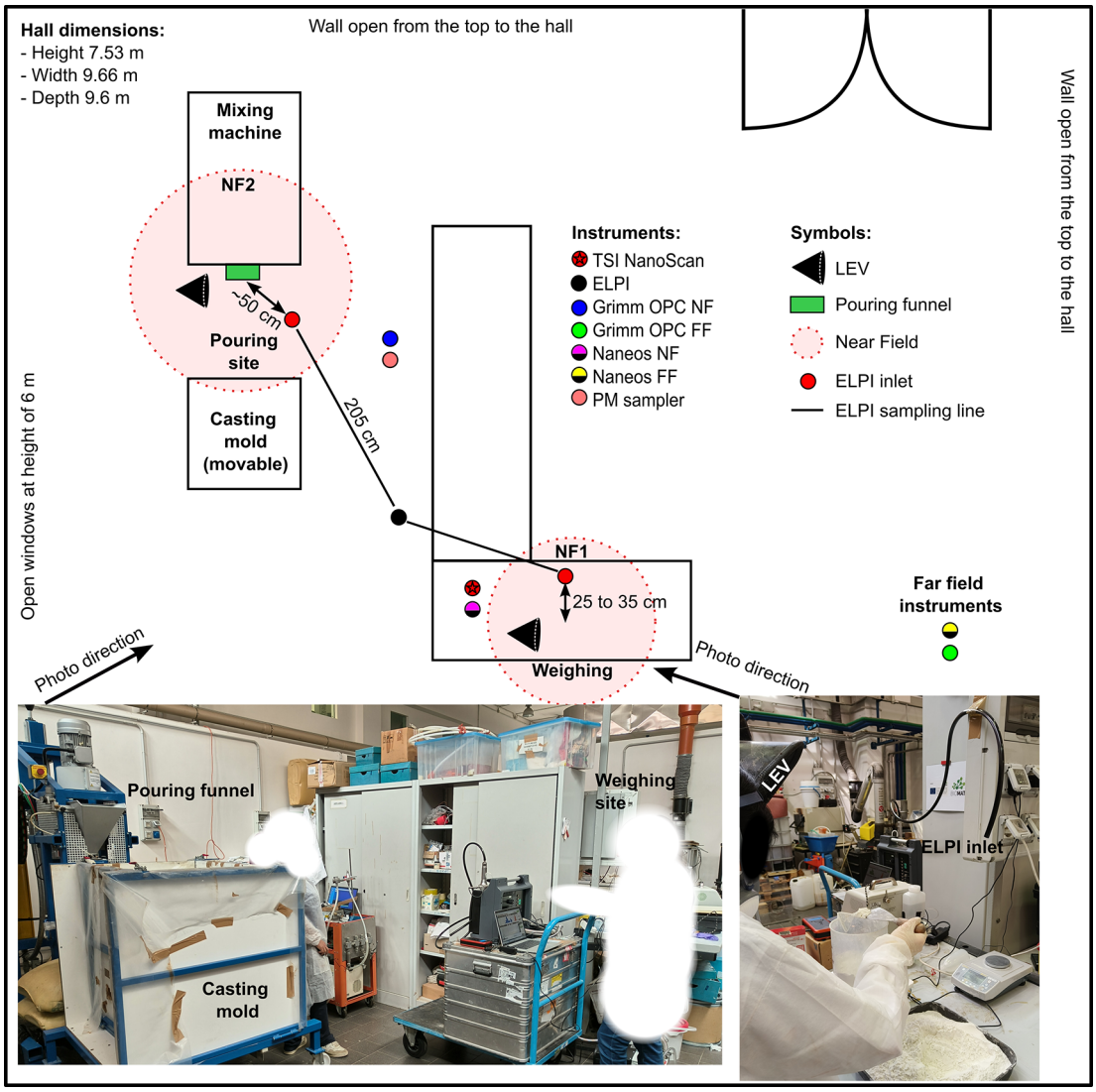


Figure 1. PU panels manufacturing area.

The PU foam manufacture consisted of following process steps: i) loading of the *Component A* (5 kg) into a cylindrical chamber, where the mixing occurs at 1000 rpm for 5 min; ii) weighing of the liquid precursors (namely compatibilizer and n-pentane) iii) weighing the powder fillers into separate jars, iv) loading and mixing of the compatibilizer and n-pentane, v) pouring the powder fillers (700 g) into an hopper (placed on top of the reactive chamber) within 1 min, vi) mixing the powder fillers with the liquid components at 7000 rpm for 5 min, vii) loading of the *Component B* (7 kg) and mixing with the Component A+ filler mixture for 25 s; viii) casting into a rectangular mold (70 cm x 70 cm) and, viii) foaming.

Particle concentration levels were measured for weighing (iii), pouring (v), and casting (viii) processes. Powder filler weighing was performed by first weighing functionalized silica, then adding either GasBeton® or diatomite. Weighing was performed in NF1, while pouring and casting were performed in NF2 (Figure 1). Powder weighing was performed in ca. 2 minutes, pouring into the hopper within 1 minute, and casting within 1 minute (Extended data, Tables, sheet "Process times"; Koivisto et al., 2026).

The PU manufacturing area was separated from a hall with open-top walls (Figure 1). The hall was mechanically (9 inlets) and naturally ventilated via open windows and a door, and the manufacturing room contained 7 LEVs. LEV exhaust flow rates were 308 and 314 m^3/h at the weighing and pouring sites, respectively, and the total flow rate was 3050 m^3/h from all 7 LEVs. The mechanical ventilation supply air flow rate from 9 inlets was 5560 m^3/h in total. The manufacturing area

ventilation rate remained unknown because the natural ventilation rate and the air mixing between the manufacturing area and the rest of the hall were unknown. Random air velocities at a distance of 50 cm were 0.17 ± 0.07 and 0.05 ± 0.02 m/s at the weighing and pouring sites, respectively, when the LEVs were on. The random air velocity in the room without LEVs nearby was 0.014 ± 0.03 m/s. The manufacturing area temperature was 22.2 ± 1.8 °C (±STD).

