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RESEARCH ARTICLE

# REVISED Particle Emissions by Mechanical Treatment of Nanocomposites: Emission Library and Applications in Exposure and Risk Assessment

[version 3; peer review: 2 approved, 1 approved with reservations]

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## Abstract

### Background

Reworking and use of nanocomposites (materials with incorporated or embedded nanomaterials) are shown to release relevant quantities of particles that can cause risk for the workers or product users. It is mandatory to provide Conditions of Use (CoU) in Exposure Scenarios for the REACH legislation. This requires information on emissions that the registrant is required to report. Regardless of the REACH legislation, emissions are rarely studied or reported. Here, we revised the available emission/release studies considering the mechanical treatment of nanocomposites.

### Methods

A literature review of mechanical treatment emissions measurements was conducted for the years 2017 – 2024. Emission scaling and CoU assessment were demonstrated for sanding, drilling, milling, sawing, and abrasion scenarios. Exposure model performance testing was performed by comparing predicted concentration levels with

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concentration levels measured in an industrial sanding scenario.

**Results**

One out of 32 studies reported emissions and 12 studies contained sufficient contextual information to calculate the emissions. We developed guidelines and created a data collection sheet to help researchers and developers report the emissions from mechanical stress tests. Most studies reported particle number concentrations that are insufficient for risk assessment, where hazard profiles are given in mass dose/concentration. Modelled concentrations were 2.4 times higher than measured concentrations in the industrial sanding scenario. However, due to differences in materials and measurement techniques, uncertainty assessment was not possible to conduct, and the model applicability was not confirmed.

**Conclusions**

In REACH legislation, reporting emissions and quantifying CoU for emissions containing nanomaterials is mandatory. Regardless of this, emissions are rarely reported. Emissions are the key factor in predictive exposure modelling and risk assessment. Here, we provide guidance and emission reporting templates and demonstrate how CoU can be quantified efficiently.

**Plain language summary**

In REACH regulation, emissions and exposure are mandatory to evaluate the life cycle of nanocomposites. Reworking of nanocomposites by mechanical machining and during the use phase abrasion can release airborne particles and cause relevant inhalation exposure. Emissions from nanocomposites are measured during the materials development phase for assessment of the composition of released materials and exposure potential and to collect released fragments for toxicological studies. Here, we revised emission studies considering nanocomposite mechanical stress studies, developed guidelines, and created a data collection sheet to help researchers and developers report the emissions from mechanical stress tests. We present how to scale emissions, perform quantitative risk assessment, and assess safe conditions of use. Emission scaling and mechanistic exposure model performance were evaluated by comparing modelled concentration levels with concentration measured during sanding tasks in real occupational settings. This study established a framework for systematic documentation of emissions from mechanical treatment and how to assess safe conditions of use for nanocomposites.

**Keywords**

Emission, Nanoparticles, Exposure modelling, Risk assessment, Conditions of Use, Inhalation exposure, REACH, Chemical safety

Any reports and responses or comments on the article can be found at the end of the article.



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**REVISED** **Amendments from Version 2**

We added in introduction ". Particle emissions from industrial processes are rarely reported. This is because ECHA allows the use of qualitative exposure models in occupational exposure assessments (Koivisto & Jayjock, 2025b, under review, https://doi.org/10.12688/openreseurope.19510.1) that do not require information on emissions (ECHA, 2016a; DOI 10.2823/678250)."

We revised the PubMed search and added an explanation that we also performed a non-systematic review. This was explained as: "The rest of the articles (1361) were unrelated to airborne emissions or did not contain nanomaterials (e.g., plastics or micron-sized additives). In addition, we performed a non-systematic literature search by using Google, Google Scholar, and Web of Science and revisiting review articles. The non-systematic review resulted in 18 additional articles, and 34 articles were selected for further evaluation." We updated the underlying data 1 - Emission library for mechanical treatment "Review" sheet.

We added in the "Recommendations for emission measurements" section: In addition to reporting quality, the emission chamber and sampling losses should be measured using a well-characterized particle emission source. None of the studies reported the particle losses in the experimental setup.

We added in the "Recommendations" section: Emission assessment allows quantification of broadly applicable CoUs, which are mandatory to report in the chemical safety report.

**Any further responses from the reviewers can be found at the end of the article**

## List of abbreviations

| | |
|---|---|
| ABS | Acrylonitrile Butadiene Styrene |
| AER | Air Exchange Rate |
| AIHA | The American Industrial Hygiene Association |
| ART | The Advanced REACH Tool |
| CB | Carbon Black |
| CNT | Carbon Nanotube |
| LPM | Liters Per Minute |
| OEL | Occupational Exposure Limit |
| OPC | Optical Particle Counter |
| P90 | Exposure distribution 90th percentile |
| P95 | Exposure distribution 95th percentile |
| PETG | Polyethylene Terephthalate Glycol |
| PP | Polypropylene |
| RCR | Risk Characterization Ratio |
| REACH | Registration, Evaluation, Authorisation and Restriction of Chemicals |
| RWC | Reasonable Worst-Case |
| StM | Stoffenmanager |
| TEAS | Task Exposure Assessment Simulator |
| TPU | Thermoplastic Polyurethane |

## Introduction

A nanocomposite is a solid material formed by two or more phases in which at least one of the phases shows dimensions in the nanometer range (Roy *et al.*, 1986). Mechanical stress can release nanomaterials or nano-containing fragments from nanocomposites. Typical processes considering occupational exposure are sanding, drilling, sawing, and cutting. Abrasion is associated with product use, and shredding can be a relevant process at the end of the life cycle. Relevant particle number emissions occur both in high and low-energy mechanical stresses; emissions from sanding and drilling were up to $10^{10}$ #/s (# denotes particle number) and $10^{8}$ #/s, respectively, while emissions from wind erosion, dynamic friction, and abrasion varied from below the lower limit of quantification to $30\times10^{4}$ #/s (Koivisto *et al.*, 2017). Released fragments consisted mainly of pristine matrix fragments, matrix fragments with embedded or protruding nanomaterials, and occasionally free nanomaterials. Release assessment should consider both new and aged nanocomposites that bring challenges to the exposure assessment (Wohlleben *et al.*, 2024).

The hazard of fragments released from nano-enabled products by mechanical treatment is shown to be determined primarily by the identity of the matrix and potentially modulated by embedded or protruding nanomaterials. Toxicity modulation by nanomaterials is shown to be limited or not detectable for epoxy, cement, polyoxymethylene, polyacrylic, and polyurethane matrices containing various nanomaterials (Wohlleben *et al.*, 2024). A more realistic risk assessment can be conducted if the fraction of free and protruding nanomaterials is assessed, as, e.g., Kang *et al.* (2017) performed for ABS containing CNTs.

Environmental degradation of the matrix can liberate embedded and protruding nanomaterials from the matrix, which should also be considered in the risk assessment (Wohlleben *et al.*, 2024). For particle-lung interactions, inhaled fragments' dissolution rates are highly relevant to estimating the liberation of nanomaterials in the lungs (Brown & Diamond, 2023). Particle characterization is relevant for justifying the use of relevant limit values rather than worst-case limit values for the pristine matrix and the nanofiller. Wohlleben *et al.* (2024) provides a list of commonly applied characterization techniques for assessing the properties of nanocomposite fragments.

In registration, evaluation, authorisation and restriction of chemicals (REACH) Regulation (EC) No 1907/2006 registrant are required to assess the safety of nanomaterials separately. In risk assessment, quantitative exposure estimates need to be done for all exposure scenarios where hazardous emissions occur to support the risk characterization (ECHA, 2016a). Regulation (EC) No 1907/2006 - Annex I §5.2.1 specifies that "*The exposure estimation entails three elements: (1) emission estimation; (2) assessment of chemical fate and pathways; and (3) estimation of exposure levels*". Considering various processes and use scenarios for nanocomposites, the safety assessment requires a systematic approach where documentation of emissions is a key factor; the emission source is a point-of-departure for exposure and health effects. A proper understanding of emission potentials can be used to estimate the upper limit

for exposure during the nanocomposite life cycle by using mechanistic exposure models (WHO/IPCS, 2005). This can be used to quantify Conditions of Use (CoU) where the exposure is considered adequately controlled.

Identification of relevant exposure determinants and quantification of CoU was introduced by Koivisto *et al.* (2021). CoU describes the operational conditions and risk management measures that are needed to maintain exposure at a well-controlled level and is mandatory in chemical safety reporting (ECHA, 2016a; ECHA, 2023). Koivisto *et al.* (2025a) presented how to optimize CoU so that the operational conditions are broadly applicable. However, the assessment requires quantitative information on emissions, emphasizing the need to understand emissions better. Particle emissions from industrial processes are rarely reported. This is because ECHA allows the use of qualitative exposure models in occupational exposure assessments (Koivisto & Jayjock, 2025b, *under review*) that do not require information on emissions (ECHA, 2016a).

Emission/release tests by mechanical treatment are systematically conducted in material durability tests (e.g. ASTM D4060-19; ASTM D1044-19; Bossa *et al.*, 2021; Witkowski *et al.*, 2024), particle collection for toxicological studies (Aznar Mollá *et al.*, 2022; Mantecca *et al.*, 2017; Moreno-Martín *et al.*, 2025; Netkueakul *et al.*, 2020), and characterizing properties of released particles and exposure potential (e.g. Bott & Franz, 2019a; Bott & Franz, 2019b; Fransman *et al.*, 2016; Kuijpers *et al.*, 2020; Wang & Qi, 2022). These experiments are generally conducted for material development and to understand the potential hazards of released particles, especially for nanocomposites. However, these studies rarely report emissions or emission factors, as Koivisto *et al.* (2017) recommended, that are needed for quantitative exposure assessment.

In this study, we 1) update the emission library related to mechanical treatment, 2) provide recommendations for emission/release measurement requirements to produce quantitative and useful information for generic exposure and risk assessment, 3) demonstrate CoU assessment, and 4) how well mechanistic models can predict exposure levels in a real work environment. Emission scaling is applied to demonstrate extrapolation of the emissions for different process parameters. These examples should bring motivation to systematic emission reporting instead of concentrations.

