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Chemical Accidents Involving Nanomaterials: Potential Risks and Review of Prevention, Preparedness and Response Measures – Project Report

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Chemical Accidents Involving Nanomaterials: Potential Risks and Review of Prevention, Preparedness and Response Measures – Project Report

IOMC
INTER-ORGANIZATION PROGRAMME FOR THE SOUND MANAGEMENT OF CHEMICALS
A cooperative agreement among **FAO, ILO, UNDP, UNEP, UNIDO, UNITAR, WHO, World Bank and OECD**

Environment Directorate
ORGANISATION FOR ECONOMIC COOPERATION AND DEVELOPMENT
Paris 2022

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Foreword

This document presents the outcome from a project of the OECD Working Party on Chemical Accidents (WPCA) that aimed to investigate safety issues related to the prevention of, preparedness for, and response to accidents involving manufactured nanomaterials. Initiated during the 2009-2012 Programme of Work, the project was managed by a Steering Group comprised of Switzerland as the lead, France, Germany, Japan, the United Kingdom, and Business at OECD (BIAC). A first draft report entitled "Risk of Major Accidents involving Nanomaterials" prepared by Daniel Bonomi, Federal Office for the Environment, Switzerland, and supported by Steve Hankin, Institute of Occupational Medicine (IOM), United Kingdom, was issued in 2014. However, because of the complexity of the issue and the range of comments received requiring further consideration, the publication had to be postponed.

In 2020, the WPCA decided to revive the project and finalise the report with the purpose of changing the target audience from 'chemical accident inspectors' to 'chemical safety policymakers'. The work plan included taking into account information published by the OECD Working Party on Manufactured Nanomaterials (WPMN) and cooperating with it during the revision process. A new Steering Group was established with participants from both Working Parties, from Costa Rica (Melissa Camacho Elizondo, Andrea Araya Sibaja), Germany (Arne Krietsch, Doris Völker) and Switzerland (Daniel Bonomi), with the support of Kyeong Wha Chung from the OECD Secretariat. This project was financially supported by the Federal Office for the Environment, Switzerland.

The 2014 draft report and comments received were analysed for identifying gaps. Further information was collected from WPMN documents and literature from academia and industry. Additional data was given by WPCA delegations on accidents cases having involved nanomaterials, and on authority guidelines relating to nanomaterial handling in the workplace. The WPCA and WPMN were consulted on successive versions of the draft document in October 2021 and April 2022, with significant inputs received from experts from Germany, the Netherlands and Sweden. The report was finalised accordingly.

This document is published under the responsibility of the Chemicals and Biotechnology Committee of the OECD.

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Acronyms

AGS	Committee on Hazardous Substances (Germany)
BARPI	Bureau for Analysis of Industrial Risks and Pollutions (France)
BMBF	Federal Ministry of Education and Research (Germany)
BSI	British Standards Institution (United Kingdom)
CEN	European Committee for Standardization
CNT	Carbon Nanotube
CNF	Carbon Nanofiber
DNA	Deoxyribonucleic Acid
ENM	Engineered Nanomaterial
EC	European Commission
EPA	Environmental Protection Agency (United States)
EU	European Union
EUON	European Union Observatory for Nanomaterials
EU-OSHA	European Union information agency for occupational safety and health
FP	Framework Programme
GBP	Granular Biopersistent Particle
HSE	Health & Safety Executive (United Kingdom)
IARC	International Agency for Research on Cancer
IPCS	International Programme on Chemical Safety
IRSST	Institute for Research in Occupational Health and Safety (Canada)
ISO	International Organization for Standardization
MEC	Minimum Explosion Concentration
MIE	Minimum Ignition Energy
MNM	Manufactured Nanomaterials
MOF	Metal Organic Framework
MWCNT	Multi-Walled Carbon Nanotubes
NASA	The National Aeronautics and Space Administration (United States)
n.d.	no date
NIOSH	National Institute for Occupational Safety and Health (United States)

NM	Nanomaterials
NNI	National Nanotechnology Initiative
NOAA	Nano-Objects and their Aggregates and Agglomerates
NP	Nanoparticles
OECD	Organisation for Economic Cooperation and Development
PANI	Polyaniline
P_{max}	Maximum Explosion Pressure
PPE	Personal Protection Equipment
ROS	Reactive Oxygen Species
SDS	Safety Data Sheet
SWA	Safe Work Australia
SWCNT	Single-Walled Carbon Nanotubes
TG	Test Guideline
UN	United Nations
WHO	World Health Organization
WPCA	Working Party on Chemical Accidents (OECD)
WPMN	Working Party on Manufactured Nanomaterials (OECD)

Introduction

Background

1. This report constitutes the final outcome of the project "Risk of Major Accidents involving Nanomaterials", initiated under the 2009-2012 Programme of Work and suspended after the first draft was prepared in November 2014. A proposal to revive the project and finalise the report was agreed upon at the 30th meeting of the Working Party on Chemical Accidents (WPCA) in October 2020. The work plan included taking into account information published by the OECD Working Party on Manufactured Nanomaterials (WPMN) and cooperating with it during the revision of the document. A Steering Group was established in November 2020 for preparing the revised report, comprising delegates from Costa Rica, Germany and Switzerland. The WPCA and WPMN delegations were consulted on successive versions of the draft document in October 2021 and April 2022, and the report was finalised by the Steering Group and the OECD Secretariat accordingly.

Objectives

2. This report follows the two objectives of the original project of 2009:

- addressing potential risks for humans and the environment resulting from accidents involving manufactured nanomaterials (MNMs), for example, accidental releases of larger quantities of nanomaterials into the area surrounding an establishment;
- reviewing measures for prevention of, preparedness for and response to accidents involving nanomaterials.

Target audience

3. This report is prepared for policy makers and regulators in charge of chemical accidents not yet familiar with safety issues regarding nanomaterials.

Focus

4. This document provides an overview of the broad topics of chemical accidents involving nanomaterials in plain and straightforward language with the target audience in mind. It has been prepared using existing academic papers and relevant reports from governments and international organisations. Each topic would deserve to be presented in more depth than this report provides. However, the document intends to briefly introduce issues related to chemical accidents involving nanomaterials and to serve as a gateway to guide readers into more detailed information sources. Readers who want to learn more about this topic are encouraged to refer to the cited references.

Report format and topics covered

5. The report is structured in a question-and-answer format. It is composed of nine questions divided into three thematic Parts. Two to four pages of information are provided in response to each question.

Part I. Nanomaterials: Definitions and Market Penetration

Q.1. What are nanomaterials? (definitions)

Q.2. Which nanomaterials are produced, and how much? What are their uses? (market penetration)

Part II. Potential Risks of Accident involving Nanomaterials

Q.3. Do nanomaterials have the potential to cause chemical accidents? Are they more dangerous than their conventional counterparts? (physical hazards)

Q.4. Are there realistic accidents scenarios involving nanomaterials? (accident scenarios)

Q.5. Are there any real accident cases involving nanomaterials? (real accident cases)

Q.6. What are the health effects of exposure to nanomaterials? (toxicity)

Q.7. If large amounts of nanomaterials are released due to a chemical accident, what kinds of damage can occur in the receiving environmental compartments? (ecotoxicity)

Part III. Review of Prevention, Preparedness and Response Measures

Q.8. Is it necessary to implement measures to prevent chemical accidents involving nanomaterials in addition to the existing safety protocols? (prevention)

Q.9. Considering current knowledge and information, what needs to be done to prepare for and respond to chemical accidents involving nanomaterials? (preparedness and response)

Definition and usage of key terms

6. “Chemical accident” and “nanomaterials (NMs)” are the two terms used most frequently in this document. Although the definition of “chemical accident” is covered under Question 5, it is presented here for clarification. The OECD defines an accident or a chemical accident as “Any unplanned event involving hazardous substances that cause, or is liable to cause, harm to health, the environment, or property. This excludes any long-term events (such as chronic pollution).” (OECD, 2003[1]). Definitions of NMs from different institutions are included under Question 1. In this document, NMs refer to manufactured or engineered NMs, excluding natural or incidental ones.