2.2 Instrumentation

Particle measurements were conducted in the weighing (NF1), pouring funnel (NF2), and far field (FF) sites by using the following online instruments:

- An Electrical Low Pressure Impactor (ELPI; Dekati model ELPI+, Dekati Ltd., Tampere, Finland) measured particle aerodynamic sizes in 14 size channels between 6 nm and 10 μm with 1 s intervals. Sampling was conducted from the NF1 and NF2 using a 205 cm conductive tube with an inner diameter of 8 mm at a height of 150 cm.

- NanoScan (TSI NanoScan model 3091, TSI Inc., Shoreview, MN, USA) measured particle mobility size distributions in 13 size channels between 10 and 420 nm in 60 s intervals.

- An optical particle counter (OPC-NF, Grimm mod. 11-D, Software revision: 1179-V2.03, Grimm Aerosol, Ainring, Germany) measured particle optical sizes in the 0.3–30 μm size range (32 size channels) with 6 s intervals. Sampling was conducted from the NF2 at a height of 100 cm.

- Diffusion chargers (Naneos Partector, Switzerland) measured particle concentrations in the size range from 10 to 400 nm from the NF1 and FF.

- Off-line gravimetric particulate matter (PM) samples were taken in the NF2 at a height of 150 cm by collecting the particles on absolute filters (Polytetrafluoroethylene, 1 μm porosity, Ø 47 mm) at a 50 L/min flow rate through a 130 cm sampling tube with an inner diameter of 8 mm (Bravo H-Plus, TCR Tecora, Italy). The mass concentrations of total suspended dust were determined by filter weighing before and after sample collection using an analytical balance (Mettler Toledo AX105). In parallel, another PM sampler was used to collect particles onto a polycarbonate filter for electron microscopy and chemical analysis.

- An optical particle counter (OPC-FF, Grimm mod. 11-A, Software revision: 4–1 Rev II, Grimm Aerosol, Ainring, Germany) measured particle optical sizes in the 0.3–30 μm size range (32 size channels) with 6 s intervals. Sampling was conducted from the FF at a height of 100 cm.

Airflow measurements were conducted using a hot-wire anemometer (Testo Inc., model Testo 405i, Pennsylvania, US) with a detection limit of 0.01 m/s.

The morphology and composition of particles collected on the filters were analysed by a Field Emission Scanning Electron Microscope (FESEM—Carl Zeiss Sigma NTS, Gmbh Öberkochen, Jena, Germany) coupled with an Energy-Dispersive X-ray (EDX) micro-analyser (EDS, mod. INCA Energy 300, Oxford Instruments, Abingdon, UK). We recorded FESEM images at different magnifications on a piece of polycarbonate filter attached to an aluminium holder using carbon tape. Samples were gold-coated (thickness = 2.5 nm).

The elemental concentrations of particles in the filter were evaluated by Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES) using an ICP-OES 5100 – vertical dual-view apparatus (Agilent Technologies, Santa Clara, CA, USA) coupled with OneNeb nebulizer and equipped with an Autosampler. The measurements were calibrated by the use of calibration curves with a correlation coefficient limit higher than 0.999. The calibration fit was linear, including a blank in calibration. The precision of the measurements expressed as RSD % for the analysis was always less than 5%. The limit of detection at the operative wavelength was 0.001 mg/L for all elements. Before each analysis, samples were acid digested, adding HNO_3 (65%), H_2SO_4 (96%), H_2O_2 (30%), and HF (48%), as reported in the Extended data, Section 6; Koivisto et al., 2026). Calibration curves were obtained in the range of 0.01–100.00 μg/mL.

2.3 Calculation of particle mass concentrations

Mass concentration was derived from particle number concentration by assuming spherical particles and a constant effective density across all particle sizes. Aerodynamic and optical diameters were assumed to be the same. As a first estimate, a unit density (1 g/cm^3) was used for background particles, GasBeton®, diatomite, and functionalized silica.

Table 1. Compositions and OELs for GasBeton® and Diatomite.

Substance (CAS no.)	Concentration	Respirable, mg/m^3	Inhalable, mg/m^3
GasBeton®			
Autoclaved aerated concrete (CAS 1319-31-9)	70 to 90%	2.5 to 5 as inert dust (IMA, 2024)	4 to 10 as inert dust (IMA, 2024)
Sand (CAS N/A)	25–35%	2.5 to 5 as inert dust (IMA, 2024)	4 to 10 as inert dust (IMA, 2024)
Crystalline silica (CAS 014808–60-7)	15–30%	0.05 to 0.15 (IMA, 2024)	Not considered here
Anhydrite gypsum (CAS 7778-18-9)	4–9%	1.5 to 6 (IFA, 2016)	4 to 15 (IFA, 2016)
Diatomite			
Diatomaceous earth (CAS 61790–53-2)	100%	Not specified	1 to 5 (IMA, 2024)

The respirable fraction, as defined by the EN481 (1993) and the ACGIH (2005), was calculated by multiplying the mass distributions by the simplified respirable fraction penetration efficiency according to Hinds (1999).