## Methods

### Emission library update for mechanical treatment

A literature review on emissions by mechanical treatment processes was performed using PubMed for years ≥2016 (a search was conducted in Dec 2024). The search string was (sanding OR abrasion OR drilling OR sawing OR cutting OR grinding OR milling OR shredding) AND nano* AND (emission OR concentration OR release) NOT drug NOT food).

### Exposure modelling

Exposure modelling was conducted using Task Exposure Assessment Simulator (TEAS; version 1.05, Exposure Assessment Solutions, Inc., Missouri, U.S., www.easinc.co) well-mixed air model 1Box.CE.Gv (Hewett & Ganser, 2017). A well-mixed air model assumes that air in the room is always thoroughly mixed and that there are no other losses for concentrations than general ventilation exhaust. TEAS is a similar exposure model to the free software IH-MOD 2.0 provided by the American Industrial Hygiene Association (https://ihmod.org/). A primary difference between the two models is that TEAS explicitly addresses local exhaust ventilation while IH-MOD 2.0 does not.

## Results and discussion

### Literature review

The literature review resulted in 1390 results, and based on the title and abstract, 29 studies were considered to provide information on emission or release or sufficient information to calculate emissions. The rest of the articles (1361) were unrelated to airborne emissions or did not contain nanomaterials (e.g., plastics or micron-sized additives). In addition, we performed a non-systematic literature search by using Google, Google Scholar, and Web of Science, and revisiting review articles. The non-systematic review resulted in 18 additional articles, and 34 articles were selected for further evaluation. Bossa *et al.* (2021) was the only study reporting emission rates. Other studies did not provide information about emission rates (e.g., mg/min) or release rates (e.g., mg/(min × per treated surface area) or mg/(per treated surface area)). However, 10 of the 34 studies allowed for calculating emission rates, which are reported here (Underlying data 1, sheet "Review").

Emission rates were obtained for sanding (Bossa *et al.*, 2021; Cooper *et al.*, 2017; Kang *et al.*, 2017; Lee *et al.*, 2020; Neubauer *et al.*, 2017; Singh *et al.*, 2022), drilling (Blazquez *et al.*, 2020; Ding *et al.*, 2017; Starost *et al.*, 2017a; Starost *et al.*, 2017b), sawing (Ding *et al.*, 2017), milling (Blazquez *et al.*, 2020), and abrasion (Bressot *et al.*, 2017). Grinding or shredding studies were not found.

Measurements were mainly reported as number concentrations and/or mass concentrations. Concentrations were used to calculate the emissions by using dilution volume and process duration (Koivisto *et al.*, 2017). Emission calculations are given in Underlying data 1, sheet "Emission calculations".

Typically reported process parameters were matrix material and concentration of potential additives, tool speed (m/s or RPM; rounds per minute), tool properties (e.g., sander/abrader grade and area, drill tip diameter), perpendicular force, and process speed (e.g., mm/min for milling). Underlying data 1, sheet "Emissions," gives contextual information and emissions for each study, such as underlying assumptions in calculations, composition of released particles, or particle measurement size range.

Tangential force, specific power input, or friction coefficients were reported only by Bossa *et al.* (2021). Without specific power input, the results apply only to the particular material and process (Bossa *et al.*, 2021; Koivisto *et al.*, 2017; Le Bihan *et al.*, 2013).

#### *Sanding*

Particle number concentrations were reported for belt sanders and rotary sanders. Calculated particle number emissions varied from $10^4$ to $10^8$ #/s (Figure 1). Sanding experiments with

different sandpaper grades suggest that fine-grade sandpaper (higher P-value) reduced the particle number emissions as compared to coarse-grade sandpaper (Figure 1; Kang *et al.*, 2017; Lee *et al.*, 2020).

Mass concentrations for the sanding process were reported for belt sanders and random orbital sander processes (Cooper *et al.*, 2017; Kang *et al.*, 2017; Lee *et al.*, 2020). Calculated emissions for glass fiber coated with epoxy resin varied from ca. 0.2 to 0.3 µg/s, ABS from 0.01 to 0.05 µg/s, PP from 0.004 to 0.03 µg/s, and plywood from <153 to 929 µg/s (Figure 2). Higher mass emission rates for plywood can be partially explained by the sanding surface area that was 42 times higher than in belt sanding experiments (Figure 2). Mass emissions were similar for glass fiber coated with epoxy resin and ABS for sandpaper grades P150 and P320

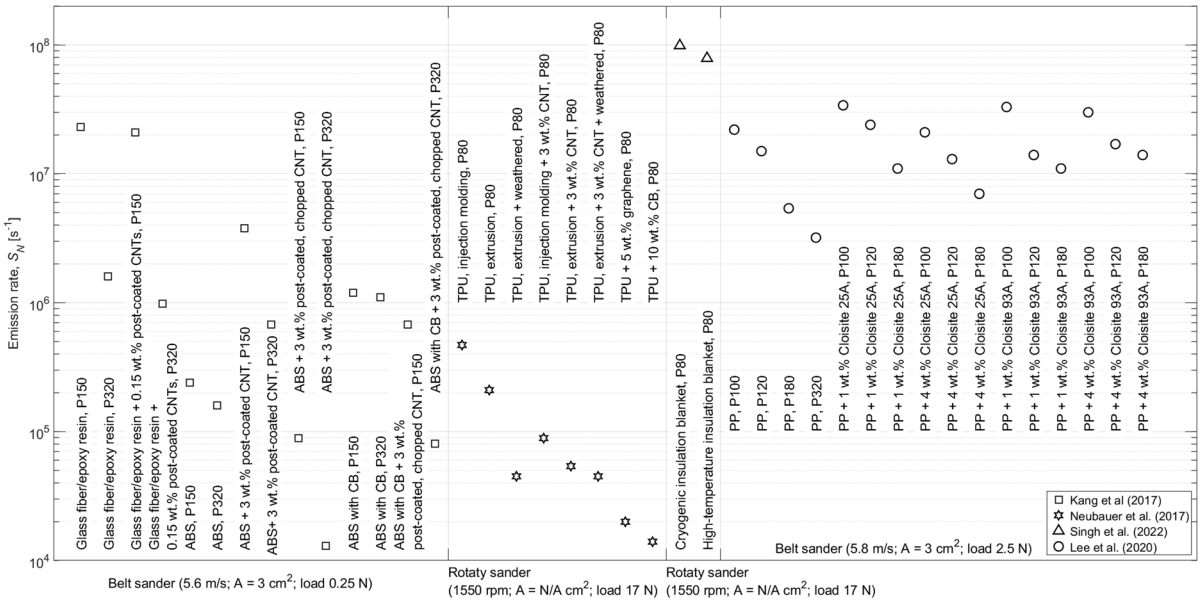


**Figure 1. Particle number emissions for belt sanding.** Abbreviations: ABS acrylonitrile butadiene styrene; TPU thermoplastic polyurethane; PP polypropylene.

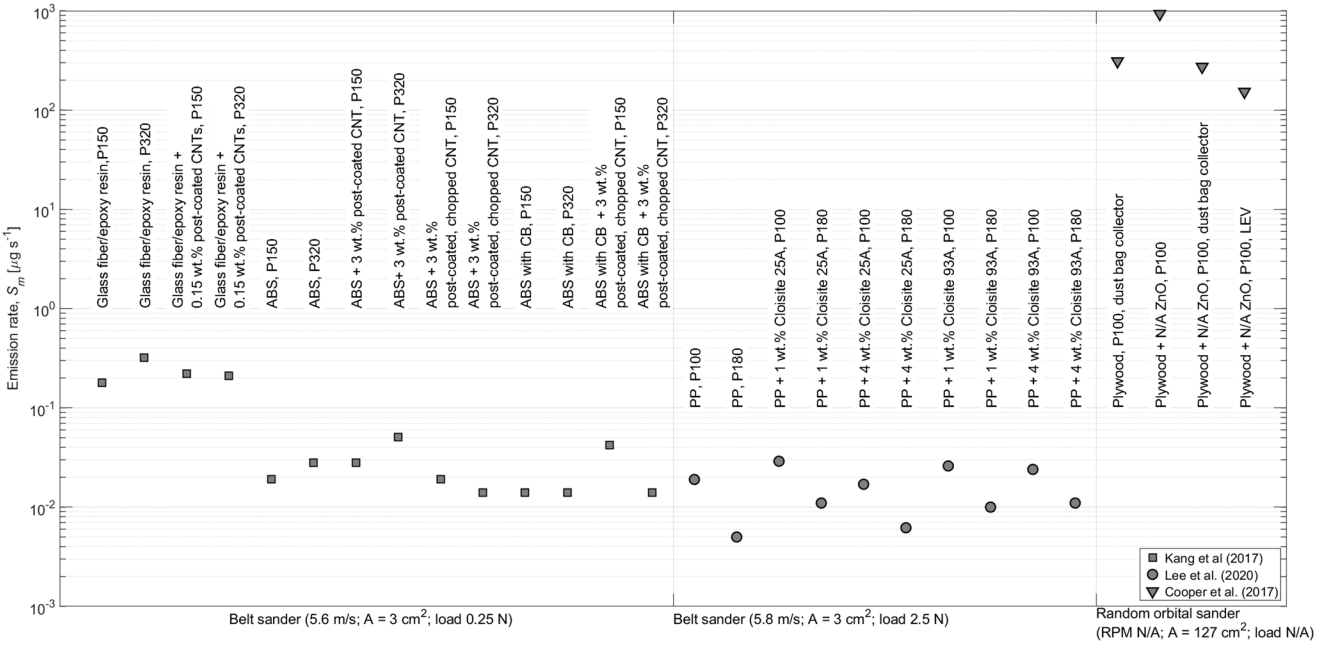


**Figure 2. Particle mass emissions for belt sanding.** Abbreviations: ABS acrylonitrile butadiene styrene; PP polypropylene.

(Figure 2). During PP sanding, mass emission rates were reduced when the sandpaper grade was changed from P150 to P180 (Figure 2).

***Drilling***

Drilling experiments were conducted using drill bits with 3.5-,4-, and 8-mm diameters, rotation speeds of 10000, 1880, and 1550 rpm, and drilling velocities of 78 mm/min and 13 mm/min (Figure 3). Calculated emissions for polyester and epoxy drilling were in the range of $4\times10^{9}$ to $10^{10}$ #/s, while polypropylene emissions were in the range of $2\times10^{5}$ to $8\times10^{5}$ #/s even though the drilling parameters were the same (Figure 3). Polyurethane drilling emissions ranged from $9\times10^{5}$ to $5\times10^{6}$ #/s depending on the nanomaterial filler type, bit diameter, and rotation speed. Mass emission rates were not reported for drilling.