Limitations

7. This document constitutes a brief introductory report on chemical accidents involving NMs and is not designed for readers having already in-depth knowledge about the subject. In addition, due to data scarcity, some of the topics covered by the report are based on limited information available, such as accident scenarios and real accident cases involving NMs. This also resulted in limited information on possible measures to prevent, prepare for and respond to accidents.

Policy Implications

8. Regarding chemical accidents involving NMs, policy implications for the attention of policymakers and regulators in charge of chemical accidents are summarised as follows:

- There is no single definition of NMs common to all relevant regulatory purposes. Although there are some commonalities in existing definitions, each regulatory agency adopted a customised definition (or description) of NMs tailored to the purpose of its regulation. So far, no definition of NMs has been developed in terms of chemical accidents. It might be helpful to consider whether a new definition of NMs is necessary and, if so, what approach should be taken as the first step.
- Production (including import and export) and consumption statistics are essential for chemical management. Such data can provide the basis for understanding which industries, companies or products are at risk of accidents related to NMs. Some countries[1] have introduced registration systems for NMs. This registry is helpful to estimate NMs production and consumption volume at a national level. In the future, more accurate global statistics for NMs production volume will be made when these data become available from more countries.
- To take appropriate measures in case of an accident involving NMs, information on NMs being part of the accident must be available. Safety Data Sheet (SDS) is a valuable tool for providing information to relevant personnel, including downstream users. In addition, if an NMs registry includes information on NMs properties necessary to prevent and respond to chemical accidents, it will serve as an information platform for regulators and responders of those accidents.
- In general, the small size and greater surface area of NMs give them the following characteristics compared to larger chemical substances: 1) they can stay longer in the air; 2) they can be easily charged electrostatically; 3) they can be more easily ignitable, and; 4) they may provide the potential for unexpected adverse reaction due to catalysis. All of these NMs characteristics may increase the likelihood of chemical accidents.
- When preparing appropriate measures for the prevention or response to chemical accidents involving NMs, it is necessary to consider both the nanoform and non-nanoform properties of the substance. In this way, the hazards and risks of the NM can be viewed as a whole, so more appropriate measures can be prepared.
- Considering the seven real accident cases involving NMs presented in this report, it is reasonable to assume that a certain number of chemical accidents involving NMs have occurred and will occur in the future. However, in the current absence of a requirement to report whether a chemical accident involves NMs or not, the competent authorities may not be aware of occurrences of NMs-related accidents.
- Although much knowledge about the safety of NMs has been accumulated through the efforts of the scientific community and several national and international initiatives, some existing standardised OECD Test Guidelines (TGs) to assess the safety of chemicals are still not suitable for NMs. To address this, the OECD Programmes on Manufactured Nanomaterials and on Test Guidelines are conducting several projects to develop standardised test methods for NMs.

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[1] France, Belgium, Denmark, Norway and Sweden

- Already a decade ago, several governmental agencies had tentatively concluded that there was no need for more than the existing chemical safety regulations to prevent accidents involving NMs. So far, no country has been identified as having introduced additional regulations specific to NMs-related chemical accidents. However, as new NMs are being developed, their applications and usage are increasing, scientific research on safety issues continues, and it seems necessary to review regularly new research findings and regulatory developments in the context of accident prevention and response.

Part I. Nanomaterials: Definitions and Market Penetration

Q.1 - What are nanomaterials?

9. NMs consist of small objects with at least one dimension in the nanoscale (1 nm – 100 nm). International organisations and national regulatory authorities have provided definitions of NMs (Roebben et al., 2014[2]). The complexity of NMs and differences in the purpose of regulations make it challenging to agree on “a uniform definition across all regulatory areas” (Allan et al., 2021[3]). Although the definitions are not all the same, there are several common elements:

- consisting of objects with at least one dimension in the nanoscale (1 nm – 100 nm);
- including their aggregates and agglomerates; and
- satisfying distributional threshold based on the number or weight of the nano-objects and their aggregates and agglomerates (not all but in many cases).

10. The definition of NMs by the International Organization for Standardization (ISO) is mainly to encourage the consistent use of terms and to provide clear criteria to identify materials for additional risk consideration (ISO, 2017[4]). Meanwhile, the definition recommended by the European Commission (EC) aims to ensure conformity “in adoption and implementation of legislation and policy and research programmes concerning products of nanomaterials” (EU, 2011[5]). This recommended definition has been implemented in various European Union regulations which have nano-specific obligations like REACH and regulations on biocidal products and medical devices (Mech et al., 2020[6]). It is currently under review for potential revision or replacement (EC, 2021[7]).

- ISO definition: material with any external dimension in the nanoscale or having an internal structure or surface structure in the nanoscale (This general term is inclusive of nano-object and nanostructured material.)
- European Commission (EC) recommended definition:
  - A natural, incidental or manufactured material containing particles, in an unbound state or as an aggregate or as an agglomerate and where, for 50 % or more of the particles in the number size distribution, one or more external dimensions is in the size range 1 nm - 100 nm
  - In specific cases and where warranted by concerns for the environment, health, safety or competitiveness the number size distribution threshold of 50 % may be replaced by a threshold between 1 and 50 %
  - By derogation from the above, fullerenes, graphene flakes and single-wall carbon nanotubes with one or more external dimensions below 1 nm should be considered as NMs
  - Where technically feasible and requested in specific legislation, compliance with the definition […] may be determined on the basis of the specific surface area by volume. A material should be considered as falling under the definition […] where the specific surface area by volume of

> the material is greater than 60 m^2/cm^3. However, a material which, based on its number size distribution, is a nanomaterial should be considered as complying with the definition […] even if the material has a specific surface area lower than 60 m^2/cm^3.

11. On the other hand, regulatory agencies need to target NMs of their concern as precisely as possible for pursuing their mission, such as protecting human health and the environment in general or securing the safety of specific products, e.g. cosmetics or food additives. For example, even materials bigger than 100 nm might be regulated as NMs by the EU Novel Food Regulation. According to this legislation, structures, agglomerates and aggregates bigger than 100 nm are regarded as NMs if they "retain properties that are characteristics of the nanoscale" (EU, 2015[8]).

12. No legislation defining NMs in relation to chemical accidents could be found when preparing this report. However, definitions of two terms that might include NMs were identified. Firstly, the United Nations (UN) defined "combustible dust" as "finely divided solid particles of a substance or mixture that are liable to catch fire or explode on the ignition when dispersed in air or other oxidizing media" (UN, 2019[9]). According to this definition, NMs that have the potential to cause fires or explosions on the ignition when dispersed in the air can be categorised as combustible dust. The other term is "powders containing nano-objects", defined by the European Committee for Standardization (CEN) as "powder containing a specific relative amount of nano-objects in number or displaying a specific surface area per volume, above a specific threshold value" (CEN, 2018[10]). However, no specific threshold values were provided there.

