
Gottschalk, Fadri; Debray, Bruno; Klaessig, Fred; Park, Barry; Lacome, Jean-Mark; Vignes, Alexis; Pomar Portillo, Vicenç; Vázquez-Campos, Socorro; Ogilvie Hendren, Christine; Lofts, Stephen; Harrison, Samuel; Svendsen, Claus; Kaegi, Ralf. 2023. **Predicting accidental release of engineered nanomaterials to the environment.** *Nature Nanotechnology*, 18. 412-418. https://doi.org/10.1038/s41565-022-01290-2

Predicting accidental release of engineered nanomaterials to the environment

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Abstract: Challenges in distinguishing natural and engineered nanomaterials (ENM) and the lack of historical records on ENM accidents have hampered estimating the accidental release and associated environmental impacts of ENM. Building on knowledge from the nuclear power industry, we provide an assessment of the likelihood of accidental release rates of ENM within the next 10 and 30 years. We evaluate risk predictive methodology and compare the results with empirical evidence, which enables us to propose modelling approaches to estimate accidental release risk probabilities. Results from two independent modelling approaches based on either assigning 0.5% of reported accidents to ENM-releasing accidents (M1) or based on an evaluation of expert opinions (M2), correlate well and predict severe accidental release of 7% (M1) in the next 10 years and of 10% and 20% for M2 and M1, respectively, in the next 30 years. We discuss the relevance of these results in a regulatory context.

Main:

Particles of all kinds of elemental compositions and sizes between roughly 1 nm and 1 µm, generally referred to as colloids, have been present in large quantities throughout terrestrial history [1]. Within the past two decades concerns have been raised regarding the health and environmental impacts of engineered nanomaterials (ENMs), which, following the EU's recommended definition, are manufactured materials where more than 50% of the particles are between 1 and 100 nm. [2] The overlapping size ranges between natural nanomaterials and ENMs challenge traditional risk assessment techniques, especially for ENMs having natural (geogenic) counterparts. For example, experiments with paints for exterior use revealed that nanoscale titanium dioxide (TiO_2) particles were washed off from facades and reached the (aquatic) environment. [3] Recent analytical advances in the field of mass spectroscopy based single particle analysis either used as stand a alone technique [4–7] or in combination with characteristic total elemental ratios of bulk samples [8,9] allowed estimating the share of selected ENMs in complex matrices. Although these developments are very promising, they only allow detecting a limited selection of ENMs, as for example carbon based EMNs cannot be detected using these methods. Thus, distinguishing between engineered and natural nanomaterials in the environment is still challenging, [10–12] which hampers connecting the ENM release from production processes and product uses to exposure concentrations for either the public or the environment. The traditional strategy of detecting and quantifying contaminants in the environment to validate release models and inform on potential environmental relevance and significance of laboratory-based ecotoxicity values has, therefore, not been fruitful.

In response, significant effort has been directed towards estimating the future quantities of ENMs that might enter the environment to assess the risks associated with the increasing use of ENM.[13] Assessments of potential ENM releases during production or product use were based on probabilistic reasoning [14–20] and were expanded to include unintended ENM releases during ENM product use over the course of their life cycles. Yet, there are limited opportunities for model evaluation and validation considering the fragmentary knowledge of production volumes and the remaining analytical challenges surrounding field studies. [18] There is abundant literature on risk assessments on ENM that can be sourced from multiple EU funded projects. [21–24] However, none of these projects, addressed the accidental release of ENM and the associated risks beyond the research and development stage. Various papers consider the governance of ENM, but an accidental release of these ENM is outside the scope of such governance, e.g., [25]. This paper, therefore, stands as a unique attempt to provide a basis for assessing the likelihood the accidental release of ENM to the environment. The output from this study serves as a basis for reviewing risk management methodologies to ensure their applicability for the accidental release of ENM.