***Sawing, milling, and abrasion***

Particle number concentrations were reported for sawing, milling, and abrasion experiments (Figure 4). Sawing was conducted with a polyurethane matrix by using a hand-held saw with a blade recommended for stainless steel cutting. For sawing, calculated emissions ranged from ca. 370 to 4300 #/s with an increasing trend when CNTs or carbon black were embedded in the matrix. Calculated emissions for Computer Numerical Control milling emitted from 5600 to $2\times10^{4}$ #/s (Blazquez *et al.*, 2020). The abrasion experiment was conducted with commercial tiles without and with $TiO_2$ coating, for which the calculated emissions were $6\times10^{6}$ #/s and $4\times10^{4}$ #/s, respectively.

## Statistical evaluation of the emissions

Emissions can be extrapolated for different process conditions when sufficient information is available. However, because the effects of process parameters and materials on the emissions and specific power input are not reported, the evaluation can be made only for measurements where one variable is changed at a time. Most of the studies were performed under specific conditions, and statistical relations cannot be calculated because of few measurements, even though clear trends can be seen between process parameters and emissions.

Lee *et al.* (2020) conducted PP sanding by using a belt sander (belt velocity 5.8 m/s, contact area 3 $cm^2$, and load 0.25 N) and P100, P120, P180, and P320 sandpapers. Emissions showed a limited correlation for linear fit ($R^2$ =0.72; $S_n$ (#/*s*) = -75850 × *Pvalue* + 3 × $10^7$) and good correlation for power fit ($R^2$ =0.98; $S_n$ (#/*s*) = $5.0\times10^{10}\times Pvalue^{-1.70}$ (Underlying data 1, sheet "emissions", Figure S1). The relation can be used to estimate emissions for other sandpaper grades. For example, based on an exponential fit, emissions for P1000-grade sandpaper would be $4\times10^{5}$ #/s. However, emission extrapolation is uncertain because the specific power input may change significantly and may not follow the relation specified for the measurement range. Interpolation is expected to be reliable based on the correlation coefficient.

Lee *et al.* (2020) sanding experiments with PP showed a decreasing trend in particle number emissions when the sandpaper grade was changed from P100 to P180 (Figure 1). Similarly, Lee *et al.* (2020) showed that PP mass emissions were decreased when P100 was changed to P180 (Figure 2).

If the specific power input is known, more generic rules for mechanical machining emissions for specific materials can be made. Bossa *et al.* (2021) quantified the mass removed as a

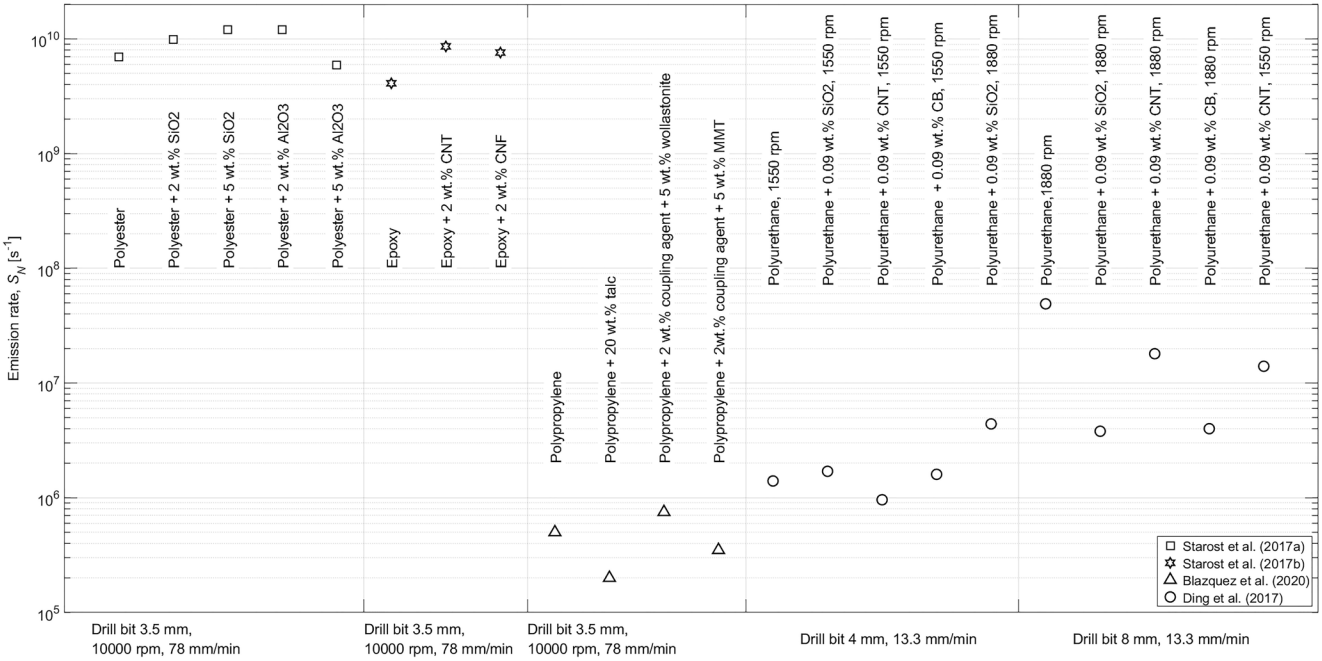


**Figure 3. Particle number emissions for drilling.**

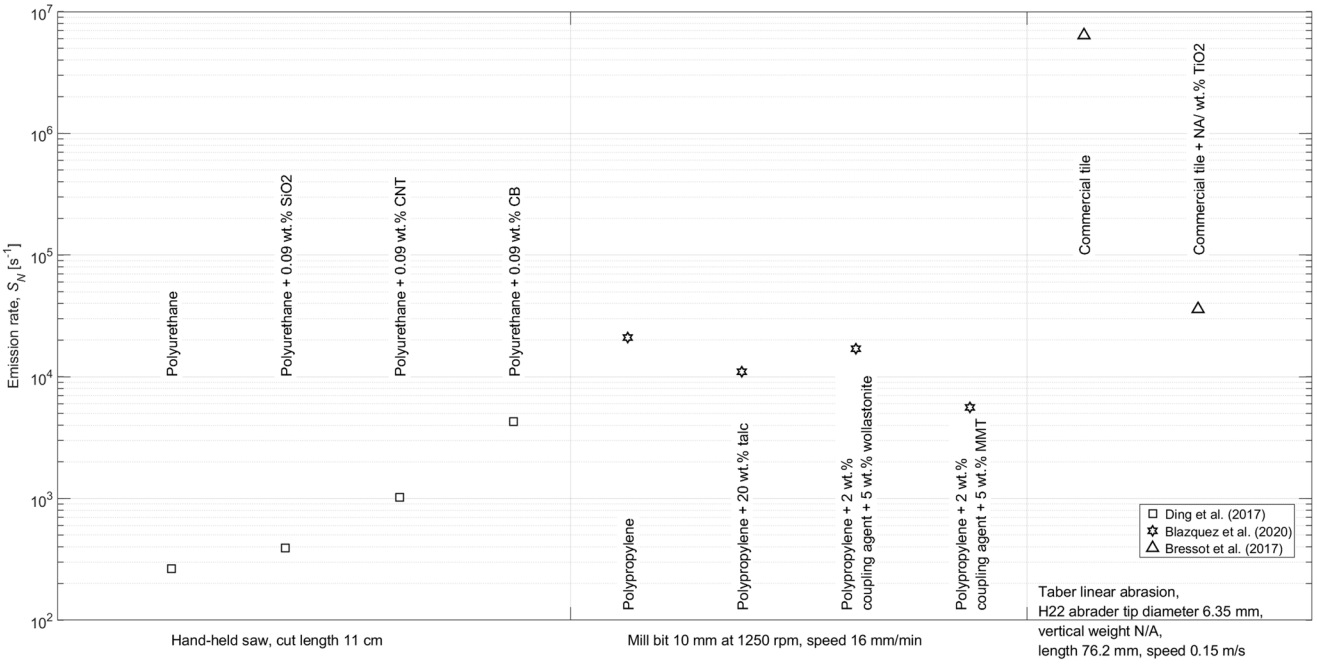


**Figure 4. Particle number emissions for sawing, milling, and abrasion.**

function of specific input power for polyethylene terephthalate glycol (PETG) containing 0, 0.5, and 2 wt.% CNTs. They calculated a relation for material removal rate (*RMM*, g/m$^2$/s) and specific input power (*P*, J/s) as $MRR = a \times A \times P$, where *a* is a linear fit parameter and *A* (m$^2$) is the abrasion surface area. The correlation ($R^2$) between MMR and P was good ranging from 0.96 to 0.996. They applied this empirical relationship to estimate how much PETG is removed by adults chewing the plastic (Bossa *et al.*, 2021). They also measured the fraction of airborne particles released by sanding for cut sizes of 10, 50, and 90 µm. This relation can be used to calculate air emissions for the respective PETG materials for various mechanical processes.

## Recommendations for emission measurements

Koivisto *et al.* (2017) provided generic recommendations for emission/release measurement reporting. Here, more specific contextual information requirements for mechanical process emission reporting were identified (Table 1). For reporting, we provide an MS Excel data collection sheet that is recommended to provide easy access to the results and make the results applicable for exposure assessment (Underlying data 1, sheet "emissions"). In addition to reporting quality, the emission chamber and sampling losses should be measured using a well-characterized particle emission source. None of the studies reported the particle losses in the experimental setup.

Considering emission measurements, it is recommended that tool developers/manufacturers include them in their testbench emission measurements and reporting. The measurement conditions and reporting can be standardized to obtain harmonized emission measurements. This can be beneficial for a tooltip because the emissions would be measured for the materials that the tool is designed to be used, and CoUs can be specified and communicated in the tool use specifications.