13. Below are definitions of terms related to NMs suggested by ISO (2017[4]).

- nanoscale: length range approximately from 1 nm to 100 nm
- nanoscale phenomenon: effect attributable to the presence of nano-objects or nanoscale regions
- manufactured nanomaterial: nanomaterial intentionally produced to have selected properties or composition
- nano-object: discrete piece of material with one, two or three external dimensions in the nanoscale
  - nanoplates: discrete piece of material in one dimension in the nanoscale
  - nanofibers: discrete piece of material in two dimensions in the nanoscale
  - nanoparticles: discrete piece of material in three dimensions in the nanoscale
- agglomerate: collection of weakly or medium strongly bound particles where the resulting external surface area is similar to the sum of the surface areas of the individual components
- aggregate: particle comprising strongly bonded or fused particles where the resulting external surface area is significantly smaller than the sum of surface areas of the individual components
- nanostructured materials: materials with an internal structure or surface structure in the nanoscale
- nano-enabled: exhibiting function or performance only possible with nanotechnology
- nano-enhanced: exhibiting function or performance intensified or improved by nanotechnology

14. In Table 1, the number of articles searched online for several terms referring NMs shows their usage frequency, with a clear predominance of the words 'nanoparticles' and 'nanomaterials'. Additional explanations on frequently used terms are:

- engineered nanomaterials (ENMs): being used interchangeably with "manufactured nanomaterials (MNMs)" (EU, 2019[11]).
- nanopowders: powdered materials with individual particles in nanometre-scale or materials with crystalline in nanometre-scale (Wang et al., 2019[12]). This term refers to NMs in the dry particulate state and is frequently used to describe the physical hazards of NMs.

Table 1. Number of academic articles searched for the terms referring to NMs

Keywords	Number of retrieved articles
nanoparticles	About 2,180,000
nanomaterials	About 1,130,000
engineered nanomaterials	About 258,000
nanopowders	About 114,000
manufactured nanomaterials	About 87,700

Source: Search for keywords online (Google Scholar) on March 31, 2021.

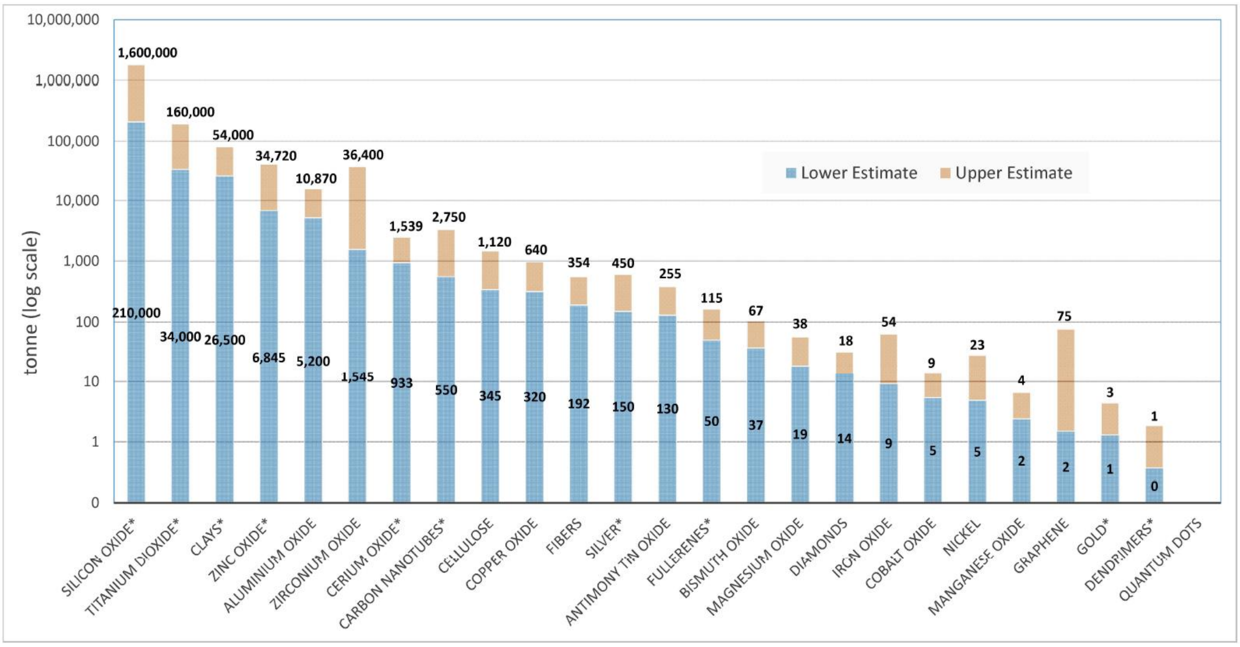
Q.2 - Which nanomaterials are produced and how much? What are their uses?

15. This section aims to identify what kinds of NMs are being used in which industrial sectors. Decision-makers can use this information to estimate roughly the likelihood of chemical accidents involving NMs in specific industrial sectors or facilities where NMs are being used.

16. Although NMs have been infiltrating our everyday life for several decades, even basic information about NMs, such as production volume, is difficult to access. This situation is related to the fact that only a few countries, such as France, Belgium, Denmark, Norway and Sweden, have a system to register NMs (Pavlicek et al., 2021[13]).

17. In 2019, a paper was published outlining the annual production volume and technological maturity of 25 selected NMs using various data sources (Janković and Plata, 2019[14]). It provides a good bird's-eye view of the market landscape of NMs. However, the accuracy of the production volume data is limited because those data mainly depend on voluntary reporting from companies. Figure 1 shows the annual production volume (lower and upper estimates, log scale) of 25 selected NMs[2]. It is in decreasing order of lower estimates. The five NMs that are produced in the largest amount are silicon dioxide (SiO_2), titanium dioxide (TiO_2), (nano)clays, zinc oxide (ZnO) and aluminium oxide (Al_2O_3).

Figure 1. Global production volume estimates of 25 selected MNMs in 2015



Notes: The quantum dot market was not reported on a mass basis. The global quantum dot revenue for 2015 was USD 400–600 million.
Source: (Janković and Plata, 2019[14])

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[2] In 2015, the OECD finalised its Testing Programme launched in 2007 on 11 representative NMs regarding their physicochemical properties, toxicities, environmental fate and material safety (see: https://www.oecd.org/chemicalsafety/nanosafety/testing-programme-manufactured-nanomaterials.htm). When selecting representative NMs, the main criteria were commercial use, production volume, availability of NMs for testing, and existing available information on materials (OECD, 2016[112]). The 11 NMs tested by the OECD Programme are marked with asterisks among the 25 NMs covered by Figure 1 (Only ten * marked NMs are visible here because carbon nanotubes (CNTs) were tested separately as single-walled and multi-walled CNTs in the OECD Programme).

18. Although the data presented in the preceding graph look clear, it is necessary to refer to other estimates considering the uncertainty attached to the data. The global NMs production data in 2010 was presented in a report published by the European Commission (EC, 2012[15]), with the top five NMs as follows: carbon black[3] (9.6 million tonnes); synthetic amorphous silica (1.5 million tonnes); aluminium oxide (200,000 tonnes); barium titanate (15,000 tonnes); and titanium dioxide (10,000 tonnes). Even considering there is a five-year interval between the two sets of data, there are significant differences between the production volumes estimated in 2010 and 2015 (e.g. aluminium oxide: 200,000 tonnes in 2010 vs. 5,200-10,870 tonnes in 2015). When referring to the global production volume of NMs, it is important to keep in mind that estimation was made in the absence of reliable statistics.