2.4 Exposure limit values

GasBeton® consists of 70 to 90% autoclaved aerated concrete (CAS 1319-31-9), 25–35% sand, 15–30% crystalline silica (CAS 014808–60-7), and 4–9% anhydrite gypsum (CAS 7778-18-9) (Koivisto et al., 2025b). Diatomite was 100% diatomaceous earth (CAS 61790–53-2) (Koivisto et al., 2025b). The lowest inhalation exposure limits were used in the risk assessment for GasBeton® as the respirable fraction and for diatomite as the inhalable fraction (Table 1). The recommended exposure limit value of 0.3 mg/m^3 was applied for nano-sized functionalized silica, given as an 8-h TWA for the respirable fraction (Mihalache et al., 2017). The risk characterization ratio (RCR) was calculated by dividing the exposure level by OEL.

3. Results and discussion

3.1 Concentration measurements

Particle number concentration and mass concentration time series are shown in Figures 2 and 3, respectively. Process durations were comparable to the logging resolution of 1 minute, so the weighing and pouring times were selected based

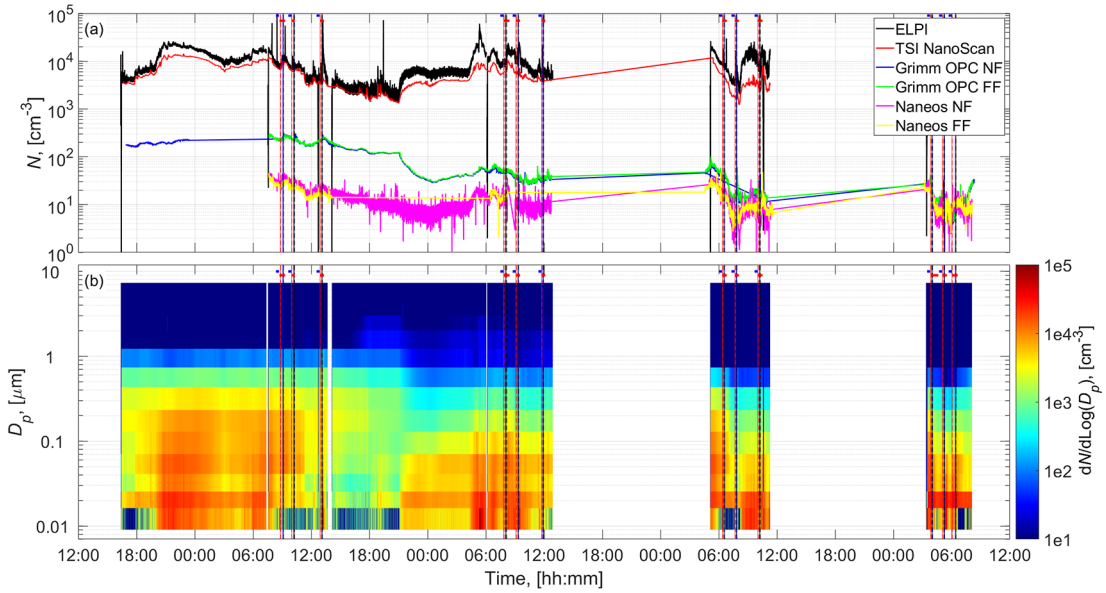


Figure 2. Particle number concentration time series: A) total concentrations measured in the NF and FF, and B) size distributions measured in the NF using ELPI and OPC-NF. The vertical solid and dashed black lines show the start and end times of the cutting for each panel. The blue and red horizontal lines show the background concentration measurement period and gravimetric sampling periods, respectively. Vertical bars indicate weighing (red), pouring (blue), and casting (black), with the solid line starting and the dashed line ending the process.

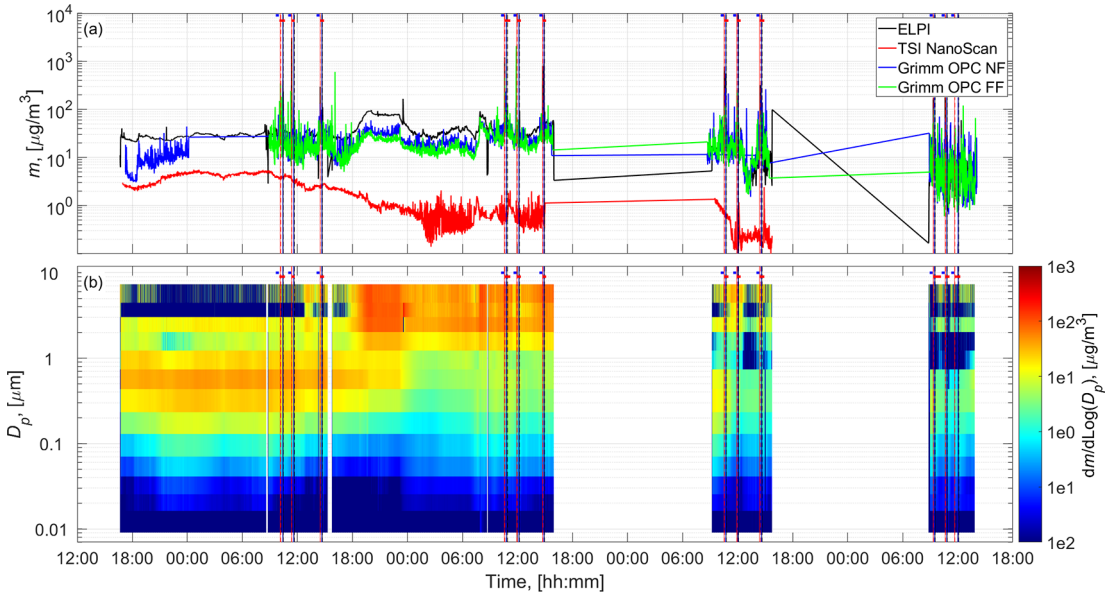


Figure 3. Particle mass concentration time series: A) total concentrations measured in the NF and FF, and B) size distributions measured in the NF using ELPI and OPC-NF. The vertical solid and dashed black lines show the start and end times of the cutting for each panel. The blue and red horizontal lines show the background concentration measurement period and gravimetric sampling periods, respectively. Vertical bars indicate weighing (red), pouring (blue), and casting (black), with the solid line starting and the dashed line ending the process.