## Exposure and risk assessment under Reasonable Worst-Case Conditions

A worker exposure assessment was performed for an 8-h work shift under a reasonable worst-case condition (RWC). The room volume is assumed to be 20 m$^3$, and air exchange rate (AER) is 0.6 1/h, as specified in ECHA (2016b). Deposition losses were assumed to be negligible favoring higher inhalation exposure, room air was considered to be thoroughly mixed, and the process was assumed to be continuous through the work shift. Exposure potential was calculated by using a well-mixed air model (TEAS, Model 1Box.CE.Gv; Hewett & Ganser, 2017). Exposure assessment was performed using different process parameters to demonstrate the emission scaling (Table 2). Modelling reports are given in Underlying data 2, and the calculated exposure levels are given in Table 2.

Particle number concentrations varied from 0.11 #/cm$^3$ (sawing) to 5100 #/cm$^3$ (drilling) (Table 2). There are no health-based exposure limit values for particle number concentrations except for fibers (Pietroiusti *et al.*, 2018), so a risk assessment cannot be conducted.

The exposure level for belt sanding glass fiber laminated with epoxy resin + 0.15 wt.% post-coated CNTs was 186 µg/m$^3$

**Table 1. Recommendations for reporting mechanical treatment emission measurements.**

| Parameter | Reporting requirement | Recommendation |
|---|---|---|
| Material | Manufacturer and type of material and a generic description of materials. | Provide a simple description of the treated material (e.g., glass fiber/epoxy composite (70/30 wt.%). |
| | For layered materials, provide a description of which layers were treated. | |
| Measurement method | Measurement technique, calculation methods, and assumptions (e.g., the density of particles was assumed to be matrix density). | Measurement of inhalable mass concentration by gravimetric method is a standard requirement for risk assessment. Currently, number or surface area concentrations are not used for risk assessment. |
| | Uncertainty related to the measurements. For example, uncertainties in unit conversions and how well emissions were captured by instruments (air mixing, sampler capturing efficiency). | Log normal fit values if particle size distribution is measured. |
| Process | Process machine/tool manufacturer and model. | Provide a short description of the process with key properties (e.g., sanding, P120 sandpaper, rotation velocity/belt velocity, local controls, automated/manual, power delivery (e.g., pneumatic/electric), power input or torque, friction coefficient, material removal rate, contact force/pressure, and process duration. |
| Additional requirements for specific processes | Sanding | Contact area |
| | Drilling | Drill bit diameter and type, and drilling velocity. |
| | Cutting/sawing | Blade dimensions, blade type, cutting velocity, and cutting depth. |
| | Milling | Mill bit diameter, type, milling velocity, and milling depth. |
| | Abrasion | Abrader type and abrader velocity. |

(Table 2). Kang *et al.* (2017) did not observe CNT protrusions in the particles collected from the air at a CNT concentration of 0.15 wt.%. However, protrusions were detected at higher concentrations, but individual CNT fibres were not detected. For fibrous nanomaterials, such as carbon nanotubes, the proposed OEL value is 0.01 fibers/cm$^3$ (Mihalache *et al.*, 2017). Detecting nanofibers at the concentration level of 0.01 fibers/cm$^3$ would require evaluation of >10$^5$ micrograph images and is not currently feasible to conduct (Koivisto *et al.*, 2018). Thus, a risk assessment is not possible for potential CNT exposure, and exposure level compliance cannot be declared for the proposed OEL for nanofibers.

For belt sanding PP + 4 wt.% Cloisite 93A scenario, the exposure level was 16 µg/m$^3$ (0.64 µg-nanoclay/m$^3$) (Table 2). Nanoclay protrusions were detected in 59% of the particles (Lee *et al.*, 2020). For nanoclay, the proposed OEL value is 300 µg/m$^3$ for respirable fraction and 4000 µg/m$^3$ for inhalable fraction (Mihalache *et al.*, 2017). As a worst-case assumption, all nanoclay can become bioavailable. Nanoclay concentration of 0.64 µg/m$^3$ results in risk characterization ratios (RCRs; predicted concentration divided with the limit value) of 0.002 and 0.0002 for respirable and inhalable dusts, respectively. This is well below the proposed RCR of 1, and the nanoclay exposure can be considered adequately controlled. The results can be applied to the sanding scenario with the same process parameters and matrix as specified by Lee *et al.* (2020) and any room condition that favors lower exposure as specified here.

## Emission scaling reliability testing by modelling exposure against workplace measurements

High-quality workplace measurement data with sufficient contextual information for predictive modelling was acquired from (OECD, 2021). One mechanical reworking emission scenario was found by Jensen *et al.* (2015) while other scenarios were mainly related to powder handling, synthesis, or spraying (Underlying data 1, sheet "Jensen *et al.*").

### *Workplace measurements*

Jensen *et al.* (2015) reported respirable mass concentrations during sanding of glass fiber/epoxy composite (70/30 wt.%, respectively) in an enclosed tent (12 m$^3$; no ventilation). Sanding was performed using a pneumatic-driven angle grinder (GTG21 8500 RPM, Atlas Copco, Nacka, Sweden) without local exhaust ventilation. Sanding disk diameter or sandpaper type was not reported. We assumed that a maximum sanding disk diameter of 18 cm was used. Pneumatic angle grinders use pressurized air for power delivery that is considered not to emit particles. The airflow ranges from 600 to 1810 LPM, resulting

**Table 2. Exposure assessment for selected processes.** Operational conditions: continuous process for 8-h, room volume 20 $m^3$, air exchange ratio 0.6 1/h, emission controls are not applied. See scaling calculations from Underlying data 1, sheet "Emission scaling".

| Scenario | Emission measurement | Sanding scenario | Emission scaling | Comments | Exposure level |
|---|---|---|---|---|---|
| 1. Belt sanding: Glass fiber laminated with epoxy resin + 0.15 wt.% post-coated CNTs (Kang *et al.*, 2017) | 0.22 µg/s for P150 sandpaper, a 3 $cm^2$ contact surface area, belt speed of 5.6 m/s, and load of 0.25 N | P150 sandpaper, contact surface area 12 $cm^2$, belt speed 5 m/s and load of 0.25 N | Contact surface area 12/3= 4<br>Belt speed 5/5.6 = 0.89<br>Expected emission is 0.78 µg/s | Emission scaling by contact area is likely overestimated due to limited particle escape | 186 µg/$m^3$ |
| 2. Belt sanding: PP + 4 wt.% Cloisite 93A (Lee *et al.*, 2020) | 0.024 µg/s for P100 sandpaper and 0.011 µg/s for P180 sandpaper, a 3 $cm^2$ contact surface area, belt speed of 5.8 m/s, and load of 2.5 N | P150 sandpaper, contact surface area 12 $cm^2$, belt speed 6 m/s and load of 2.5 N | Sandpaper P150 by using a liner regression (-0.0001625*150+0.0403 = 0.016 µg/s)<br>Contact surface area 12/3 = 4<br>Belt speed 6/5.8 = 1.03<br>Expected emission is 0.067 µg/s | Emission scaling by contact area is likely overestimated due to limited particle escape | 16 µg/$m^3$ |
| 3. Drilling: Polyurethane + 0.09 wt.% SiO2 (Ding *et al.*, 2017) | $3.8\times10^6$ #/s for bit 8 mm, 1880 rpm, 13.3 mm/min | Bit 8 mm, 1880 rpm, 76 mm/min | Drilling speed 76 /13.3 = 5.7<br>Expected emission is $2.2\times10^7$ #/s | Higher drilling speed may not increase linearly particle number emissions | $5.1\times10^3$ #/$cm^3$ |
| 4. Sawing: Polyurethane + 0.09 wt.% SiO2 (Ding *et al.*, 2017) | 265 #/s for cut length 11 cm | Cut length 20 cm | Cut length 20/11 = 1.8<br>Expected emission is 482 #/s | Blade velocity is assumed to remain the same. | 0.11 #/$cm^3$ |
| 5. Milling: Polypropylene + 2 wt.% coupling agent + 5 wt.% MMT (Blazquez *et al.*, 2020) | $5.6\times10^3$ #/s or bit 10 mm at 1250 rpm, speed 16 mm/min | Bit 20 mm at 1250 rpm, speed 32 mm/min | Bit 20/10 = 2<br>Milling speed 32 /16 = 2<br>Expected emission is $2.2\times10^4$ #/s | The drill bit cone surface area is not scaled | 5.3 #/$cm^3$ |
| 6. Abrasion: Commercial tile + NA/ wt.% TiO2 (Bressot *et al.*, 2017) | $3.6\times10^4$ #/s Taber linear abrasion apparatus Model 5750, H22 abrader tip (diameter 6.35 mm; vertical weight N/A), abrasion speed 0.15 m/s | Abrasion with 10 mm tip, abrasion speed 0.3 m/s | Abrasion area $\frac{\pi\cdot10^2}{\pi\cdot6.35^2}$<br>Abrasion speed 0.3/0.15 = 2<br>Expected emission is $1.8\times10^5$ #/s | Abrasion vertical force is not considered; tip material is the same as at the H22 tip. | 430 #/$cm^3$ |

in the average tent ventilation volume flow of 72.3 $m^3$/h (range 36 to 109 $m^3$/h). In a 12 $m^3$ tent, this corresponds to an average ventilation rate of 6 1/h (range 3 to 9 1/h). Natural ventilation across the tent shell is assumed to be insignificant. The average sanding duration was 20 min per task. Jensen *et al.* (2015) mentions sanding papers P36 and P60 for another case performed in the facility for a similar sanding scenario. One of the sandpaper types is expected to be used in this sanding scenario because of task similarities.

***Emission scaling***

Emission rates for sanding of glass fiber/epoxy mixture was not found (PubMed [(glass AND (fiber OR fibre) AND epoxy) sanding]). Thus, emission scaling was performed by using emissions measured by Kang *et al.* (2017) during belt sanding of glass fiber laminated with epoxy resin. Uncertainties in emissions extrapolation from Kang *et al.* (2017) to Jensen *et al.* (2015) are summarized in Table 3. Kang *et al.* (2017) sanding scenario represents more sanding of epoxy rather than glass fiber/epoxy mixture as performed in Jensen *et al.* (2015). Emission scaling for material differences is impossible because of the lack of emission measurements.