19. There are other information sources of NMs production volume. For example, France is one of the earliest countries having introduced a mandatory reporting scheme for NMs. According to the 2016 annual report, NMs produced or imported over 1,000 tonnes in France in 2015 were as follows: carbon black; silicon dioxide; calcium carbonate; titanium dioxide; boehmite (Al(OH)O); vinylidene chloride copolymer; silicic acid (magnesium salt); a mixture of cerium dioxide and zirconium dioxide; polyvinyl chloride, and; aluminium oxide (Ministry of the Environment, Energy and the Sea, 2016[16]). More accurate global NMs production volume will be available only after many countries publish similar data.

20. Four different production estimates for NMs are presented in this report. The top 10 most-produced NMs in each estimate are given in Table 2. In the grey shaded row of the table, NMs appearing in all four estimates are highlighted. They are silicon dioxide, titanium dioxide, aluminium dioxide and cerium oxide.

Table 2. Top 10 NMs list in four production estimates

Year		2015	2015	2010	2010
Geographical coverage		Global	France	Global	Global
Top 10 most produced NMs	NMs appearing in all four estimates	1) Silicon oxide 2) Titanium dioxide 5) Aluminium oxide 7) Cerium oxide	Silicon oxide Titanium dioxide Aluminium oxide Mixture of cerium dioxide and zirconium dioxide	2) Silicon oxide 3) Aluminium oxide 5) Titanium dioxide 6) Cerium oxide	1) Silicon oxide 2) Titanium dioxide 4) Aluminium oxide 7) Cerium oxide
	NMs appearing in less than three estimates	3) Clays 4) Zinc oxide 6) Zirconium oxide 8) Carbon nanotubes 9) Cellulose 10) Copper oxide	Carbon black Calcium carbonate Boehmite Vinylidene chloride copolymer Silicic Acid (magnesium salt) Polyvinyl chloride	1) Carbon black 4) Barium titanate 7) Zinc oxide 8) Carbon nanotubes 9) Carbon fibres 10) Silver	3) Iron and iron oxide 5) Zinc oxide 6) Clays 8) Carbon nanotubes 9) Silver 10) Copper and copper oxide
Data source		Private market report	French NMs registry	Private market report	Private market report
Reference		(Janković and Plata, 2019[14])	(Ministry of the Environment, Energy and the Sea, 2016[16])F	(EC, 2012[15])	(Keller et al., 2013[17])

Notes: The list of NMs from Keller et al. (2013) is mainly mentioned under Question 7. Numbers (1-10) are displayed before the name of NMs in the decreasing order of the production estimate. The French NMs registry report showed the NMs production volume band only, and the 10 NMs included in the table are those produced in or imported into France in excess of 1,000 tonnes.

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[3] Carbon black often ranks first in many production data overviews for NMs, but it does not appear in Figure 1 and the 2010 top 10 NMs list (final column in Table 2). Janković and Plata (2019) and Keller et al. (2013) used the same report of different years published by a market research company. According to an official from the company, the industry generally does not consider carbon black as NMs because of not having the enhanced properties of more "recent" NMs, and the reports do not include carbon black (personal communication on 19 January 2022). The company publishes a separate market report on carbon black.

21. Physicochemical properties and common uses of five types of NM are summarised in Table 3. The five types are carbon-based, dendrimers, metal-based, quantum-dots and composite-based. More detailed commercial application areas of the previous 25 MNMs can be found in Annex A.

Table 3. Physicochemical properties and common uses of NMs

Types of NMs (Occurrence)	Physical/Chemical Properties	Common Uses	Examples
Carbon-based (Natural or Engineered)	Stable, limited reactivity, excellent thermal and electrical conductivity.	Biomedical applications, battery and fuel cell electrodes, super- capacitors, adhesives and composites, sensors and components in electronics, aircraft, aerospace and automotive industries.	Fullerenes, multi-walled and single-walled carbon nanotubes (CNTs) and graphene materials.
Dendrimers (Engineered)	Three-dimensional nanostructures engineered to carry molecules encapsulated in their interior void spaces or attached to the surface.	Drug delivery systems, polymer materials, chemical sensors and modified electrodes.	Hyperbranched polymers, dendrigraft polymers and dendrons.
Metal-based Materials (Natural or Engineered)	High reactivity, varied properties based on type, some have photolytic properties and ultraviolet blocking ability. Capping agents are used in some cases.	Solar cells, paints and coatings, cosmetics, ultraviolet blockers in sunscreen, environmental remediation.	Nanogold, nanosilver, metal oxides such as titanium dioxide (TiO_2), zinc oxide (ZnO), cerium dioxide (CeO_2) and nanoscale zero-valent iron (nZVI).
Quantum Dots (Engineered)	Reactive core composed of metals or semiconductors controls the material's optical properties. Cores are surrounded by an organic shell that protects from oxidation.	Medical bioimaging, targeted therapeutics, solar cells, photonics and telecommunication.	Quantum dots made from cadmium selenide (CdSe), cadmium telluride (CdTe), indium phosphide (InP) and zinc selenide (ZnSe).
Composite-based (Natural or Engineered)	Composite nanoparticles, which are made by the combination of two or more different materials, mixed together in order to merge their best properties.	Optics, microelectronics, smart coatings, health and diagnostics, photovoltaics, fuel cells, pollutant remediation, catalysis, and sensing	Polymer, layered silica, metal-organic frameworks (MOFs)

Sources: (EPA, 2017[18]; Meroni and Ardizzone, 2018[19]; Rizwan et al., 2021[20])

22. The above information is suitable for identifying various uses of NMs, but it is challenging to know which of them are the most frequent. Keller et al. (2013[17]) estimated global life cycle releases of the ten most produced NMs in 2010. Although their goal was to provide global ENM emissions, the major application areas of most produced NMs could be identified thanks to their life cycle approach. They categorised eight application areas and presented the usage of NMs for each category as follows: coatings, paints & pigments (80,500 tonnes); electronics and optics (48,700 tonnes); cosmetics (48,000 tonnes); energy and environment (43,700 tonnes); catalysis (37,500 tonnes); automotive (23,500 tonnes); medical (13,400 tonnes), and; others (22,900 tonnes) (Keller et al., 2013[17]). This information is straightforward, but it does not show a detailed picture.

Part II. Potential Risks of Chemical Accident Involving Nanomaterials

Q.3 - Do nanomaterials have the potential to cause chemical accidents? Are they more dangerous than their conventional bigger counterparts?

23. For conventional chemicals, the physico-chemical hazard categories of explosivity, flammability, self-reactivity, pyrophoricity and self-heating, emission of flammable gases after contact with water, oxidising behaviour, corrosivity and catalytic properties are well defined (GHS, 2009[21]), with validated and standardised test methods available for evaluating these properties. Whilst all of these physico-chemical properties are also relevant for NMs, it is uncertain whether existing test methods are applicable to NMs and there is currently a lack of available information to enable meaningful conclusions to be drawn on most of them (SWA, 2013[22]).

24. It is well known that fire and explosion can be caused by flammable dust clouds of particle size below 500 µm (Baron et al., 2015[23]). NMs in a dry powder state (nanopowders) are no exception. It is worth looking at whether NMs are more dangerous than their bigger counterparts in terms of the potential to cause chemical accidents such as fire and explosion. Due to their small size and greater surface area, NMs can stay longer in the air and be easily charged electrostatically, thus increasing the ignition risk and the explosion severity (EC, 2014[24]). However, relevant studies suggest that explosion severity cannot be accurately understood by considering the size of NMs alone, and other factors such as dispersion (including agglomeration/fragmentation), concentration, turbulence and humidity must also be considered (Nazneen, Wang and Kay O'Connor, 2019[25]; Santandrea et al., 2019[26]).