on the ELPI mass concentrations and logged times to capture all concentrations relevant to the processes. We could not distinguish silica pouring from GasBeton® or diatomite pouring concentrations (Extended data, Tables, sheet "ProcessC"; Koivisto et al., 2026). Thus, the weighing concentrations were integrated over both powders (Figures 2 and 3). An average background concentration was used for all processes because the powder-specific concentrations could not be specified. Background concentration was defined as the 20-minute interval starting ca. 30 min before weighing, yielding a total background measurement time of 240 min.

Total background number concentrations were similar to the process concentrations (Table 2). ELPI mass concentrations were elevated by 25, 6, and 2 times from background concentrations during weighing, pouring, and casting, respectively (Table 2). The ELPI particle size distributions showed that weighing, pouring, and casting increased particle concentrations >1 μm in diameter (Extended Data, Tables, sheet "ELPI"; Koivisto et al., 2026). OPC-NF mass concentrations remained at levels similar to background concentrations (Table 2). OPC-FF mass concentrations were 2 times higher during the weighing period and 0.7 and 0.8 times lower during pouring and casting periods than the background mass concentration, respectively (Table 2).

For OPC-FF, the background concentration should be similar to that measured during the process and lower than that measured by OPC-NF, indicating an unknown uncertainty in the background concentration assessment for OPC measurements. During weighing, pouring, and casting, the concentration of particles with diameters >1 μm was increased during both OPC-NF and OPC-FF measurements (Extended Data, Tables, sheets "OPCNF" and "OPCFF"; Koivisto et al., 2026).

Gravimetric mass concentration measurements were carried out over the weighing, pouring, casting, and the beginning of the foaming phase (Figures 2 and 3; Extended data, Tables, sheet "Gravimetric sampling"; Koivisto et al., 2026). During weighing, the PM sampling was conducted at the PM sampler site, while during pouring, casting, and foaming, the PM sample was taken next to the ELPI sampling location (Figure 1). One sample was collected across three manufacturing cycles performed in a single day. Gravimetric mass concentrations averaged 51 μg/m^3, ranging from 19 to 74 μg/m^3 (Table 3). For comparison, ELPI mass concentrations were calculated for the PM sampling periods using unit density, yielding an average of 70 μg/m^3 (Table 3). The higher average ELPI mass concentration is due to a closer ELPI sampling location than the PM sampling in weighing. However, the sampling size range for ELPI is lower than for PM sampler (total suspended dust). High standard deviation for ELPI measurements shows that concentrations varied significantly during the averaging period (Table 3).

Table 2. Average particle concentrations (standard deviation), geometric mean diameter (GMD), and geometric standard deviation (GSD) of the GMD. *N/m* is number/mass concentration.

Scenario	Units	ELPI			OPC-NF			OPC-FF		
		N/m	GMD, nm	GSD	*N/m*	GMD, nm	GSD	*N/m*	GMD, nm	GSD
Weighing	#/cm^3	8551	27.4	2.5	28.0	345	1.5	65.1	324	1.4
Pouring	#/cm^3	8582	30.4	2.5	28.6	345	1.5	94.7	312	1.3
Casting	#/cm^3	8667	28.7	2.5	28.0	346	1.5	82.6	321	1.4
Background	#/cm^3	9391	27.9	2.5	34.2	340	1.4	85.4	315	1.3
Weighing	µg/m^3	559	5297	1.6	22.3	9430	2.7	58.5	12240	2.5
Pouring	µg/m^3	138	4219	2.2	22.8	9436	2.7	21.2	6648	3.3
Casting	µg/m^3	46.3	2650	2.9	22.4	9365	2.7	24.2	6513	3.2
Background	µg/m^3	22.1	1498	3.5	22.0	9051	2.8	28.8	10879	3.4

Table 3. Gravimetric mass concentrations measured using PM and calculated mass concentrations measured by the ELPI for the respective PM sampling periods.

Filler	PM sampler	ELPI	
	Mass concentration, µg/m^3	Mean, µg/m^3	Std, µg/m^3
Diatomite and functionalized silica	74	55	99
GasBeton® and functionalized silica	41	86	518
GasBeton® and functionalized silica	69	51	315
Diatomite and functionalized silica	19	90	2015
Average	**51**	**70**	**736**

Particle concentrations measured by NanoScan and Naneos NF/FF were not detected during the process and are not further evaluated here.

3.2 Process-specific concentrations

Process-specific concentrations were calculated by subtracting the average background concentration from the average concentration during weighing, pouring, and casting (Extended data, Tables, sheets "ELPI", "ELPI_resp", "OPSNF", and "OPSFF"; Koivisto et al., 2026). Process-specific particle number concentrations were not considered relevant at any of the instruments (Table 4), even though there was a ca. 10-fold increase in particle number concentrations of 1 µm particles according to ELPI measurements (Extended data, Tables, sheet "ELPI"; Koivisto et al., 2026).

A clear increase in process mass concentrations was measured by the ELPI and OPC-FF (Table 4). However, the OPC-FF increase in mass concentration is likely associated with an activity other than weighing, because weighing emissions should have been detected in OPC-NF as well. Process-specific mass concentrations were associated with particles predominantly larger than 1 µm in diameter (Figure 4; Extended data, Tables, sheet "ELPI"; Koivisto et al., 2026). Respirable mass particle concentration size distribution mode was between 4 and 5 µm (Figure 4; Extended data, Tables, sheet "ELPI_resp"; Koivisto et al., 2026).