Emissions measured by Kang *et al.* (2017) for P150 and P320, sandpaper grades were 0.18 and 0.32 µg/s. Extrapolation of Kang *et al.* (2017) emission measurements to P36 and P60 sandpaper grades are not expected to be linear for epoxy composites, as shown by Huang *et al.* (2012) (Table 3.1). Here, emissions are assumed to be between 0.18 and 0.32 µg/s (uniform distribution). The emission scaling of the sanding area was assumed to be linear (254 $cm^2$/3 $cm^2$), resulting in a scaling factor of 84.8. Huang *et al.* (2012) showed that sanding velocity increases emissions. The maximum velocity without load for the pneumatic angle grinder is 8500 RPM. Rotation speed with load is unknown, and the sanding velocity scaling was not performed. The effect of contact pressure on emissions is not studied, and the contact pressure during handheld sanding is not known why it was not applied here. Sanding emissions with

**Table 3. Assumptions and unknown uncertainties in the emission assessment.**

| Uncertainty factor | Description | Unknown uncertainty |
|---|---|---|
| Material | Glass fiber/epoxy composite is like glass fiber laminated with epoxy resin. | Kang *et al.* (2017) did not report the detection of glass fiber particles, and the materials are representative only of the epoxy part. It is assumed that the friction between sandpaper and material. |
| Sandpaper | Epoxy sanding emission extrapolation from P150 and P320 sandpapers to glass fiber/epoxy composite emissions sanded by P36 to P60. | Emission extrapolation from fine to coarse grades is not expected to be linear (Table 3.1). Thus, emissions are assumed to be between 0.18 and 0.32 µg/s (uniform distribution) as measured for P150 and P320 sandpapers. Scaled emissions by sanding surface area result in an emission range of 15.3 to 27.1 µg/s.<br>**Table 3.1. Sandpaper grade effect on emissions for Epoxy composites (Huang *et al.*, 2012).**<br>P-value: 80 — Emission rate, µg/s: 49<br>P-value: 150 — Emission rate, µg/s: 39<br>P-value: 320 — Emission rate, µg/s: 123 |
| Sanding area | The sanding area was 3 $cm^2$ at Kang *et al.* (2017) and 254 $cm^2$ at Jensen *et al.* (2015). This results in a scaling factor of 84.8. Scaled emissions. | Sanding emissions may not increase linearly to the surface area because increased surface area limits the emissions to air. The contact area may vary during hand-held sanding. |
| Contact pressure | Contact pressure was 833 Pa in Kang *et al.* (2017). In Jensen *et al.* (2015), pressure based on a sanding machine weight of 1.6 kg was 624 Pa. | The effect of contact pressure on sanding emissions is not studied. |
| Sandpaper contact speed | The sanding belt speed was 5.6 m/s, while the pneumatic angle grinder sanding disk speed was at a 4.5 cm radius of 40 m/s (8500 RPM). | Huang *et al.* (2012) showed that mass emission rates were increased from 25 to 71 µg/s when sanding disk speed was increased from 586 RPM to 2167 RPM during sanding of Epoxy +2 wt.% CNTs (Koivisto *et al.*, 2017). This was not considered here. |
| Measurement methods | Kang *et al.* (2017) calculated mass concentration from CPC and OPC (<30 µm particles) measurements, while Jensen *et al.* (2015) performed a gravimetric analysis of respirable samples (<4 µm particles). | Kang *et al.* (2017) used base material density and optical diameter, which depends on particle refractive index (e.g., Pinnick *et al.*, 2000). Uncertainty related to size measurement was not considered. Sanding-generated airborne particles range up to tens of micrometers with mass size distribution mode around 10 µm (Huang *et al.*, 2012; Kang *et al.*, 2017). Ca. 20% of the released mass is in the respirable size range based on visual estimation from figures in Huang *et al.* (2012) and Kang *et al.* (2017). |
| Particle deposition | Particle deposition rate by gravitational settling is not considered at the model. | Particle mass size distribution was in the range of 2 to 30 µm based on OPC measurements (Kang *et al.*, 2017). The deposition rate by gravitational settling is 1 and 7 1/h for 4 and 10 µm particles, respectively (Hussein *et al.*, 2006). Compared to the tent average ACH of 6 1/h, the model overestimates the mass concentration of particles > 1 µm. |
| Other emission sources | Emission measurements consist of particles released from substrate and sandpaper. Engine emissions are separated from sanding emissions and ventilation air is filtered. | Sandpaper particle emissions were assumed to be outside of the respirable particle sampling range. |

the scaling factor from surface area results in 15.3 to 27.1 µg/s used in the calculations.

***Exposure modelling***

Exposure assessment was performed by a single-compartment model, which assumes that concentrations are always fully mixed (TEAS, Model 1Box.CE.Gv; Hewett & Ganser, 2017). Modelling was conducted by using Table 4 parametrization for a single task (20 min). Ventilation air caused by the pneumatic angle grinder was assumed to be a triangular distribution with minimum, average, and maximum values corresponding to the pneumatic angle grinder's minimum, average, and maximum flow rates. Modelling results for 10000 random days show that the geometric mean exposure level is 581 µg/$m^3$, and the exposure distribution 95$^{th}$ percentile (P95) is 797 µg/$m^3$ (see Underlying data 2 for the modeling report). The average

**Table 4. Model parametrization.**

| Parameter | Value | Comment |
|---|---|---|
| Emission rate | Uniform distribution: range 15.3 to 27.1 µg/s | Surrogate for sandpaper grades between P36 and P60 |
| Tent volume | 12 $m^3$ | Worker and process equipment volume is assumed to be insignificant compared to the tent volume. |
| Air changes per hour | Triangular distribution: mode 6, minimum 3, and maximum 9 1/h | Based on average, minimum, and maximum pneumatic angle grinder volume flows and the tent volume of 12 $m^3$. Angle grinder power was assumed to be used mainly at average power. |
| Process duration | 20 min | Average sanding time at Jensen *et al.* (2015) |
| Emission time | 20 min | Continuous process |

respirable mass concentration measured inside the tent was 0.240 mg/$m^3$ during the process (near-field concentration in Jensen *et al.*, 2015).

***Model reliability***

Model reliability is related to the selected model construct and parameterization. Here, the emissions were likely to be well mixed, tent dimensions were well known, and process time was well known. Thus, the single-compartment model can be considered a reliable model to describe the concentrations inside the tent when the deposition of coarse particles is not considered. However, there are numerous uncertain factors that affect the emissions that are not studied, such as using epoxy as a surrogate for glass fiber/epoxy composite, scaling the emissions for smaller sandpaper grit sizes (smaller grit size refers to larger particle size of the abrasive media), and calculating mass concentration from OPC measurements (Table 3). It is likely that some of these unknown factors were underestimated, and others overestimated the emissions (e.g., sanding speed).

The calculated geometric mean exposure (581 µg/$m^3$) level was 2.4 times higher than the measured respirable mass concentration *in situ* (240 µg/$m^3$). However, modelling was performed for emissions in the particle size range up to 32 µm, and *in situ*, measurement was performed for respirable particles (4 µm particle size corresponding to the cumulative frequency of 50%) (Table 3). Uncertainty of mass concentration calculated from OPC number concentration measurement is not known because the light scattering signal depends on the particle properties (Pinnick *et al.*, 2000). Thus, the uncertainty in comparing the measured respirable mass concentration with the mass concentration calculated from OPC measurements is unknown.

The assessment shows promising results considering the predicted and measured concentration ratio. However, emission rates can vary by several orders of magnitude depending on materials, tools, and tooltips (Figure 2). Without further emission measurements, assessing uncertainties or minimum-maximum ranges related to sanding emission extrapolation is challenging. Without proper uncertainty assessment, these modeling results provide subjective exposure estimates for the Jensen *et al.* (2015) scenario.

**Comparison with modelling results reported in OECD (2021)**

OECD (2021) applied Jensen *et al.* (2015) (scenario K5 in OECD (2021) Underlying data 1, sheet "Jensen *et al.*") for performance testing as a part of the evaluation of tools and models for assessing occupational and consumer exposure to manufactured nanomaterials. Model testing was conducted for the Advanced REACH Tool (ART), MEASE, and Stoffenmanager (StM). Instead of using near-field concentration, they applied personal exposure measurement for comparison, which was 260 µg/$m^3$. It is good to note that there is an error in unit conversion and OECD (2021) reports concentrations as 0.00026 µg/$m^3$, which was used to calculate modelled and measured concentration ratios. Corrected model/measurement ratios were for ART, MEASE, and StM 3.6 (P90, inhalable fraction), 17.6 (respirable fraction), and 10.6 (inhalable fraction), respectively. However, modelling was performed for >1000 $m^3$ of naturally ventilated rooms. This scenario does not reflect the work conditions described in Jensen *et al.* (2015) and should not be used for model evaluation or exposure assessment. ART and StM are qualitative models that are challenging to associate with a real work environment (Koivisto *et al.*, 2022; Koivisto & Jayjock, 2025b). MEASE theoretical background is like ART and StM and has similar challenges. It is also good to address that it is questionable to classify glass fiber/epoxy composite without nanomaterial additives as a nanomaterial, as classified in OECD (2021).

***Interpretation of modelling results***

The ECHA Guidance R.14 (ECHA, 2016a) recommends using the P90 exposure level as a critical percentile to reflect all operational conditions described in a particular contributing scenario. The exposure is considered as adequately controlled if the P90 is below the OEL value. This accepts that 10% of the workers can have overexposure, which is not very convenient considering modelling uncertainties, variability in operational conditions, and uncertainties in modelling approaches, as demonstrated here.

A more convenient approach is the American Industrial Hygiene Association (AIHA) exposure category scheme that classifies exposure based on P95 as: 1. non-existent (P95 ≤ 0.01×OEL), 2. highly controlled (0.01×OEL ≤ P95 ≤ 0.1×OEL), 3. well controlled (0.1×OEL ≤ P95 ≤ 0.5×OEL), 4. controlled (0.5×OEL ≤ P95 ≤ OEL), and 5. poorly controlled (P95 > OEL) (Hewett *et al.*, 2006; Torres *et al.*, 2014). Based on the exposure rating there is an action list that needs to be conducted in order to minimize the overexposure (Hewett *et al.*, 2006).