Accidental release will lead to spatially and temporally elevated ENM concentrations, making it more pertinent for assessing potential risks to the public and the environment as bystanders. Read, Kass et al., [26] recommend: *"identifying proactive measures to prepare for the occurrence of a negative event in order to ensure that the broader market for all products utilising a new technology are not unduly affected by an isolated incident".* Therefore, investigating the probability of accidental ENM release is a key component of horizon scanning exposure and risk assessment efforts.

The goal of this study was to make an assessment of the likelihood of ENM released as a consequence of accidents occurring during ENM-product fabrication, transport and end-of-life processes. Earlier investigations of such accidents were primarily qualitative discussions of ENM production equipment failure [27] and an accompanying commentary on the need for regulation to avoid accidents, [28] or were examinations of workplace exposures to incidental releases of nanoaerosols.[29,30] In making this first assessment, we provide methodologies that may be readily applied to groups of chemicals for which conventional risk assessments of accidental release are limited due to lack of knowledge on accident rates, extents and material hazard.

Adjusting modeling approaches from the nuclear power industry.

The developed approach relies on stochastically varying and combining uncertain or fragmentary (as well as assumptive) past accident frequency data to compute a multitude of probability generating functions (PGFs) for future accident probabilities. The generated PGFs serve as a basis for organizing and running the developed stochastic-probabilistic computations (see the method section below and supplementary S3 for more detailed information). To assess the frequency of accidental releases of ENMs, we searched for information and analogies from neighboring fields. In the chemical industry, the estimation of the accident probability is usually done based on process risk analysis at the plant scale [31,32] and involves the determination of the likelihood of occurrence of each of the undesired situations defined in the hazard identification step. This can be done typically by extrapolating historical failure frequency data. However, these data are missing for ENM sectors and do not encompass accidents occurring at customer plants, where the ENM is an ingredient, or during the transportation of ENMs to customer sites.

In that context, we decided to evaluate alternative approaches developed in the nuclear power sector for which an extensive probabilistic risk analysis (PRA) methodology has been developed. [33–35] (see also supplementary S3 for a review of the method).

There are differences between the nuclear power and the ENM sectors (see also supplementary table S5). The nuclear power industry can focus on a limited spectrum of plant sites and possible events, has a well-established definition of release of radioactive material and benefits from the technological similarity among nuclear power plants which share a rather uniform set of operational practices. The ENM sector lacks these information affecting the development of a predictive risk analysis method for accidental release of ENMs. We, therefore, reviewed experiences and challenges regarding model uncertainty and predictability of (major) accidents in the nuclear power plant sector to identify adjustments required for bridging the approaches to the ENM sector. The major adjustment is that mechanistic-technical considerations of accident-initiating and other events (and their probabilities) had to be discarded. We instead used a theoretical approach to derive probabilities of accidental release from a more superordinate point of view that projects such release frequencies (probabilities) from the past into the future without considering what went or may go wrong from a mechanistic point of view.

Selected combinatory and probability calculations for predicting ENM accident frequency and likelihoods emerged from our comparative analysis and were embedded into a stochastic Monte Carlo framework designed to cover as many accident frequency/probability scenarios as possible. Such a spread of model input scenarios also addresses unspecified differences between past and future ENM market and technology developments, including safety progress of ENM producing and handling technologies.

We collected data from the chemical industry on accidents involving chemical compounds, as well as the frequency of such accidents. Special attention was given to the Analysis, Research, and Information on Accidents (ARIA) database [36] of the French Ministry of the Environment, which is a compilation of (worldwide) accidents that led to environmental releases of chemicals. We searched this database to identify accidents involving chemical compounds which may have resulted in the accidental release of ENM. The actual presence of the substance in the nanoform is not specified explicitly in the database, which introduces an uncertainty when interpreting the data. The proposed modeling approach based on stochastic analysis is designed to address this uncertainty.