25. Based on a comprehensive analysis of data available in the published literature, it was found that (Eckhoff, 2003[27]; Kearns, 2004[28]; Mark, 2004[29]; Bouillard et al., 2009[30]; Vignes et al., 2009[31]; SWA, 2009[32]; Wu et al., 2010[33]; HSE, 2010[34]; SWA, 2013[22]):

- The minimum ignition energy (MIE) required to initiate a dust explosion indicates NMs which are potentially very sensitive to ignition when their microfine counterparts are also sensitive. However, if a micro-size substance is not likely to be ignited, reducing the particle sizes down to the nanoscale does not necessarily mean it becomes sensitive to ignition.
- The minimum explosive concentration (MEC, measured in mass per unit volume) is independent of the particle size of NMs. There is potential for air concentrations in a localised area to result in an explosion. In addition, the dust of NMs stays airborne longer than dust comprised of micron-size particles.
- The potential severity of an explosion (P_{max}, maximum explosion pressure) increases with decreased particle size in the micron size range. However, it appears this trend does not continue into the nanometre range. The available data indicates P_{max} may exhibit a sharp decrease in magnitude for NMs when particle size decreases below approximately 0.3 µm.

26. In summary, the explosion severity of NMs might be similar to or less than that of their microscale counterparts, even though there is a possibility that NMs could be more easily ignitable. However, it should

be noted that these results are derived from carefully designed experiment settings that may differ from situations at actual workplaces. In the workplaces where NMs are manufactured or used, many kinds of different materials are probably dealt with in the same place. In this condition, fires and explosions caused by dispersed NMs may lead to the possibility of relatively inert materials becoming combustible (ISO, 2018[35]).

27. The OECD dossiers have a section on their physical hazards, such as flashpoints, auto-flammability, flammability, explosiveness and oxidizing properties (OECD, n.d.[36]). The physical hazards of 11 selected MNMs were summarised in Table 4. Physical hazard tests have not been conducted for most NMs, and only flammability and explosiveness of silicon dioxide and titanium dioxide were indicated (Lee et al., 2017[37]).

Table 4. Physical hazards summary of 11 representative MNMs from OECD dossiers

MNMs	FLASH POINT	AUTO-FLAMMABILITY	FLAMMABILITY	EXPLOSIVENESS	OXIDIZING PROPERTIES
Fullerene	Not tested	Not tested	Not tested	Not tested	Not tested
SWCNT	Not tested	Not tested	Not tested	Not tested	Not tested
MWCNT	Not tested	Not tested	Not tested	Not tested	Not tested
Silver NPs	Not tested	Not tested	Not tested	Not tested	Not tested
Gold NPs	Not tested	Not tested	Not tested	Not tested	Not tested
Silicon dioxide	Not tested	Not tested	VDI 2263-1 Material does not catch fire. Brennzahl (BZ) 1	No risk of dust explosion	Not tested
Titanium dioxide	Not tested	Not tested	NM 105, TiO2 (P25) is not dust explosible and the burning behaviour corresponds to Burning Class 1(no ignition); (Bresh et al., 2012)	NM 105, TiO2 (P25) there is no ignition or explosion (Bresh et al., 2012)	Not tested
Cerium dioxide	Not tested	Not tested	Not tested	Not tested	Not tested
Dendrimer	Not tested	Not tested	Not tested	Not tested	Not tested
Nanoclay	Not tested	Not tested	Not tested	Not tested	Not tested
Zinc oxide	Not tested	Not tested	Not tested	Not tested	Not tested

Notes: MWCNT: multi-walled carbon nanotubes; SWCNT: single-walled carbon nanotubes; Brennzahl indicator of flammability ranging from 1 to 6 from no to very flammable.
Source: (Lee et al., 2017[37])

28. Catalysts can change the rate of a chemical reaction while not being consumed by the reaction itself. It was suggested that some NMs might initiate catalytic reactions that would not otherwise be anticipated (NIOSH, 2009[38]). If a substance is innately a catalyst, it would be more efficient in small particle size (Pritchard, 2004[39]). Is it possible that a non-catalyst would become a catalyst by virtue of becoming nano-sized? A review on gold nanoparticles by Daniel & Astruc (2004[40]) suggests that a reduction in particle size can lead to the conversion of a non-catalyst to a catalyst. NMs may therefore provide the potential for unexpected adverse reactions due to catalysis (SWA, 2013[22]).

29. More recent studies show examples of the unique and dangerous characteristics of handling mixtures of NMs and other materials (Torrado et al., 2017[41]; Martin et al., 2018[42]):

- For fuel-lean mixtures, the insertion of carbon black nanoparticles into pure gas can increase the explosion pressure (Kosinski et al., 2013[43]) as well as the maximum rate of pressure rise, especially at high initial turbulence levels.
- The reaction between sulfuric acid and aluminium powder, which is not considered highly explosive when performed with microparticles, leads to a violent explosion when a mixture of H_2SO_4 and Al-nanopowders is ignited by an open flame.

Q.4 - Are there realistic accidents scenarios involving nanomaterials?

30. Chemical accidents involving NMs can be divided into two types: one is when NMs are the cause of chemical accidents such as explosion or fire, or both; the other is when NMs are accidentally released due to some other causes. For the former type of accident, the physical hazard of NMs should be a primary consideration. While, for the latter type, the (eco)toxicity of NMs becomes more important.

31. The following scenarios are considered to be realistic causes of accidents involving NMs (Steinkrauss et al., 2010[44]; Krug et al., 2013[45]; Nowack et al., 2014[46]). (non-exhaustive list).

- Accident scenarios during the production of NMs:
    - In milling processes, an accident with consequences for the general population can practically be excluded, as this process takes place in suspension and only uses small amounts (ca.100 kg) of metallic or ceramic NMs such that an explosion can be excluded. However, as in actual accident cases (Case No. 2) in Question 5, there may be minor explosions that are hard to notice during the milling process.
    - Deflagration and, with readily flammable solvents, a fire hazard cannot be excluded in gas-phase processes. However, provided the necessary measures are taken, a chain of different events would be necessary to cause a release of the NMs beyond the fabrication site. A possible scenario is an explosion of distillation equipment with subsequent fire during which all NMs in the same fire compartment are released.
    - During the in-factory transport of NMs that can explode using the pneumatic conveying system, an explosion may happen if prevention measures fail. If the NMs leak, they can create an explosive atmosphere (ATEX zone) outside the conveying pipe. Leaked NMs may spread out of the plant and cause damage to health, the environment and property. An actual accident case of carbon black leaking from a pneumatic pipe (Case No. 5) was given in the next question.
    - Fire is a possible hazard, resulting in the release of NMs into the air (when present in powder form) and to the ground and surface waters (when present in suspension). The cause of the accident could be due to internal (e.g. technical) and external factors. Deflagration is possible for metallic NMs, but they are usually stored in dispersion or under an inert atmosphere. An example is a nano-zero-valent iron, for which also hydrogen production and the danger of hydrogen explosion need to be considered.
    - A fire can occur in a warehouse containing both metallic (pyrophorous) and non-metallic NMs. Through the rapid combustion of the metallic NMs, a large fire breaks out. The resulting cloud of smoke possibly contains toxic nanoparticles.
    - NMs in a dry powder state can deposit outside the production, or the fabrication process may ignite on hot surfaces. Dust deposits may also create dust clouds which may ignite and explode.
- Accident scenarios during transportation of NMs:
    - Transported amounts of NMs are currently rather limited (at most several hundred kg) compared to the total quantity of material produced in any size. Nevertheless, a road or rail accident could lead to leakage of dispersions/powder or fire through which NMs could reach the air, soil, wastewater or surface and groundwater.