OECD (2021) reported 10 mg/m$^3$ occupational exposure limit value as respirable dust for the Jensen *et al.* (2015) sanding dust emissions. The P95 concentration was calculated by using scaled emissions from Kang *et al.* (2017) was 797 µg/m$^3$, which results in an RCR of 0.08. According to AIHA's human exposure categorization scheme, this limit corresponds to "highly controlled" exposure category 2, where "Exposures infrequently exceed 10% of the OEL" (Hewett *et al.*, 2006). Typical safety actions for the "*well controlled*" category are "*Chemical specific hazard communication*" (Hewett *et al.*, 2006).

## Recommendations

We repeat the recommendations given by Koivisto *et al.* (2017) for emission/release measurements. We emphasize that particulate matter losses in the emission chamber and sampling should be evaluated in a systematic manner. It is recommended to develop emission chamber measurement standards for particulate emissions, such as volatile organic compounds (see, e.g., ISO 12219 series or ASTM D5116-17 guide). Specific reporting recommendations for mechanical treatment emissions are given in Table 1. REACH regulation (Regulation (EC) No 1907/2006) does not request specific surface area or particle number concentration measurements, but it is recommended to measure if legislation changes. Recently, particle number concentration was significantly associated with all-cause and cancer mortality (Pond *et al.*, 2022), and surface area is associated with the acute influx of polymorphonuclear neutrophils in the lungs (Schmid & Stoeger, 2016). For manufacturers, it is recommended that they include emission measurements in their test benches. It would provide valuable information considering the tool tip efficiency and optimize the process considering emissions. Emission assessment allows quantification of broadly applicable CoUs, which are mandatory to report in the chemical safety report.

## Conclusions

In REACH legislation, emission estimation is a mandatory part of exposure assessment. Process emission is the key parameter in predictive exposure assessment and setting Conditions of Use (CoU) for processes.

In this study, we updated the emission library compiled by Koivisto *et al.* (2017) for mechanical treatment of nanocomposites. From 34 emission studies, one reported emission rates, and for 10 studies, it was possible to calculate emissions. With a small effort, other studies could have reported emissions or provided sufficient contextual information to calculate the emissions. Thus, we provided emission reporting guidelines and an emission registry to help researchers and process developers report the emissions. For motivation, we presented examples of how to scale the emissions and assess CoUs for different processes. Nanomaterials hazard profiles are assessed in mass dose/concentration, which is why CoU assessment is not possible to perform for particle number emissions.

Exposure model performance was tested by reproducing concentration levels measured in a real industrial sanding scenario. Predicted concentration levels were 2.4 times higher than measured concentration levels suggesting sufficient predictive accuracy for regulatory chemical safety decision-making. Unfortunately, the assessment uncertainties were not possible to quantify due to differences in composite materials and measurement techniques. Currently, there are no statistical databases to evaluate the reliability of the emission extrapolation, and thus, the model result was considered a qualitative estimate for representing the workplace exposure scenario.

## Ethic and consent

Ethical approval and consent were not required

## Institutional review board statement

Not applicable.

## Informed consent statement

Not applicable.

## Data availability

### Underlying data

Zenodo: Underlying data for "Particle Emissions by Mechanical Treatment of Nanocomposites: Emission Library and Applications in Exposure and Risk Assessment". https://doi.org/10.5281/zenodo.15193570 (Koivisto *et al.*, 2025c). The project contains the following underlying data:

- Underlying data 1 - Emission library for mechanical treatment
- Underlying data 2 - Particle Emissions by Mechanical Treatment of Nanocomposites.docx: TEAS simulation reports.

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/).

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Wohlleben W, Bossa N, Mitrano DM, *et al.*: **Everything falls apart: how solids degrade and release nanomaterials, composite fragments, and microplastics.** *NanoImpact.* 2024; **34**: 100510.
**PubMed Abstract** | **Publisher Full Text**

# Open Peer Review

## Current Peer Review Status: ✔ ? ✔

**Version 3**

Reviewer Report 03 June 2025

https://doi.org/10.21956/openreseurope.21872.r54516

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✔ **Ajay Vikram Singh**
German Federal Institute for Risk Assessment (BfR), Berlin, Germany

I have no further comments to add. The authors have addressed all previous concerns satisfactorily, and I support the indexing of the revised article in its current form.

***Competing Interests:*** No competing interests were disclosed.

***Reviewer Expertise:*** Nanotoxicology, QSAR, PBPBK Modelling, Chemical Toxicology, Nanomedicine, Materials Science

**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.**

**Version 2**

Reviewer Report 17 April 2025

https://doi.org/10.21956/openreseurope.21748.r52713

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✘ **Ajay Vikram Singh**
German Federal Institute for Risk Assessment (BfR), Berlin, Germany

The study addresses a critical gap in emission reporting for nanocomposites under REACH, yet several areas require refinement to enhance scientific rigor and translational impact. The

literature review, while comprehensive, lacks transparency in the selection process of the 32 studies from 1,337 initial hits. A PRISMA-style flowchart or explicit exclusion criteria (e.g., non-nanocomposite focus, incomplete metadata) would clarify methodological rigor and reduce selection bias. The reliance on extrapolated emissions from Kang et al. (2017) for modeling introduces unquantified uncertainties, particularly when applied to dissimilar materials (e.g., glass fiber/epoxy vs. epoxy alone). A sensitivity analysis or Monte Carlo simulation could better characterize these uncertainties, which are critical for regulatory acceptance.

The figures (1–4) suffer from inadequate contextualization; for instance, Figure 1's particle number emissions lack error bars or confidence intervals, undermining reproducibility. Differentiating materials (e.g., ABS, PP) via color-coding or symbols would clarify trends in sandpaper grit effects. The discussion of REACH compliance omits actionable pathways for industry adoption. Case studies illustrating how manufacturers integrated emission data into Safety Data Sheets (SDS) or Exposure Scenarios would bridge theory and practice.

The single-compartment model (TEAS) assumes perfect mixing, neglecting particle deposition dynamics—a significant limitation for respirable fractions. Incorporating deposition rates (e.g., Hussein et al., 2006) or comparing with multi-zone models (e.g., CONTAM) would strengthen exposure predictions. The 2.4× overestimation in modeled vs. measured concentrations suggests systemic biases; exploring machine learning corrections or Bayesian calibration could improve predictive accuracy.

Toxicological implications are underexplored. While mass-based hazard profiles dominate, emerging evidence links particle surface area/reactivity to inflammatory responses (Schmid & Stoeger, 2016). Including such relationships would justify why particle characterization (beyond mass/number) is essential for risk assessment. The recommendations for tool manufacturers lack enforceability; proposing collaborative frameworks (e.g., pre-competitive consortia for emission benchmarking) could incentivize industry participation.

Finally, the conclusion should prioritize future research—e.g., harmonizing emission protocols across ASTM/ISO standards or longitudinal studies on aged nanocomposites—to align academic outputs with regulatory needs citing some latest seminal work such as https://doi.org/10.1021/acs.jafc.3c06466 & https://doi.org/10.37349/ebmx.2024.00009 to update the related literature. Addressing these points would transform the paper from a descriptive review into a foundational guide for next-generation risk assessment.

**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?**
Yes

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

**Are the conclusions drawn adequately supported by the results?**
Partly

***Competing Interests:*** No competing interests were disclosed.

***Reviewer Expertise:*** Nanotoxicology, QSAR, PBPBK Modelling, Chemical Toxicology, Nanomedicine, Materials Science

**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 09 April 2025

https://doi.org/10.21956/openreseurope.21748.r52574

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**Michael Riediker**
Swiss Centre for Occupational and Environmental Health, Winterthur, Switzerland

Dear Antti Joonas, in your response, you politely explain that you have chosen not to modify your manuscript in response to most of my comments. However, I found your manuscript lacking important details and provided specific suggestions for improvements. I expect, at the very least, that the wording will be improved so that the readers of the main text can also benefit from the thoughts you shared in the comments to the reviewer.

Thus:

**Point 1:** Please adapt your manuscript to clearly reflect your rationale and better describe the approaches of the different guidelines in the manuscript.

**Point 2:** The manuscript requires significant improvement in its reasoning. As it stands, the article comes across as overly critical of all the authors of well done studies who did not follow your recommendations.

**Point 4:** You have misunderstood my input. My comments were not related to power input but rather to the type of authors. My personal experience in working with industry was that, if they do collaborate, the quality of data is usually quite good. Do you see any pattern in the 32 articles you studied closer?

**Point 5:** Your response is confusing. If you are currently developing recommendations for authorities such as ECHA, it would be straightforward to mention this in your manuscript. Actually, this is an opportunity to highlight your ongoing research.

**Point 6:** You have not addressed my criticism adequately. You identified 1337 articles and **somehow** narrowed them down to 32 studies that you investigated more closely. I expect a clear explanation of this selection process. While I do not expect the degree of detail expected from a formal systematic review, I do expect **more transparency than** what currently simply looks like **a** „**miracle**". For example, you could specify in the results: „xx articles did not address nanomaterials, xx did not assess airborne nanomaterials,…" and so on. Also, as you contacted authors but did not receive answers, you should report this in your findings: „xx authors of studies were contacted for more details. However, xx did not answer, and xx could not provide sufficient details for our purpose."

**Point 8:** The graphs are not effectively aiding in the understanding of the findings. My recommendations were intended to make the graphs more readable. It is not helpful to readers if you tell me in the section „response to the reviewer comments" to look up another section of the manuscript.

***Competing Interests:*** No competing interests were disclosed.

**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.**

Author Response 14 Apr 2025

**Antti Joonas Koivisto**

Dear Antti Joonas, in your response, you politely explain that you have chosen not to modify your manuscript in response to most of my comments. However, I found your manuscript lacking important details and provided specific suggestions for improvements. I expect, at the very least, that the wording will be improved so that the readers of the main text can also benefit from the thoughts you shared in the comments to the reviewer.

**Response:** Thank you for your valuable comments. We agree that the response letter did not adequately answer your comment regarding revision methods. We hope the current version addresses all the comments adequately.
Thus:

**Point 1:** Please adapt your manuscript to clearly reflect your rationale and better describe the approaches of the different guidelines in the manuscript.

**Response:** The rationale is explained in the introduction as:

- In REACH legislation, reporting emissions and quantifying CoU for emissions containing nanomaterials is mandatory.
- Quantitative CoU assessment requires information on emissions that the registrant is required to report.