Modelling approaches using fixed shares and expert opinions

We considered major accidents with high release volumes but low frequencies of occurrence as well as smaller incidents with low release volumes but higher frequencies of occurrence. This resulted in two data sets which were used for two different modelling approaches (model 1 (M1) and model 2 (M2)), but both including global data on accident frequencies (see comments on data limitations in the supplementary S2). Both approaches aimed at assessing the probability of the accidental release of ENM, whereas the fate of the released ENMs was not addressed. In M1 we used the ARIA accidents collection to derive generic accident frequencies for varying release volumes of chemicals in general (see supplementary Figure S1 and Tables S1-S3). In principle, ARIA distinguishes between non-transport accidents, including all on-site plant events, and accidental release off-site, during transport on roads or in pipelines (see supplementary Table S1 and S2). We combined these two categories to one general accident category. We assumed that past and future accidental release rates of ENM correspond to the market share of ENM currently amounting to 0.5% of the total chemical market (see supplementary section S1.1).[37] Consequently, on average 0.5% of accidents in the ARIA database were associated with the release of ENMs. An uncertainty range of 50% was considered on each side of all annual accident frequencies derived from the empirical data. We constructed empirical (hypothetical) accident frequency data as input for M1, using a Monte Carlo approach to address the uncertainty of the future market share of ENM and the relative frequencies of various release levels. The amount of ENM released during accidents increases by a log10 unit from one level to the next. In M2, the ARIA data were evaluated and out of 1000 chemical accidents, a dozen accidents possibly resulting in the release of ENM were identified. The reports of those accidents were classified by a panel of 11 experts from academia, with a background in chemistry, according to the likelihood of ENM release. Four categories were defined, ranging from very unlikely release of ENMs (category 1) to very likely release of ENMs (category 4). The 12 accidents were scaled to 192 out of 16,000 events reported in total. Based on the expert judgements of the probability of ENM release in these accidents, the frequencies of past accidents associated with such release were estimated and used as input data for M2 (see supplementary Figure S1 and Tables S1-S4). Such input was fed into individual, expert-based predictive Monte Carlo simulations. These calculations for M2 were conducted for the lowest release level (level 1); the M2 results of higher release levels were derived by extrapolating the level 1 accident probabilities to lower accident numbers and frequencies of higher level (more severe) accidents. The supplementary S1 gives a full description of data sets and methods of M1 and M2.

Based on the aforementioned dual evaluation of empirical data following risk analyses concepts from nuclear power and chemical industry, we assessed for the first time the probability of accidents associated with the release of ENM in the near (10 years) and mid-term (30 years) future considering different accident severity levels.

High likelihood of nano accidents within the next 10 years

The results from the two approaches (M1, M2, supplementary Figure S1) predicting the occurrence of minor to major accidental release of ENM were in excellent agreement. Predicted probabilities resulting from the models M1 and M2 are shown in Figures 1-4 and Table 1. These predictions revealed a wide range of accident numbers (0-200 and more) and associated probability of occurrence and – for pessimistic scenarios – suggested a 100%

likelihood for level 1 ENM accidents within the next 10 or 30 years (Table 1). We note that the ranges of uncertainty of the predicted accident probabilities often comprise a factor larger than 2, when comparing the extremes of the model output (Figures 1 and 2, Table 1). Furthermore, the central values, as given in Figures 3 and 4, only reflect probable estimations, which still may deviate from the real (precisely known) values.

For limited ENM release rates of level 1 (see supplementary Table S2 for a description of the levels), the results from the 10-year simulation from M1, predict 21–30 accidents with a very high probability (96%, Figure 3). This translates roughly into 2 - 3 ENM accidents per year. In the 30-year forecast, the predicted range of 61–80 accidents has the highest probability (80%). This is in line with the 10 year predictions and would also lead to (roughly) 2 - 3 events annually. The results of M2—although they are based in large parts on another modelling approach and an entirely different model's input data —agree well with the results of M1. For level 1, the 10 year forecast of M2 predicts > 3 ENM accidents with a high probability (99%), which is in line with the results from M1 suggesting (with 100% probability) at least 3 minor ENM accidents in 10 years. Most probable results from M2 further suggest with about 80% probability > 20 accidents within the next 10 years and > 60 events within the next 30 years, which agrees with the predictions derived from M1.