32. It should be noted that conductive nanopowders, such as carbon nanopowders, are not likely to present an electrostatic hazard. However, should these powders penetrate into electrical and electronic equipment, they could give rise to short-circuit problems and lead to the generation of ignition sources (HSE, 2010[34]). The possibility of nanopowders penetrating electrical and electronic equipment may be greater due to their reduced particle size and the aforementioned persistence. Therefore, the design of

electrical equipment protection should consider the fine granulometry and very long settling time of nanoparticles, which necessitate dust protection (BSI, 2007[47]).

Q.5 - Are there any real accident cases involving nanomaterials?

33. The OECD defines a chemical accident as "any unplanned event involving hazardous substances that causes or is liable to cause harm to health, the environment or property, such as loss of containment of hazardous substances, explosions, and fires. This definition excludes any long-term events (such as chronic pollution)." (OECD, 2003[1])

34. Seven chemical accident cases involving NMs (Table 5) were collected through a literature search and information provided by the OECD Working Party on Chemical Accidents (WPCA) in 2021. There are no systemic or obligatory reporting schemes to identify accidents related to NMs. Therefore, please note that the cases presented here are limited, and this collection cannot be considered an exhaustive list. There is also ambiguity as to whether the materials involved in the accidents are NMs or not. Brief descriptions of the seven cases are as below (in chronological order).

Case No. 1: Explosion caused by aluminium flakes about 100 nm thick (1973)

- This accident happened in a premix plant of slurry explosive factory in 1973, long before the boom of nanotechnology (SWA, 2013[22]). The explosion caused the most extensive human and property damage among seven cases collected in this report (5 death, 4 injuries, and a partially demolished plant) (Eckhoff, 2003[27]). The aluminium flakes[4] (about 100 nm thickness) that caused the accident could be called "nanoplates" if it follows the ISO definitions provided in question 1. Although nitrogen gas was in use and an oxygen sensor was installed to prevent accidents, an investigation found that both nitrogen gas inlet and oxygen sensor positions were inadequate (Eckhoff, 2003[27]).

Case No. 2: Minor explosion within nanoscale attrition millers (2005)

- The information on the other aluminium explosions within three nanoscale attrition millers is minimal[5]. The information source, a journal article, just mentioned the existence of the explosions in the article's abstract (Wu et al., 2010[33]). It seems that these cases may not have been known without an investigation conducted afterwards. Given that those explosions were proved only after the follow-up investigation, it can be cautiously assumed that the explosions were difficult for field managers to recognise and did not cause any visible damage.

Case No. 3: Explosion caused by nanostructured explosive materials in a lab (2008)

- According to a weekly chemical magazine, a graduate student was injured in an accident that happened in a university laboratory in 2008 (Jyllian N. Kemsley, 2008[48]). The explosion occurred when he was dealing with nanostructured explosive materials. His supervisor was known to work on energetic nanocomposite materials, which are composed of mixtures of nanoscale oxidizers and fuel particles. In the article, the exact cause of the accident was not suggested, and no other document could be found on the cause of the explosion.

Case No. 4: Explosion caused by polyaniline nanowire in a lab (2011)

- This accident happened during weighing $H_2O_2/HClO_4$ post-treated dried polyaniline (PANI) nanowire in a laboratory (Zhang et al., 2011[49]). When some PANI (about 6.8 - 8.5 g) was put on

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[4] Because there was also sulphur in the mixer, the source of ignition, it is pointed out that it is difficult to confidently attribute the nanoscale properties of aluminium flakes to the sole cause of the accident (SWA, 2013[22]).

[5] Strictly speaking, this case is three similar but distinct incidents. However, due to the similarity of specific cases and the lack of information on individual cases, it is treated as a single case here.

the balance, an explosion happened abruptly. Although the article reporting this accident called the compound "polyaniline nanowire" or "polyaniline nanomaterials", it was not NMs according to the ISO or EU definitions. The diameter of the "nanowire" is about 150 nm, and the length is about several microns. Therefore, all three dimensions of the polyaniline compound were outside the nanoscale range (1 nm – 100 nm).

Case No. 5: Accidental release of carbon black from a pneumatic pipe (2012)

- This case is the only accidental release of NMs (carbon black) due to a tear on a pneumatic pipe in a tyre factory (BARPI, n.d.[50]). There was no description of the size or morphology of leaked carbon black in the information source. However, it is well known that nanoscale carbon black is widely used as a filler for tread wear and traction improvement of tyres (OECD, 2014[51]), so this case was included as one of the accident cases involving NMs.

Case No. 6: Titanium nanomaterials fire caused by electrostatic charges in a lab (2012)

- A fire ignited by about 1.8 kV electrostatic charges when 75 nm Ti particles were moved from a polyethylene bag to a plastic plate in a laboratory (Wu, Wu and Ko, 2014[52]). In the references, this case was just mentioned as an example to show that electrostatic charges may ignite NMs.

Case No. 7: Titanium nanomaterials fire in a lab (2012)

- Titanium NMs (30 nm – 50 nm) were ignited when a researcher was using a spatula to remove 2 grammes of powder from a 50-grammes bag in a fume hood in a university laboratory (The Chemical Safety Mechanism, 2012[53]). The researcher tried to put out the fire with water, but hydrogen gas was released, making the situation worse. Then an ABC-rated fire extinguisher was applied. Although it was not an appropriate extinguisher choice[6], the fire could be controlled due to the small amount of metal involved. The ignition is probably caused by a static charge or chemical contamination of the spatula.

35. Among the collected cases, two accidents were not selected as chemical accidents involving NMs:

- One is health damage to seven female workers due to exposure to polyacrylate, consisting of nanoparticles, for 5 -13 months (Song, Li and Du, 2009[54]). This case is not considered a chemical accident according to the OECD definition and is not presented here because the health damage occurred over a long period of time.
- The other case is a fire probably caused by accumulated titanium powder in a central vacuum cleaner system installed in a metal processing company in 2019 (P Källin, internal fire investigation report, 4 September 2019) [7]. According to the report, it was suspected that Ti powder accumulated in a bent part (Y-coupling) of incoming pipe to the central vacuum cleaner was mechanically ignited by a metal object when the vacuum cleaner was in operation. The primary fire happened in the pipe. Then, sparks were driven towards the cyclone part of the vacuum cleaner, and the secondary

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[6] D-rated extinguisher is designed to control fires involving combustible metals (e.g. Mg, Ti and Na).

[7] Two additional Ti powder fires in the vacuum cleaner system happened in the same company afterwards. They were probably started by a spark in the filter unit caused by bad grounding. After the first fire, the vacuum cleaner had moved outside of the building, so the latest two fires only caused damage to the equipment. The company is considering the installation of fire extinguishers activated by spark detectors in the vacuum cleaner (personal communication on 25 February 2022).

fire occurred there, where Ti powder also existed. Given the properties[8] of the Ti powder inside of the vacuum cleaner confirmed by a company official, it would be reasonable to view it as micron-sized material.

36. As may be noticed while examining the accident cases, it was often difficult to find detailed information (such as identity, size and morphology) about NMs suggested as the cause of the accident from the references. If the information source mentioned that NMs caused the accident, it was included in the above accident case list, even if data about the size of NMs could not be confirmed or the size of material was outside the nanoscale. Considering that there are no definitions of NMs in terms of chemical accidents and there are few identified accident cases involving NMs, it seemed appropriate to take a flexible approach without being overly constrained by the current definitions of NMs.