- Mechanical treatment of nanocomposites releases airborne nanomaterials, which are mainly embedded or protruding from the matrix.
- Systematic documentation of emissions helps to understand emission potentials that can be used to estimate the upper limit for exposure during the nanocomposite life cycle by using mechanistic exposure models.

The approaches of the different guidelines:

- The only guideline considering nanomaterial emission measurements and reporting is Koivisto et al. (2017). We could not find any other guidelines. Also, there exist emission studies that do not report only concentrations, but these do not give guidelines for reporting emission measurements. This is considered to be discussed adequately. We would be grateful if you could let us know if you have guidance on process particle emission measurements and reporting.

**Point 2:** The manuscript requires significant improvement in its reasoning. As it stands, the article comes across as overly critical of all the authors of well done studies who did not follow your recommendations.

**Response:** See rationale and reasoning above As explained, the primary objectives of the studies are mainly durability tests, particle collection for toxicological studies, and characterizing properties of released particles and exposure potential. These studies do not claim that quantitative emission rates or release factors would have been investigated. These studies compare the concentrations sufficient to draw conclusions for their objectives. However, the impact of the studies could be increased with a small effort by following our recommendations.

**Point 4:** You have misunderstood my input. My comments were not related to power input but rather to the type of authors. My personal experience in working with industry was that, if they do collaborate, the quality of data is usually quite good. Do you see any pattern in the 32 articles you studied closer?
**Response:** Data quality is considered in two parts: 1) characterization of the measurement setup and 2) reporting quality (e.g., transparency, assumptions, relevant parameters, calculations, etc.). Industry follows standard procedures closely to verify the quality requirements. No particle emission measurement standards for this emission measurement have been developed, as recommended here. Different experimental settings are used depending on the process, and performance evaluation between different settings is challenging. None of the studies measured particle losses in the system using a known source, such as deposition rates or sampling efficacies. This is unnecessary if relative changes are investigated or particles are collected for further analysis. Thus, it is not reasonable to investigate if there are any patterns between studies made by industry or the academy unless they have the objective of reporting quantitative emissions. We added to Recommendations for emission measurements “In addition to reporting quality, the emission chamber and sampling losses should be measured by using a well-characterized particle emission source. None of the studies reported the particle losses in the experimental setup.”

**Point 5:** Your response is confusing. If you are currently developing recommendations for authorities such as ECHA, it would be straightforward to mention this in your manuscript.

Actually, this is an opportunity to highlight your ongoing research.
**Response:** The original comment and response were “Related to point 3: Do the authors have any recommendations for REACH authorities and legislators? Response: According to the REACH regulation, emissions must be reported. However, ECHA does not require this, and thus, the emissions are rarely reported. We have a separate study related to this topic, which was submitted to Open Research Europe on January 24, 2025, and is pending the Editor's decision. No changes were made.”
The REACH regulation (Regulation (EC) 1907/2006) specifies that exposure models must be appropriate. In addition, ECHA R.14 specifies that quantitative exposure estimates are required for hazardous emissions. Thus, exposure models must be *appropriate* and *quantitative* for hazardous emissions. However, ECHA does not recognise the term *quantitative*, and they do not have quality criteria or require transparency from the exposure models. Without quality criteria or transparency, there is no quality assurance or control. This is why ECHA allows use of qualitative exposure models in occupational exposure assessment, such as Stoffenmanager, ART, ECETOC-TRA, MEASE, EASE, and EMKG-EXPO-TOOL (ECHA R.14). Qualitative exposure models do not require quantitative information on emissions. This is why emissions are not measured, even though the REACH regulation requires emission measurements. We added in introduction “. Particle emissions from industrial processes are rarely reported. This is because ECHA allows the use of qualitative exposure models in occupational exposure assessments (Koivisto and Jayjock, 2025a, *under review*, https://doi.org/10.12688/openreseurope.19510.1) that do not require information on emissions ( ECHA, 2016a).”

**Point 6:** You have not addressed my criticism adequately. You identified 1337 articles and **somehow** narrowed them down to 32 studies that you investigated more closely. I expect a clear explanation of this selection process. While I do not expect the degree of detail expected from a formal systematic review, I do expect **more transparency than** what currently simply looks like **a** „**miracle**". For example, you could specify in the results: „xx articles did not address nanomaterials, xx did not assess airborne nanomaterials,…“ and so on. Also, as you contacted authors but did not receive answers, you should report this in your findings: „xx authors of studies were contacted for more details. However, xx did not answer, and xx could not provide sufficient details for our purpose.“
**Response:** We agree that this is not explicitly presented. We revised the PubMed search and added an explanation that we also performed a non-systematic review. This was added: "The rest of the articles (1361) were unrelated to airborne emissions or did not contain nanomaterials (e.g., plastics or micron-sized additives). In addition, we performed a non-systematic literature search by using Google, Google Scholar, and Web of Science and revisiting review articles. The non-systematic review resulted in 18 additional articles, and 34 articles were selected for further evaluation.” Note that the review resulted only in 29 articles and not 32 as previously reported. This was because non-systematic review articles were misleadingly included in the previous count. We apologise for this inconvenience. We added the PubMed articles in the Underlying data separately.

**Point 8:** The graphs are not effectively aiding in the understanding of the findings. My recommendations were intended to make the graphs more readable. It is not helpful to readers if you tell me in the section „response to the reviewer comments“ to look up another section of the manuscript.

**Response:** The original comment was "*Figures 2 to 4: Some of the drivers of emission rates become obvious when reading in great detail the individual points' labels. This could be improved by labelling relevant grouping (e.g. Glass fibre / ABS, PP, Plywood) and subgrouping (e.g. by sandpaper grit) -> check also if sorting by or colouring of most relevant subgroups would improve readability.*" The figures can be organized depending on the objective. The objective for sanding emissions is to show how process parameters affect sanding emissions because the emission extrapolation/interpolation is demonstrated using sandpaper grade. Thus, we follow the order where first control material emissions are given with different sandpaper grades, followed by the materials with additives and different sandpaper grades. Alternatively, we could arrange the figure to show how additives affect the emissions, where the sandpaper grade is constant and the material changes. Because materials are very specific and the data is limited, we considered it more valuable to investigate the process parameters' effect on emissions (here, sandpaper grade). In Figures 3 and 4, experiments were performed by varying up to one process parameter (rpm in drilling) for one matrix material. Reorganisation of these figures does not provide added value. The data is presented in the Underlying Data Sheet "Emissions", where it is possible to calculate how additives affect the emissions. For example, adding Cloisite to PP can double the particle number/mass emissions. However, this is a material-specific property and is not as useful as showing that finer sandpaper grades produce fewer emissions. However, total emissions depend on the process objective regarding the amount of material removed and the surface finish.

***Competing Interests:*** No competing interests were disclosed.

**Version 1**

Reviewer Report 26 March 2025

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**Michael Riediker**
Swiss Centre for Occupational and Environmental Health, Winterthur, Switzerland

This article reports about a review of 32 publications on mechanical treatment emission measurements published during the years 2017 to 2024. They assessed to what extent these publications inform regarding conditions of use in exposure scenarios for REACH. Few of the articles contained sufficient information to inform on this regard. The authors propose (yet another) set of reporting guidelines.

General Criticism:

1) The rationale for focusing on the last few years only is not sufficiently well established. Several major EU-funded projects had published very relevant work - including publication guidance before this date (one of them was by Koivisto et al. but it was not the only one). This should be better described and relevant literature reviewed in the introduction.

2) One of the insights of the here presented review is that too many publications report on concentrations near emission sources without sufficiently well describing the emission and release process. Another set of emission studies insufficiently describes the setup so that it is not possible to estimate e.g. losses in the test environment. In a nutshell, too many studies provide too little metadata. Unfortunately, this is not a novelty. In this regard, it would be helpful to assess in more detail how the quality of reporting has evolved compared to the different earlier recommendations. Maybe they did not follow Koivisto-et-al-recommendations but others? This is why I recommend in point 1 a brief review on previous release reviews and reporting recommendations.

3) The recommendations in this article focus on emission reporting done by researchers. However, REACH legislation is addressing industry. Do the authors have any suggestions how industry can contribute? Do they see ways to make more information about release and emissions publicly available? Discussions on this had started already during NanoImpactNet. Could it be that the industry has not yet taken up the idea of them making their internal data available?

4) Related to point 3: Did the authors study which of the assessed publications had co-authors from industries? How do those publications fare in the assessment compared to those without any industry-involvement?

5) Related to point 3: Do the authors have any recommendations for REACH authorities and legislators?

Specific Criticism:
6a) the stated goal was to assess release from nano-composites. However, the literature search terms do not contain the term nano-composite. Did the authors manually assess whether a study was looking at nano-composites? How many of the studies detected with the search terms met only parts of the criteria for inclusion in the assessment? I miss a chart or at least text-description of how the initial 1337 articles were sorted to identify those meeting the review criteria (check guidance on how to report systematic reviews for an idea of how this can be done).
6b) Later in the text, a sub-search that includes specific composites is presented. It would be preferable to describe also that search and sorting approach in the methods section and the initial overview of results.

7) I miss the big picture. Currently, the article resembles a series of short paragraphs that describe individual studies and a few applications of literature to describe conditions of use in view of exposure scenarios. This could be improved by a better structuring so that the article looks less fragmented.

8 Figures 2 to 4: Some of the drivers of emission rates become obvious when reading in great detail the individual points' labels. This could be improved by labelling relevant grouping (e.g. Glass fibre / ABS, PP, Plywood) and subgrouping (e.g. by sandpaper grit) -> check also if sorting by

or colouring of most relevant subgroups would improve readability.

9) The first paragraph of the recommendations repeats the basic recommendations to article authors. Further up, the authors also phrased recommendations that could be directed to manufacturers of machines and composites. It seems worthwhile to issue also here a take home message for these groups (maybe discuss in relation to points 3 and 5).

10) The second paragraph of the recommendations is an explanation why some types of release characteristics are important beyond mere exposure modelling efforts, namely toxicological aspects. While this is a very relevant point, I wonder why it is here in the recommendations section and not in the introduction.