At level 2 (more severe accidents) and following M1, at least one ENM accident (calculated in Table 1 as 1-P(0 events)) is predicted with a high probability (64%) within the next 10 years, and such an event is even more likely (94%) in 30 years. These values are in excellent agreement with the results from M2, suggesting a very high likelihood of at least one accident every 10 years (95%) and every 30 years (almost 100%).

For level 3, the probabilities derived from M1 of one or more events within 10 years were around 50%. For a 30-year period, the probability of one or more events increased to around 85%. In M2 at least one accident of level 3 within the next 10 years seems even more likely (79%), and in 30 years the probability of one or more accidents reaches almost 99%.

At least one level 4 ENM accident is possible (29%) based on the 10 year predictions of M1. During the next 30 years, at least one event seems rather likely (probability of 62%). The results of M2 suggest slightly higher probabilities of 45% (10 years) and 91% (30 years) for at least one level 4 ENM accident and are, thus, in agreement with the results from M1.

For severe accidents at levels 5 and 6, with even more (10^4 and 10^5 times more) material released, the average 10-year probabilities resulting from M1 for at least 1 event range from 4 to 7% (Figure 3). The most conservative Monte Carlo simulations revealed probabilities of around 11% and 18% for the 10-year forecast for level 5 and 6 (Table 1), respectively. The corresponding worst-case probabilities in the 30 year predictions are 45% and 27% for levels 5 and 6, respectively. The results from the M2 computations for severe ENM accidents are generally lower compared to the corresponding results from M1, with a probability of around 10% for at least one level 5 event within a 30 year period (Figure 3). To what extent a level-6 release event can be excluded based on almost zero M2 results is difficult to evaluate. Regarding the difficulty of interpreting almost zero M2 probability values for level 6, one may refer to discussions in the nuclear power sector: "The interpretation of a probability, such as 10^{-10} per year, runs into some philosophical questions. It is mathematically correct to interpret this probability as meaning a chance for the postulated accident to occur once in 10^{10} years, a period of time exceeding the age of the earth (about 4.5 x 10^9 years)". [38] However, per our computations, the output range and uncertainty are considerable due to both the limited number of accidental release records at this maximum release level (none of the reported accidents involved nanomaterials) and the uncertainty of the extrapolation of the frequency observed in the analysed sample (1000 accidents) to this maximum release level. The past accident of Blanzy, [37] however, during which about 5 tons of carbon black were released suggests that large accidental ENM releases may happen in the future.

The good agreement observed in all the results compared above between the outputs of model M1 (fixed share of ENMs) and model M2 (expert opinions) is reflected in Figure 3 and visualized by projecting the M1 model output into the optimistic-realistic M2 simulation in Figure 2. The model values of the probabilities for an accidential ENM release for both prediction periods (10 and 30 years) are in excellent agreement (see the blue curves in 'Expert 3' calculations in Figure 2).

Based on the demonstrated validity of the calculation methodology in the nuclear power industry, [39] a systematic documentation of accidental ENM releases, also including specific information about the ENM substance and the spilled amount, would decrease the model uncertainties. Two scenarios developed during a workshop [40] are offered in the supplementary S4 that can serve as the basis for identifying the type of data that should be collected during such incidents for improving, amongst others, the predictive modeling and its benefit for policy regulation purposes. Of utmost importance are improved information on accident frequencies and on the severity of their consequences (ENM hazardous characteristics). [40] Our modeling study establishes a baseline and the results of a related workshop in our supplementary S5 the range of future challenges for accident probability estimations when also addressing questions of socio-economic regulation and ENM hazard.

Our study expands a robust methodology from the nuclear power industry to predict the likelihood of accidents involving ENMs by stochastically addressing the extreme uncertainty in the available data. The quality of such data depends on our level of understanding in relating documented chemical accidents to accidents involving ENM release and thus to reconstruct a historical database from ENM accidents. Although M1 and M2 were different and fed with independent datasets their outputs were very similar. The broad spectrum of the model input carries over to a large spread of the model output which occurred for both model calculations.