3.3 Particle analysis

The FESEM and EDS investigation, with supporting data available in the Extended data, sections 1–3, provides a comprehensive characterization of the atmospheric particulates within the facility, distinguishing between natural coastal background and industrial process emissions (Figure 5 and Extended data, sections 1–3; Koivisto et al., 2026).

Monitoring the laboratory background identified two distinct aerosol populations. The first is characterized by marine aerosols, appearing as numerous sub-micrometric cubic and sub-rounded crystals. EDS analysis confirmed these as sea-salt residues, showing dominant Sodium (Na) and Chlorine (Cl) peaks. This stoichiometric signature reflects the facility's coastal location and demonstrates the intrusion of outdoor air from windows therefore highlighting the fact that air

Table 4. Average process concentrations with background subtracted.

Scenario	Units	ELPI	OPC-NF	OPC-FF
Weighing	#/cm^3	13.7	8.5E-04	0.25
Pouring	#/cm^3	31.3	0.0021	9.39
Casting	#/cm^3	14.1	0.0019	1.38
Weighing	µg/m^3	538	0.58	31.8
Pouring	µg/m^3	116	1.02	3.2
Casting	µg/m^3	25	0.66	5.9

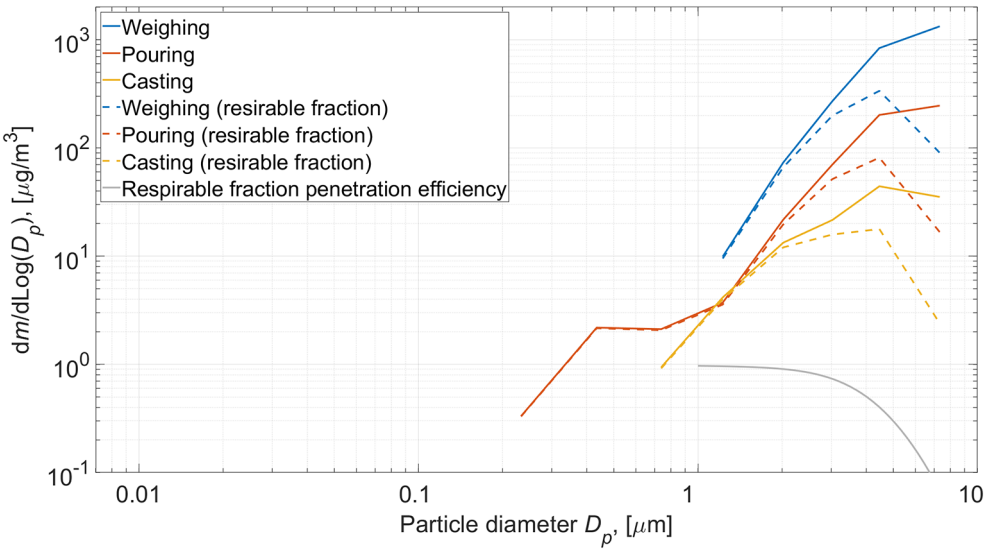


Figure 4. Process-specific mass concentrations measured by ELPI as total fraction (solid lines) and respirable fraction (dashed lines).

ventilation rate was unpredictable. The second population consists of ambient mineral dust, identified as irregular, bright silicate aggregates (Si, Al, Mg, Ca, Na) lacking Chlorine.

The study further reveals a significant morpho-chemical transition of raw materials during industrial processing, particularly during the pouring phase into molds. The pristine diatomite filler originally consists of intact, porous centric frustules with a diameter of approximately 75 µm. However, mechanical handling causes severe fragmentation, transforming these symmetric structures into a respirable dust fraction of angular shards ranging between 2 µm and 15 µm. Similarly, the raw Gasbeton® filler is characterized by a crystalline framework of interlocking acicular tobermorite needles. Upon pouring, these fragile structures undergo extensive mechanical degradation, generating an aerosolized fraction of irregular detritic shards and compact fragments where the original needle-like morphology is entirely lost. Despite these radical morphological changes, the chemical signatures, dominated by Silicon for diatomite and Calcium-Silicon for Gasbeton®, remain stable. This chemical stability allows for clear differentiation from the cubic NaCl background crystals that are consistently identified across all collected samples.

ICP-OES analysis highlights a distinct chemical signature for these particulates, primarily defined by a significantly high Calcium (Ca) concentration (0.13–0.15 mg/g, see Extended data Table ED2; Koivisto et al., 2026), which serves as the main differentiator from Diatomite-based samples where Ca levels are minimal. Conversely, Magnesium (Mg) levels are notably lower in the Gasbeton® aerosol (approx. 0.06–0.07 mg/g) compared to the Diatomite samples. The industrial particulate signature was successfully distinguished from the laboratory background, that, however, was affected by Ca, Mg and Na signals, due to the environment. Interestingly, Silicon (Si) concentrations in Gasbeton® samples remained below the detection threshold, whereas it was identified only in one sample of Diatomite. These data suggest very low release of silica or Si derived from both Diatomite and GasBeton®, which can be detected exactly in the spot by EDX, but is not sufficient in concentration on the filter to be detected by ICP-OES instrumentation.