**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?**
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?**
Not applicable

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

**Are the conclusions drawn adequately supported by the results?**
Yes

***Competing Interests:*** No competing interests were disclosed.

**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.**

Author Response 28 Mar 2025

**Antti Joonas Koivisto**

Dear Michael, thank you very much for your valuable comments. Please, see below our responses to the specific comments. This article reports about a review of 32 publications on mechanical treatment emission measurements published during the years 2017 to 2024. They assessed to what extent these publications inform regarding conditions of use in exposure scenarios for REACH. Few of the articles contained sufficient information to inform on this regard. The authors propose (yet another) set of reporting guidelines. The proposed guidelines align with those of Koivisto et al. (2017) guidelines, but offer more information

requirements for mechanical treatment emissions reporting and provide generic reporting templates. No changes were made.
General Criticism:
1) The rationale for focusing on the last few years only is not sufficiently well established. Several major EU-funded projects had published very relevant work - including publication guidance before this date (one of them was by Koivisto et al. but it was not the only one). This should be better described and relevant literature reviewed in the introduction. Guidances are related to concentration measurements and source identification rather than particulate matter emission characterisation. Currently, EPA AP-42 is the most extensive work related to emission factors, providing generic emission factors for various stationary processes. For example, the Nanoparticle Emission Assessment Technique (NEAT; https://doi.org/10.1080/15459624.2016.1167278) is used to measure particle concentrations without specifying conditions under which emissions can be quantified. Similarly, OECD guidance (ENV/JM/MONO(2009)16) focuses on concentration measurements and source identification but not emission source quantification. For specific processes, such as 3D printing, comprehensive documentation of emissions is available. However, to our knowledge, there is no guidance available for different mechanical treatment processes. This is likely because emission and concentration/exposure are often considered interchangeable. **No changes were made.**

2) One of the insights of the here presented review is that too many publications report on concentrations near emission sources without sufficiently well describing the emission and release process. Another set of emission studies insufficiently describes the setup so that it is not possible to estimate e.g. losses in the test environment. In a nutshell, too many studies provide too little metadata. Unfortunately, this is not a novelty. In this regard, it would be helpful to assess in more detail how the quality of reporting has evolved compared to the different earlier recommendations. Maybe they did not follow Koivisto-et-al-recommendations but others? This is why I recommend in point 1 a brief review on previous release reviews and reporting recommendations. Ignoring particle losses in the experimental setup causes an underestimation of the concentration measurements and emission calculation. This can lead to an underestimation of the exposure assessment. Similarly, it is often unclear whether concentrations are fully mixed in the experimental setup, which can lead to under- or overestimation of calculated emissions. Usually, the sampling ports were located close to the source, and it is expected that under such conditions, emissions are overestimated, which is considered a conservative approach in exposure assessment. However, without dilution volume, emissions cannot be calculated. This is the major reason for rejecting the studies in this study. There has been little evolution in the reporting, as mentioned in the introduction. This is why we provide examples on how to apply emission measurement data in exposure and risk assessment. This is stated as "*These examples should bring motivation to systematic emission reporting instead of concentrations.*" In principle, emission reporting is mandatory in REACH regulation (Regulation (EC) No 1907/2006), but this is not currently followed; ECHA allows the use of qualitative exposure models (e.g. Stoffenmanager, the Advanced REACH Tool, EMKG-EXPO-TOOL, ECETOC-TRA, and MEASE) in occupational exposure assessment that do not require information on emissions. This is one reason why emissions are not reported, and there has been no significant development in the field of emission characterization and reporting. **No changes were made.**

3) The recommendations in this article focus on emission reporting done by researchers. However, REACH legislation is addressing industry. Do the authors have any suggestions how industry can contribute? Do they see ways to make more information about release and emissions publicly available? Discussions on this had started already during NanoImpactNet. Could it be that the industry has not yet taken up the idea of them making their internal data available? Currently, the industry does not report emissions related to tool testing. In "Recommendations for emission measurements" section, we wrote that " *Considering emission measurements, it is recommended that tool developers/manufacturers include them in their testbench emission measurements and reporting. The measurement conditions and reporting can be standardized to obtain harmonized emission measurements. This can be beneficial for a tooltip because the emissions would be measured for the materials that the tool is designed to be used, and CoUs can be specified and communicated in the tool use specifications*." We added recommendations in the Recommendations section.

4) Related to point 3: Did the authors study which of the assessed publications had co-authors from industries? How do those publications fare in the assessment compared to those without any industry-involvement? This was not evaluated. It is challenging to evaluate this without information on specific power input. **No changes were made.**

5) Related to point 3: Do the authors have any recommendations for REACH authorities and legislators?
According to the REACH regulation, emissions must be reported. However, ECHA does not require this, and thus, the emissions are rarely reported. We have a separate study related to this topic, which was submitted to Open Research Europe on January 24, 2025, and is pending the Editor's decision. **No changes were made.**

Specific Criticism:
6a) the stated goal was to assess release from nano-composites. However, the literature search terms do not contain the term nano-composite. Did the authors manually assess whether a study was looking at nano-composites? How many of the studies detected with the search terms met only parts of the criteria for inclusion in the assessment? I miss a chart or at least text-description of how the initial 1337 articles were sorted to identify those meeting the review criteria (check guidance on how to report systematic reviews for an idea of how this can be done). The search term "nano*" also encompasses nano-composites. Based on the study title and abstract, we extracted all studies that reported emissions or releases from the mechanical treatment of nano-containing objects. This resulted in the 32 studies that were further evaluated to determine if emissions or releases can be calculated. Underlying data 1, sheet "Review," reports the studies for which emissions or releases could be calculated, or why calculation is not possible. Some authors were contacted for further information, but this approach was not effective and did not yield additional information. **No changes were made.**
6b) Later in the text, a sub-search that includes specific composites is presented. It would be preferable to describe also that search and sorting approach in the methods section and the initial overview of results. The sub-search was conducted to determine if there are studies related to emissions or releases from the sanding of glass fiber/epoxy composites that do not contain nanomaterials. This study was selected as an example of model

performance because the OECD (2021) used the Jensen et al. (2015) study in their evaluation of the nano-specific exposure models. For that, we needed emission rates for sanding glass fiber/epoxy composites, which is why the sub-search was performed. **No changes were made.**

7) I miss the big picture. Currently, the article resembles a series of short paragraphs that describe individual studies and a few applications of literature to describe conditions of use in view of exposure scenarios. This could be improved by a better structuring so that the article looks less fragmented. We have added a more detailed description of the study structure in the introduction.

8 Figures 2 to 4: Some of the drivers of emission rates become obvious when reading in great detail the individual points' labels. This could be improved by labelling relevant grouping (e.g. Glass fibre / ABS, PP, Plywood) and subgrouping (e.g. by sandpaper grit) -> check also if sorting by or colouring of most relevant subgroups would improve readability. This was conducted in the "Statistical evaluation of the emissions" section. **No changes were made.**

9) The first paragraph of the recommendations repeats the basic recommendations to article authors. Further up, the authors also phrased recommendations that could be directed to manufacturers of machines and composites. It seems worthwhile to issue also here a take home message for these groups (maybe discuss in relation to points 3 and 5). We repeat the recommendations because there has been little evolution in the reporting. We added recommendations for manufacturers.

10) The second paragraph of the recommendations is an explanation why some types of release characteristics are important beyond mere exposure modelling efforts, namely toxicological aspects. While this is a very relevant point, I wonder why it is here in the recommendations section and not in the introduction. This was moved to Introduction.

***Competing Interests:*** No competing interests were disclosed.

Reviewer Report 25 March 2025

https://doi.org/10.21956/openreseurope.21264.r52006

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**Nathan Bossa**
Duke University, Durham, USA

General comment:

This article serves as a valuable continuation of a previous publication that established the first database of particle emissions by mechanical treatment. It is designed to enable the comparison of processes and materials. In this follow-up study, the authors substantially expand the original database and demonstrate its applicability in the context of risk assessment and emissions. Specifically, they illustrate how selected data can be utilized for exposure assessment and provide detailed guidance on the extraction, processing, and integration of published data into exposure models.
This work addresses a critical need in the field by offering clear and practical recommendations for experimentalists, facilitating the reuse of experimental data in risk assessment. Furthermore, it contributes to the development of methodologies that will support future regulatory frameworks. Overall, the study represents an important step toward strengthening the connection between experimental research and regulatory science.

Comment 1: In the sentence "The room volume is assumed to be 20 $m^3$, and air exchange rate (AER) is 0.6 1/h", the L seems to be a 1.

Comment 2: Can the authors define the RCR calculation for clarity?

Comment 3: Some terms can be better described for clarity such as the grit size of sandpaper.

Comment 4: In the section "Recommendations for emission measurements", it is unclear if the reporting of such information would allow it to be among the selected studies.

Comment 5: It could be interesting, to point which study was still present in the previous library.

Comment 6: It could be interesting in a risk assessment purpose to point to potential hot spots and where data is missing.

**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?**
Yes

***Competing Interests:*** No competing interests were disclosed.

***Reviewer Expertise:*** nanosafety risk assessment, rnanomaterials exposure,

**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.**

Author Response 28 Mar 2025

**Antti Joonas Koivisto**

Dear Nathan, thank you very much for your valuable comments. Please, see below responses to the specific comments. Comment 1: In the sentence "The room volume is assumed to be 20 $m^3$, and air exchange rate (AER) is 0.6 1/h", the L seems to be a 1. It is 1, but looks a bit like l. As the ventilation volume flow, it would be 12 $m^3$/h. **No changes were made.**

Comment 2: Can the authors define the RCR calculation for clarity? We added “predicted concentration divided with the limit value”.

Comment 3: Some terms can be better described for clarity such as the grit size of sandpaper. We added “smaller grit size refers to larger particle size of the abrasive media”.

Comment 4: In the section "Recommendations for emission measurements", it is unclear if the reporting of such information would allow it to be among the selected studies. Yes, this level of information is sufficient for exposure assessment, as well as quantifying CoUs. No changes were made. **No changes were made.**

Comment 5: It could be interesting, to point which study was still present in the previous library. These were not previously evaluated in Koivisto et al. (2017). **No changes were made.**

Comment 6: It could be interesting in a risk assessment purpose to point to potential hot spots and where data is missing. The current priority is in reporting emissions, rather than concentrations. Unfortunately, concentrations and emissions are often considered as synonyms, which should be corrected. **No changes were made.**

***Competing Interests:*** No competing interests were disclosed.