Our modelling approach did not address questions relating to the hazard resulting from the exposure to accidentally released ENM [41–43] as this would further complicate the assessment. In accordance with others,[44] commercial ENM are presently compared to nuisance dusts and pigments and are not necessarily as hazardous as, for example, high-reactivity chemicals. [26] It is interesting to note that there have been very few reports from insurers regarding how to deal with ENM risks. However, others [42] have explicitly pointed out insurers' lack of scientific guidance in this regard for underwriting consumer, occupational, general, accident-based, or other ENM risks. An early report from Lloyd's of London, [45] concluded that "Our exposure to nanotechnology must therefore be considered and examined very carefully". Nanotechnology related accidents apparently caused very few financial losses, so there is little by way of example that can be used to support insurers' responses to nanotechnology driven accidents.

Conclusions

Our pioneering predictions provide a basis for further investigation of the risk of accidental release of ENM, and help to evaluate the societal impacts of accidental release of ENM, which range from emergency response to site remediation. With this contribution we provide initial numbers and uncertainties of the likelihood of future accidental ENM release events, so that risk analysts and other stakeholders no longer have to rely on their gut feelings when predicting those accidents. We were challenged by enormous uncertainties due to limited knowledge and fragmentary documentation of those accidents in the past. However, the well-corresponding results from different stochastic approaches that unfold in two largly different models, make us feel confident to have approached realistic predictions of the accidental release of ENMs happening in the future. In the study, we assume that the probability of an accidental release of ENM is independent of the type (and the hazardous potential) of the ENM. This assumptions may or may not be justified as different safety measures may be applied during for example the transport of ENMs. However, the fragmentary data available on past accidents forced us to lump all ENM accidents into one ENM category. We are aware of the limitations of our model calculations which are in large parts caused by the reconstructions of the frequency of past accidental release of ENMs. More accurate reporting of ENM accidents as suggested in our work, would, thus, greatly decrease the uncertainties associated with our model results. If, in addition, also information about the the hazardousness of the released material were reported, the accidental release predictions could be extended and be used by risk analysts for hazard forecast and classification purposes as well.

Acknowledgments

Thanks go to Bernd Giese, Nikolaus Müllner and Steven Sholly for their help in conceptualizing the work and literature review during a workshop in Vienna at the beginning of the project and to Bernd Nowack and Jeroen Kuenen for their review of initial versions of this study. COH acknowledges support by the National Science Foundation (NSF) and the Environmental Protection Agency (EPA) under NSF Cooperative Agreement EF-0830093 and DBI-1266252, Center for the Environmental Implications of NanoTechnology (CEINT), as well as the collaborative networks enabled by the US-EU NanoEHS Communities of Research as supported jointly by the US National Nanotechnology Coordination Office and the European Commission.
We thank all anonymous experts at ETH, EAWAG, Agroscope, Uni Vienna, Helmholtz-Zentrum für Umweltforschung, Building Department Canton of Zurich for their evaluation of raw data. This research was funded by the European Union's Horizon 2020 research and innovation program and delivered in the project NanoFASE (Nanomaterial Fate and Speciation in the Environment) under grant agreement No. 646002. SH, SL and CS were also supported by the UK Natural Environment Research Council (NERC) and UK Centre for Ecology and Hydrology Institute Funding award.

Author Contributions Statement

F.G. and R.K conceived and designed the study. F.K and B.P. provided insights from the industry, F.G., B.D., J.M.L., A.V., V.P.P., S.L. and S.H. developed and commented the modelling approaches, S.V.C., C.O.H., and C.S. provided context for future challenges for future accident probability estimations. F.G. and R.K. wrote and edited the paper, with contributions and support from all co-authors.

Competing Interests Statement

The authors declare no competing interests.