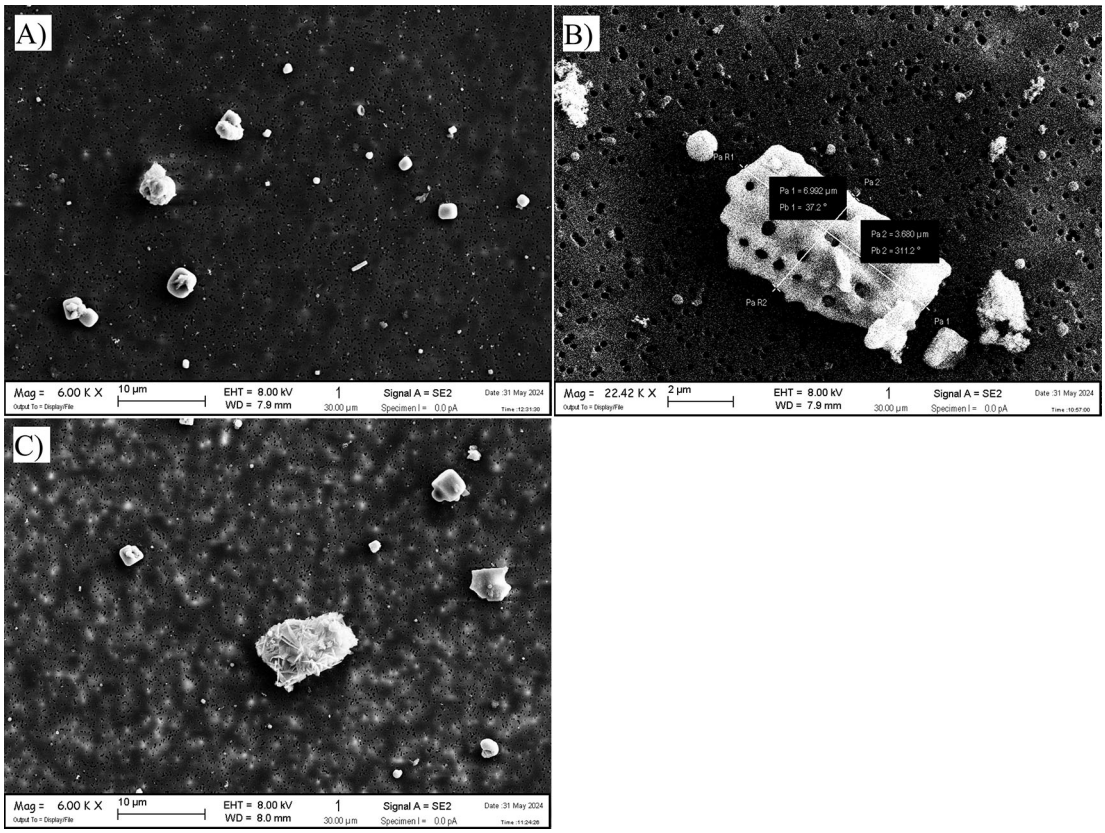


Figure 5. Examples of A) Background particles, B) Diatomite particles, and C) GasBeton® particles.

3.4 Emission estimation

Particle emission calculation requires information on particle concentrations, dispersion volume, and removal rates (Hussein and Kulmala, 2008; Nazaroff, 2004). The particle removal rate can be calculated from concentration decay by fitting an exponential decay function when no particle emissions are present. During weighing and pouring, a LEV was used to minimize particle dispersion into the hall air. Under these conditions, ELPI concentrations did not produce a systematic concentration decay profile, and it was not possible to assess the removal rates for weighing and pouring processes (Extended data, Tables, sheet "ProcessC"; Koivisto et al., 2026). Particle emissions could not be calculated because particle loss rates could not be estimated. Concentrations related to casting were inconclusive and could not clearly be associated with filler emissions (Extended data, Tables, sheet "ProcessC"; Koivisto et al., 2026). It is not

Table 5. External exposure in weighing. Total concentrations for respirable (m_{resp}) and inhalable fractions, occupational exposure limit values, and risk characterization ratios. N/S refer to not specified.

Component	Fraction	Respirable fraction			Inhalable fraction as < 10 µm		
		m_{resp}, µg/m³	OEL, µg/m³	RCR	m, µg/m³	OEL, µg/m³	RCR
Total, µg/m³	1	140	N/S	N/S	538	N/S	N/S
Autoclaved aerated concrete	0.9	63.0	2500	0.03	242.3	4000	0.06
Sand	0.35	24.5	2500	0.010	94.2	4000	0.02
Crystalline silica	0.3	21.0	50	0.4	80.8	N/S	N/S
Anhydrite gypsum	0.09	6.3	1500	0.004	24.2	4000	0.006
Diatomaceous earth	1	70.0	N/S	N/S	269.2	1000	0.3
Functionalized silica	1	70.0	300	0.2	269.2	N/S	N/S

expected that particles mixed in the suspension could be released during pouring into the foaming mold. Particle emissions for casting were not estimated.

Particle emission measurements should be conducted under well-controlled conditions in which background concentration levels and particle loss rates can be quantified with statistically acceptable accuracy. This requires high process-to-background concentration ratios with sufficient duration so that the concentrations can be clearly associated with the process. Particle loss rate assessment requires a steady initial concentration at a sufficiently high level so that the concentration decay can be measured reliably. In this scenario, it was unclear whether the concentrations were uniformly mixed at the NF volumes, as indicated by a high concentration variation in ELPI measurements. Despite this limitations the exposure risk assessment was carried out.

3.5 Exposure and risk assessment

During weighing and pouring, the powder handling rates were 350 and 700 g/min, respectively. Exposure to different handling and pouring rates can be scaled to some extent by assuming a linear increase in the emissions (Fonseca et al., 2024; Koivisto et al., 2025c). Scaling different handling and pouring rates was not possible because emission rates could not be assessed. Also, with known emission rates, the contribution of LEV to the exposure level could be evaluated.