37. It would be hasty to draw generalised conclusions from only seven accident cases. From these identified cases, however, the below points can be inferred:

- The types of chemical accidents involving NMs (explosion, fire, and leakage) do not seem different from conventional ones.
- The majority of accidents presented above involve NMs in the dry powder state (the physical state of NMs is not clear in Case No. 3).
- Several accidents involving NMs were occurring before concerns about the safety of NMs were raised, e.g. for Case No. 1. Moreover, accidents involving NMs might have been reported as ‘conventional’ dust fires or explosions because of the absence of regulations requiring the reporting of the NMs presence or involvement in a chemical accident.
- Since no scientific or regulatory definitions of NMs in terms of chemical accidents have been set, there is inevitable ambiguity as to whether an accident involves NMs or not, as in the case of the PANI explosion (Case No. 4).
- Of the seven accident cases, four of them happened in laboratories and the other three in factories. Regarding laboratory accidents, it is likely that researchers are well aware of the characteristics and properties, such as the size distribution of substances handled, so those laboratory accidents may have been better reported than industrial ones.
- No accident case was identified concerning consumer products[9] or during transportation so far. As the production and use of NMs expand, the amount and frequency of transportation of NMs will increase, so the likelihood of accidents during transportation will also increase.

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[8] The Ti powder in the vacuum cleaner was not a product or a by-product but scrap. The company also confirmed the particle size (0 – 500 µm) and specific surface area (33 m^2/kg) (personal communication on 25 February 2022). Considering these characteristics, it seems inappropriate to regard it as NMs.

[9] Two consumer spray products has been recalled from the German market after more than 97 incidents of respiratory disorder reported during 4 days in 2006. Because “nano” was used in the name of the product, there was a concern that the damage was caused by NMs. According to the investigation by German Federal Institute for Risk Assessment (BfR), NMs were not the cause of the health damage because chemical analyses confirmed that the products did not contain any NMs (BfR, 2006[114]).

Table 5. Accident cases involving nanomaterials

Case No.	1	2	3	4	5	6	7
NMs involved in accidents	Aluminium	Aluminium	Nanostructured explosive material	Polyaniline (PANI, dried)	Carbon Black	Titanium	Titanium
Size and morphology	Aluminium flakes (about 100 nm thickness)	Not specified	Not specified	PANI nanowire (about 150 nm diameter and several micron length)	Not specified	75 nm	30 – 50 nm
Specific surface area of NMs	7.5 m^2/g	Not specified	Not specified	Not specified	Not specified	Not specified	Not specified
Year of occurrence	1973	2005	2008	2011	2012	2012	2012
Facility and sector	Industry	Industry	Laboratory / Academia	Laboratory / Academia	Tire company / Industry	Laboratory / Academia	Laboratory / Academia
Cause of the accident	The design of the nitrogen inserting system of the mixer was inadequate.	An investigation conducted on three nanoscale attrition millers revealed that all three had undergone metal nanopowder explosions in the past. All factories happen dust explosion when raw material containing Al feed to a nano-powder grinder.	Not specified (A graduate student was working on nanostructured explosive materials at the university's Institute of Explosive Materials.)	During weighing, when some $H_2O_2/HClO_4$ post-treated dried PANI (Polyaniline, about 6.8 - 8.5 g) powder was put onto the balance, an explosion broke out abruptly and all PANI was burned to ashes.	A leak subsequent to a 15 to 20-cm longitudinal tear on one of the pneumatic pipes.	Electrostatic charges of approximately 1.8 kV ignited a fire when an operator moved 75-nm Ti particles from a polyethylene bag to a plastic plate	Titanium NMs were ignited when a researcher was using a spatula to remove 2 grams of powder from a 50-gram bag. The cause of the fire was presumed to be a static charge or chemical contamination of the spatula.
Consequences occurred	explosion	(minor) explosion	explsion	explosion	accidental release (5 tonnes of Carbon Black)	fire	fire
Human damage	5 deaths 4 injuries	Not specified	1 injury (lost both hands and an eye)	1 injury (burn)	Not specified	Not specified	Not specified
Property damage	A substantial part of the plant was totally demolished	Not specified	Not specified	Not specified	Fouling the roofs of facility buildings, about 100 dwellings, public buildings, vehicles, gardens, the adjoining prairie land and grazing cattle	Not specified	Not specified
Country	Norway	Chinese Taipei	Poland	China	France	Chinese Taipei	United States
Information source (type and reference)	Book (Eckhoff, 2003[27])	Academic journal (Wu et al., 2010[33])	Newspaper (online) (Jyllian N. Kemsley, 2008[48]))	Academic Journal (Zhang et al., 2011[49])	Webpage (BARPI, n.d.[50])	Academic Journal (Wu, Wu and Ko, 2014[52])	University newsletter (The Chemical Safety Mechanism, 2012[53])

Q.6 - What are the health effects of exposure to nanomaterials?

38. NMs, like conventional chemicals, can cause adverse effects on human health and the environment. Significant resources have been devoted to investigating potential human health hazards through state-led research initiatives. EU Framework Programmes (FP6: 2002-2006, FP7: 2007-2013, Horizon 2020: 2014-2020, Horizon Europe: 2021-2027) and US National Nanotechnology Initiative (NNI: 2001-) are widely known, while nanosafety initiatives/plans exist in other countries as well.

39. Research efforts so far have enabled the government agencies to make the below general statements on the toxicity of NMs.

> *The results of a number of research projects show that nanomaterials are not per se linked with a risk for people and the environment. Nor have new effects of nanomaterials on human health been described to date. Although it is becoming increasingly clear that even in the "new guise" of nanomaterials, known effects of substances, particles and fibres can still occur (BMBF, 2016[55]).*
>
> *Small particles, on an equal mass basis, can be more hazardous than larger ones and certain "legacy produced" nanomaterials, such as ultrafine titanium dioxide, carbon black, and fumed silica, are respiratory hazards (NIOSH, 2016[56]).*
>
> *In general, nanomaterials have the same kinds of health effects as coarser particles of the same material, but other effects may also occur. Nanomaterials that enter into the body can (like other substances) be absorbed, distributed and metabolised (EU-OSHA, 2018[57]).*

40. The World Health Organization (WHO) developed a guideline to classify NMs according to their inhalation toxicity. This classification divides NMs into three (four in detail) groups based on toxicity mechanisms: specific toxicity of the material; toxicity mediated specifically by their fibre structure and; inhalation and biopersistence in the lungs (WHO, 2017[58]).

- **The specific toxicity group (Group I)** [10]
  - (a) MNMs with high dissolution rates through the release of ions or amenable to biodegradation
  - (b) MNMs with low dissolution rate but with high specific toxicity, which is mediated by the specific properties of their components (e.g. nickel metal in nanoform)
- **The respirable fibres group (Group II)**
  - MNMs that are rigid, biopersistent or durable and respirable have dimensions agreed upon by a WHO working group for man-made mineral fibres in the past. These dimensions are a fibre length (FL) > 5 µm, fibre diameter (FD) < 3 µm and an aspect ratio (FL/FD) > 3
- **The granular biopersistent particles (GBP) group (Group III)**
  - respirable granular biodurable particles that are characterized by both low dissolution rates and lack of high specific toxicity (e.g. carbon black, aluminium oxide and aluminium silicate)

41. Substance-specific toxicity is the first criteria to think of. If the components that consist of NMs are toxic, they fall into Group I. This group can be divided into two subgroups depending on their solubility in water. Soluble NMs (Group I.a) lose properties as particles after inhalation, and their toxicity will be similar to their larger counterparts (WHO, 2017[58]; AGS, 2020[59]). The toxicity of insoluble and non-fibrous NMs with substance-specific toxicity (Group I.b) can be estimated from existing toxicity information of their larger forms. However, the hazardous effect of NMs may be increased due to their larger specific surface area in comparison with chemically similar but larger materials (AGS, 2020[59]). The respirable fibres NMs (Group II) may cause an asbestos-like effect as some carbon nanotubes (CNTs) do (AGS, 2020[59]). Finally, for the granular biopersistent particles (Group III), the primary health concern is the chronic, inflammatory effect in the lung after inhalation (AGS, 2020[59]). It should be noted that the boundaries among the three

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[10] Group numbers (I, II, III) were assigned by the author.

groups of NMs (I-III) are not always as clear as the categorisation might suggest. In addition, one NM could be put in more than one bin (e.g. high variability in carbon nanotubes morphology and properties).