Methods Going beyond qualitative discussion of accidental ENM release, we aimed to compute the first quantitative probabilities of accidental ENM release. The modelling approach presented here is based on probability-generating functions (PGF), which are extensively used to perform fundamental probability calculations and have also been applied to estimate accident likelihoods in the nuclear power sector.[39] With available past accident statistics, as seen in our review for this sector (supplementary S1), those calculations do as well or better in terms of their predictive precision than predictions that partly or completely follow the mathematical-mechanistic considerations of accidental release cause, process, and frequency. However, in contrast to their use with robust empirical data in the nuclear power sector, we have developed a stochastic approach to process these functions in order to account for the significant uncertainties associated with the identification of (past) ENM accidents. Those uncertainties develop in the model by varying e.g., the annual accident rates and associated probabilities of occurrence, as well as combinations thereof.

The developed stochastic methodology (for details see supplementary S3) sets alongside other parameters, values for the coefficients of the probability mass functions $p_x(x)$ and the exponents of z^x, computing a plethora of PGFs (defined by G in Equation 1).

$$G_x(z) = \sum_{x=0} p_x(x)\, z^x \quad (1)$$

These coefficients represent the probabilities that can be associated with different outcomes in a particular time period reflected in the exponent, in our case the annual number of accidental release events. However, the PGFs themselves are only a practical means for handling the probability calculations; the variable z has no further meaning for the probability considerations. We stochastically vary the data within and outside of those functions by identifying the possible (empirical or historical) numbers of accidents, their transformation into considered annual values, and their probabilities, thereby exploring a large spread of model inputs and outputs. Such a spread can be derived from highly uncertain and incomplete knowledge about the number of past accidental ENM release events.

The minimum requirement for developing ENM-based model input values is that we use a particular past time period during which accidental release events have either happened or can be assumed to have happened. Based on such initial raw data frequencies, the probability for varying numbers of accidents is computed (e.g., for 10 and 30 years) using higher-order polynomial calculations (Equation 2). These are needed for multi-year timeframe predictions and are achieved by raising the corresponding function to the needed target power, *n*:

$$\left(G_x(z)\right)^n \qquad (2)$$

Hence, expanding the polynomial reveals all possible ways of differentiating the number of accident events and their respective probabilities over varying time horizons. This, however, only works under the condition that the accident frequencies/probabilities do not substantially change during the used prediction timeframe. Thus, faced with significant ENM-accident-frequency uncertainty and knowledge gaps concerning the number of past accidents involving ENM release (or not), we transformed the deterministic use of PGFs into a stochastic one. Instead of generating one function (Equation 2) for each prediction, we conduct for example, m=10,000 iterations, based on Monte Carlo (MC) routines, allowing us to combine the emphasized broad spectrum of possible model input data. In doing so, we algebraically manipulated the polynomial coefficients, multiplying out the PGFs embedded in the MC iteration routines (Figure S1). This process allows one to vary the empirical accident frequency for each MC iteration and produce the statistical forecast output that is used to compute density (probability) curves and evaluate ranges and central tendencies (Equation 3).

$$\frac{\sum_{j=1}^{m} G_j^n}{m} \qquad (3)$$

The differences in the model input may stem from, for example, variations in the relevant time periods for deriving empirical accident data and from the different probabilities (0–100%) of the ENM being released from past accidents. We may have an sound overview of incidents that resulted in the release of chemicals during a certain time period; however, it is up to us to assess whether ENMs were released during these incidents. The data input differentiation covers the assumed differences between past, current, and future accident frequencies that may change over time due to factors such as technological developments.

The modelling was programmed in R,[46] and the possible conceptual programming procedures are shown in supplementary Figure S1 and S2. These procedures, however, vary from case to case. A single, exemplary model of a MC routine is shown in supplementary Figure S3, for iteratively drawing, for example, a die with a 1-50% probability of sampling an ENM accident.

We also tested our stochastic output (supplementary Table S6) by remodeling results from the nuclear power sector. [39] In addition, we performed a comparative evaluation of our results based on own Poisson MC computations. We modelled the reference case study on worldwide accident predictions (International Nuclear Event Scale ≥ 4), and the results were similar.