The exposure assessment could be conducted only for the conditions in the current situation. Exposure was calculated assuming continuous work over an 8-h work shift. This scenario represents upper exposure estimates and is not expected to last over a work lifetime, for which the exposure limit values are extrapolated. Exposure levels were assumed to be the same in GasBeton® – silica and diatomite – silica pourings (aggregated levels). The mass concentration was assumed to be equal for GasBeton®/diatomite and silica (50,50). For GasBeton® substances, the upper concentration (Table 1) was applied to calculate the concentration, as exact concentrations are not known (precautionary assessment). This results in 1.6 times higher concentration than the measured concentration for GasBeton®.

RCRs during weighing were up to 0.4 for crystalline silica (respirable fraction), and the exposure is adequately controlled (Table 5). The second relevant component associated with inhalation exposure risk was diatomaceous earth (inhalable fraction) with the RCR of 0.3 (Table 5). Inhalable and respirable exposure levels in pouring and casting were 0.2 and 0.05, and 0.3 and 0.07 times lower than during weighing, respectively (Extended data, Tables, sheet “RCR”; Koivisto et al., 2026). The RCRs were for pouring up to 0.11 and for casting up to 0.03 for crystalline silica (respirable fraction) (Extended data, Tables, sheet “RCR”; Koivisto et al., 2026), and the exposure is adequately controlled.

The risk assessment considered only powder filler exposure, and the risk for liquid components was not evaluated.

4. Comparison with previous measurements

Comparing concentrations across previous studies is challenging because operational conditions and powder properties differ. Bekker et al. (2015) reported particle number concentrations for weighing of CeO_2, CNT, $CaCO_3$, and SiO_2 without contextual information. Pouring halloysites at a rate of 500 g/min increased concentration levels up to 2900 #/cm^3 and 6.4 μm^2/cm^3 inside the fume hood, and the respirable mass concentration was 143 μg/m^3, including background particles (Koivisto et al., 2018). Nanodiamond powder handling at rates of 14 and 17 g/min increased respirable mass concentrations by 0.24 and 0.5 μg/m^3 after being released from an open fume chamber to the room air (Koivisto et al., 2014).

Exposures in industrial-scale pouring scenarios are investigated for pigment TiO_2 powders (Fonseca et al., 2021; Koivisto et al., 2015) and nanoscale TiO_2 powder (Koivisto et al., 2012). In industrial scenarios, handling rates range from 26 to 125 kg/min and are not comparable to those in laboratory-scale powder handling. The concentrations were similar to those here, ranging from 32.7 to 644 μg/m^3, which may be due to a longer sampling distance between the source and the sampler and to different operational conditions. Exposures to carbon materials (nanotubes, fibers, graphene flakes) during weighing are investigated as well, but the material properties are highly different from the inorganic powders investigated here (e.g., Bekker et al., 2015; Johnson et al., 2010; Methner et al., 2010; Natale et al., 2025).

5. Conclusions

In this study, particle emissions during the manufacturing of 12 biobased composite polyurethane foam panels were investigated during: 1) weighing filler powders (GasBeton®, diatomite, and functionalized silica), 2) pouring the powders into the hopper, and 3) casting the components into a foaming mold. Process times were in the order of 1 minute, and despite using online instruments with a time resolution of 1 second (ELPI), it was not possible to distinguish concentrations between two powder weighing. This was partially due to unknown mixing of concentrations within

the NF volume, which was challenged by the use of LEVs. It was not possible to calculate reliable particle loss rates, which are essential to estimate emissions. Thus, only the exposure levels were calculated.

The weighing, pouring, and casting processes increased particle concentrations above 1 μm in diameter. Process particle number and ≤ 10 μm and respirable mass concentrations were up to 31.2 #/cm^3 (pouring; average duration 1 minute; handling rate 700 g/min), 538 μg/m^3 and 140 μg/m^3 (weighing; average duration 2 minutes; handling rate 350 g/min), respectively. A maximum exposure potential was assessed for a continuous process, i.e., a process in which one worker continuously weighs powders, another pours powders into the funnel, and a third casts them into a mould. The maximum risk characterization factor for crystalline silica external exposure was 0.4, indicating an adequately controlled exposure. Electron microscopy analysis confirmed the presence of filler particles, while IPC-OES analysis was inconclusive.

The powder filler exposure was adequately controlled for continuous and manual weighing, pouring, and casting processes when LEVs are applied. Exposure risk to liquid components was not evaluated.

Ethic and consent
Ethical approval and consent were not required.

Institutional review board statement
Not applicable.

Informed consent statement
Not applicable.

Data availability
Zenodo: Extended data for "Extended data for Particle concentrations during the manufacturing of biobased composite polyurethane foam panels". https://doi.org/10.5281/zenodo.20314366 (Koivisto et al., 2026).

The project contains the following underlying data:

- Tables.xlsx: Process times, gravimetric sampling, close-up figures, averaged particle size distributions for ELPI, OPC-NF, and OPC-FF, and risk characterization ratios
- Extended data - Particle analysis.docx: Electron microscopy and IPC-OES analysis
- Measurements raw data.zip: Exported measurement data as txt files

Data are available under the terms of the Creative Commons Attribution 4.0 International license (CC-BY 4.0) (https://creativecommons.org/licenses/by/4.0/).

Underlying data
Not applicable.

Acknowledgments
This work acknowledges the GEMMA Center in the framework of project MUR TECLA "Dipartimenti di Eccellenza 2023–2027".

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Open Peer Review

Current Peer Review Status: ? ✗

Version 1

Reviewer Report 01 October 2026

https://doi.org/10.21956/openreseurope.25798.r81152

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✗

Michael Riediker
Swiss Centre for Occupational and Environmental Health (SCOEH), Winterthur, Switzerland

This article describes particle concentration measurements done in a room where polyurethane foam panels are produced using different types of fillers. There are very few observations and it is thus unclear, to what extent the measurements reflect worker exposures in other situations or on other days.

Major comment
Conclusions: You declare adequate control in a situation where emissions cannot be quantified, where respirable dust concentrations are in range of hundreds of µg/m3 and where during activities, the ratio between measured crystalline silica exposure and the occupational exposure limit is 0.4. Given the small number of samples per setup (one?) Together with the lack of repeat measurements of the same activities and baselines at other working days, a more prudent wording may seem more appropriate. There are several very informative guidelines for statistical interpretation of workplace measurements that should be helpful in this situation.

Further comments
Abstract - Methods: Be more specific regarding the „online aerosol particle monitors“. This article is about nano-enabled products and thus it is important to know from the abstract to what extent the monitors were able to inform about the nanoscale.

Please check the relevance of reference Orabona et al 2025. This article is given as reference for the classification of isocyanates as CMR though it is a research article describing the use of these substances rather than a classification statement by a relevant authority such as ECHA or IARC.

For Component A, something is missing in the list of additives. The last item is 0.1 wt% of what?

Diatomite is typically composed of amorphous silica, but some types can contain relevant quantities of crystalline silica (especially after having been heated, which can cause recrystallinisation). Please provide the proportion of (or „less than“) crystalline silica in the type of

diatomite used.

Please define „open-top walls“. Are these walls that can be opened from (or at) the top? Or are they having a gap at the top - if yes what’s the gap size and is it even along the entire wall?

In the methods section I miss how the measurement sites were defined. Near the sampling points, did you study the air flow direction relative to the source and the LEV?

It is difficult to tell from figure 1 and the pictures whether there were any LEVs in the room. Where were they? Where were room openings that can affect air flow and concentrations measured at the various locations?

TSI Nanoscan and Naneos are positioned next to each other. The figure shows them to be just outside the NearField but the naming of the Naneos suggests otherwise. Please clarify.

The two circles showing the NF1 and NF2 have different diameters. Why?

Figures 2 and 3: What is shown here? Are these activities with different materials? Such information should be given in the figure legend. It is also difficult to distinguish the different measurement periods. For example, where are the blue and red horizontal lines that are mentioned to show the background and gravimetric sampling periods?

Figures 2 and 3: The concentrations do not seem to have a direct relation to the activities with the different fillers. But nanoparticle numbers change in-between. You also observed this. But are there any other processes in the room or in the adjacent hall that could explain the observed temporal patterns?

Table 2 is quite strange in that the NearField concentrations are similar to FarField or even lower. How confident can we be that these numbers reflect the processes of interest?

Tables 3: In total, did you have only four filter samples? Do the two results for „Gas Beton and functionalized silica“ originate from one replicate procedure or two different settings?

Table 5:: How many filters were analysed?

Is the work clearly and accurately presented and does it cite the current literature?
Partly

Is the study design appropriate and does the work have academic merit?
Partly

Are sufficient details of methods and analysis provided to allow replication by others?
Partly

If applicable, is the statistical analysis and its interpretation appropriate?
Partly

Are all the source data underlying the results available to ensure full reproducibility?

Yes

Are the conclusions drawn adequately supported by the results?
No

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Exposure and release assessment, Statistics. Occupational Hygiene.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to state that I do not consider it to be of an acceptable scientific standard, for reasons outlined above.

Reviewer Report 01 October 2026

https://doi.org/10.21956/openreseurope.25798.r81151

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Francisco Silva
Technological Centre for Ceramics and Glass (CTCV), Coimbra, Portugal

This is a well-structured and clearly written manuscript.
The study addresses a relevant topic by examining particle concentrations in research workspaces and has the potential to make a useful contribution to the field.
The manuscript provides a strong basis for indexing. The following suggestions are intended to enhance its clarity, methodological transparency, and overall impact:

- The references to panel cutting in the captions to Figures 2 and 3 appear to be copy-and-paste errors and should be corrected.
- The exposure assessment is an important component of the study and could be further strengthened by addressing the following points:
  - It would be useful to state explicitly that the samples were not collected within the workers' breathing zones. A short discussion of how this limitation may influence the interpretation of the findings would increase the transparency and strength of the exposure assessment.
  - Because the occupational exposure limit values considered are time-weighted averages, exposure across the full 8-hour shift is particularly relevant. An overview of the other tasks performed during the shift would support a more comprehensive interpretation, especially because the elevated background particle concentrations may indicate additional emission sources in the workplace or surrounding environment. The assessment assumes continuous exposure throughout the shift in measured conditions, which is acceptable; acknowledging that actual exposure may vary would provide valuable context and further reinforce the conclusions.
  - The discussion could also be enriched by considering the potential additive effects of the particles, particularly their cumulative respiratory and pulmonary burden (e.g.,

lung overload).
    - Reporting the number of samples collected would allow readers to assess the strength and representativeness of the dataset more fully. For context, EN 689 recommends a minimum of three samples for a preliminary assessment.
- The authors' previous work provides valuable context for this study. At the same time, the literature review would benefit from a broader balance of sources. I therefore encourage the authors to confirm the direct relevance of each self-citation and, where possible, incorporate additional independent studies on particle emissions and occupational exposure.

Is the work clearly and accurately presented and does it cite the current literature?
Yes

Is the study design appropriate and does the work have academic merit?
Yes

Are sufficient details of methods and analysis provided to allow replication by others?
Yes

If applicable, is the statistical analysis and its interpretation appropriate?
Yes

Are all the source data underlying the results available to ensure full reproducibility?
Yes

Are the conclusions drawn adequately supported by the results?
Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Occupational Hygiene, Nanosafety

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.