The stochastic variation in our calculations may stem, as discussed, from the derivation of the empirical accident numbers from selected time periods and the expert-based assessment of the fraction (probability) of the ENMs released during the respective accidents. If we consider these probabilities at the plant scale, technological advances may be the major factor affecting plant accidents in the future (including advances in technology driven by regulation). If we consider the regional scale, the major driver controlling accidental release of ENMs in the future, is the size of the market and the number of production plants. The supplementary S1 and S3 provide a full description of the data and methods used in the modelling studies and the critical methodology review that drove our own methodology development.

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Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author / first author on reasonable request.

Code availability

R scripts are available from the corresponding author / first author on reasonable request.

Supplementary information

Supplement Information on Materials and Methods (S1), Key limitations of the data (S2), Methodology (S3), Supplementary section on a Workshop on Spills (S4), Bridging NanoEHS Workshop on Spills (S5), Figures (Figures S1 to S3) and Tables (Tables S1 to S6) (S6), References (S7)

Figures captions:

Figure 1. Accident probability predictions according to model 1 (M1). Probability (density) curves for the probabilities (x-axis) of at least one accident resulting in engineered nanomaterial release of a certain severity (level 1 - 6) in the next 10 (A) and 30 (B) years (worldwide) based on model M1. Compare these curves with the M1- results in Table 1

Figure 2. Accident probability predictions according to model 2 (M2). Probability (density) curves for the numbers of accidents associated with engineered nanomaterial release in 10 (density curves on the left side of each graph) and 30 years (density curves on the right side of each graph) worldwide. Each illustration (1-11) represents results based on data input following the assessment of one expert (1-11) and computed in model M2. In the graph of expert 3, the results from model 1(M1, blue line) and M2 (green area) are projected in the same graph for comparison (see also M2 results in Table 1 for comparison).

Figure 3. Probabilities (P in %, mean values) for engineered nanomaterial accidental release in the next 10 (top) and 30 (bottom) years (worldwide) computed based on two models (M1 and M2) and for different amounts of materials release (Level 1 – Level 6, see Table S2 for an explanation of the different levels). The most realistic scenarios are highlighted in yellow and underline the good agreement between the outputs of the two models (M1 and M2). There are no linearity or dependency between levels and between models. Due to rounding effects, the values do not necessarily add to 100%. Accident predictions lower than 0.005% (in all our tables) have been set to zero (n.c. = not computed).

Figure 4. Probabilities (P, mean values) of ENM accidental release level 1 in 10 and 30 years worldwide. These results reflect expert opinions based raw data used in the modeling for level 1 accidents (see Table S2 for an explanation of level 1). There are no linearity or other dependencies between these sub-models (for each expert 1-11) of Model 2 (M2).

Tables:

Table 1. Optimistic and pessimistic accident probability predictions. Minimum (Min) and maximum (Max) probabilities for accidental release of engineered nanomaterials (worldwide) during the next 10 and 30 years calculated based on model M1 and M2 (see main text for the description of the two models and supplementary Table S2 for a description of the different levels).

One accident (at least) in 10 years	**Min (M1)**	**Max (M1)**	**Min (M2)**	**Max (M2)**
Level 1	100.0%	100.0%	97.6%	100.0%
Level 2	31.1%	92.5%	47.9%	100.0%
Level 3	22.6%	82.1%	0.9%	100.0%
Level 4	11.5%	56.2%	0.0%	100.0%
Level 5	2.7%	17.5%	0.0%	0.0%
Level 6	1.5%	10.8%	0.0%	0.0%

One accident (at least) in 30 years	**Min (M1)**	**Max (M1)**	**Min (M2)**	**Max (M2)**
Level 1	100.0%	100.0%	98.8%	100.0%
Level 2	70.2%	99.9%	98.8%	100.0%
Level 3	51.2%	99.2%	86.7%	100.0%
Level 4	31.8%	93.5%	23.4%	100.0%
Level 5	8.3%	44.6%	0.0%	66.9%
Level 6	4.7%	27.1%	0.0%	0.0%