42. Health damage due to nanomaterials may occur through exposure routes other than inhalation. The physical state of NMs influences their exposure to humans and the environment. For example, leakage of dispersed NMs may pose a major risk to the environment, while in this case, inhalation exposure of workers might be negligible. Table 6 below, presented by WHO using OECD dossiers of 11 NMs (OECD, n.d.[36]) and IARC evidence summaries of 3 NMs (WHO, 2017[58]), shows that health damage due to NMs can occur through several exposure pathways. Hazard classes were assigned according to the GHS and IARC classification, and Health hazards of 8 NMs were identified among 11 NMs. Information on the type/extent of damage and the level of evidence is also presented. However, it should be noted that health damage test data do not exist for some items.

Table 6. Classification of hazardous properties of NMs that have an existing OECD Dossier

MNM	Acute toxicity	Skin corrosion/ irritation	Serious eye damage/eye irritation	Respiratory or skin sensitization	Germ cell mutagenicity	Carcinogenicity	Reproductive toxicity	Specific target organ toxicity (single exposure)	Specific target organ toxicity (repeated exposure)
Fullerene (C_{60})	No[a]	No	No	No	No	No data[b]	No data	No data	No
SWCNT	No	No	No	No	Cat 2B[c] (L)[d]	No data IARC[e] 3	No data	No data	Cat 1 (L)
MWCNT	No	No	Cat 2A (H)[g]	No	Cat 2 (H)	MWCNT–7: Cat 2 (M)[f], IARC 2B Other MWCNTs: IARC 3	No	No data	Cat 1 (M)[f]
AgNP	No	No	No	Cat 1B (M)	No	No data	No	No data	Cat 1 inhalation (H) Cat 2 oral (H)
AuNP	No data	No data	No data	No data	No data	No data	No data	No data	Cat 1 inhalation (H)
SiO_2	No	No	No	No	No	No data	No	No data	Cat 2 inhalation (H)
TiO_2	No	No	No	No	No	No data; IARC 2B	Cat 2 (L)	No data	Cat 1 inhalation (H)
CeO_2	No	No data	No data	No data	No data	No data	No data	No data	Cat 1 inhalation (M)
Dendrimer	No data	No data	No data	No data	No data	No data	No data	No data	No data
Nanoclay	No data	No data	No data	No data	No data	No data	No data	No data	No data
ZnO	No	No	No	No data	No	No data	No	No data	Cat 1 inhalation (M)

AgNP: silver nanoparticles; AuNP: gold nanoparticles; CeO_2: cerium dioxide; MWCNT: multi-walled carbon nanotubes; SiO_2: silicon dioxide; SWCNT: single-walled carbon nanotubes; TiO_2: titanium dioxide; ZnO: zinc oxide.

a No: no hazard class assigned based on data (green shading).

b No data: no studies available in OECD dossier. (no shading)

c GHS categories: Cat 1 usually implies serious and/or irreversible damage; Cat 2 milder or reversible damage. Within a category A implies more serious and B milder damage.

d L: low level of evidence.

e IARC refers to the International Agency for Research on Cancer categories of confidence in carcinogenicity: IARC Cat 2B = possibly carcinogenic; IARC Cat 3 = not enough evidence to draw a conclusion.

f M: moderate level of evidence.

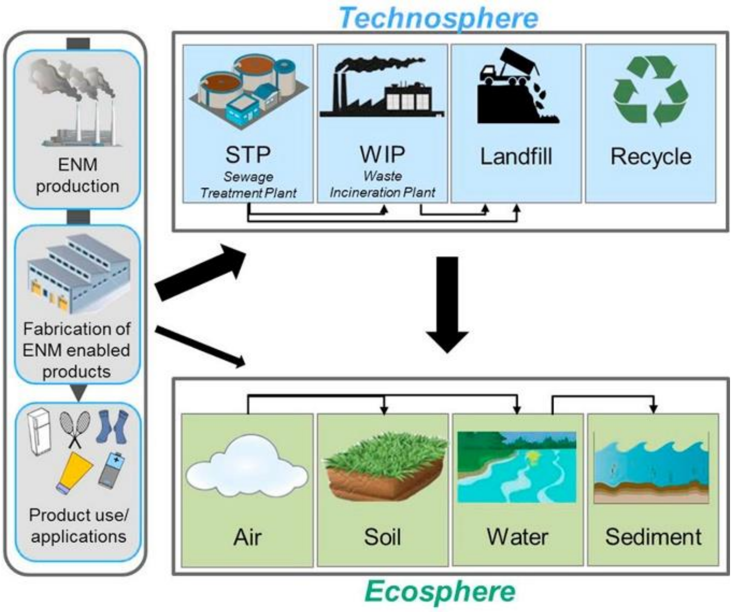
g H: high level of evidence.

Source: (WHO, 2017[58])

Q.7 - If large amounts of nanomaterials are released due to a chemical accident, what kinds of damage can occur in the receiving environmental compartments?

43. NMs are being unintentionally released into the environment from various sources, from industrial sites manufacturing and processing NMs up to the disposal of consumer products containing NMs (EPA, 2007[60]). A schematic diagram (Figure 2) shows the life-cycle flow of NMs. In the absence of accidents, most of the NMs generated during production and product use are discharged to the environment (Ecosphere in Fig 2) through wastewater or waste treatment process (Technosphere in Fig 2). A relatively small portion of NMs may directly enter the environment. On the other hand, accidental release of large amounts of NMs is likely to occur during the production and fabrication process or the transportation of NMs. In this case, the released NMs go directly into the ecosphere without going through the technosphere. Of the seven chemical accident cases involving NMs (Table 5), one carbon black leakage case happened in 2012. This case corresponds to the movement of NMs indicated by the narrow arrow in the figure below (from Fabrication of ENM enabled products → Ecosphere). However, information on the environmental impact of this case cannot be found.

Figure 2. General structure of the material-flow model to track life cycle flow of MNMs



Source: (Sun et al., 2014[61])

44. The fate of released NMs during manufacturing, use and disposal was estimated for top 10 ENMs[11] based on production estimates for 2010 (260,000-309,000 tonnes) (Keller et al., 2013[17]).

- landfills: 63-91 %
- soils: 8-28 %
- water bodies: 0.4-7 %
- atmosphere: 0.1-1.5 %

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[11] Top 10 ENMs are SiO_2, TiO_2, Fe+Fe Oxides, ZnO, Al_2O_3, CeO_2, Nanoclays, CNT, Cu+Cu Oxides, and Ag. Keller et al. (2013[17]) also used information from a private market research firm to provide ENMs production volumes.

45. The above estimation of the fate of released NMs is based on their ordinary (non-accidental) life cycle. In case of an accident, the share of landfills will converge to almost zero and the portion of environmental media is expected to increase significantly. The proportion among environmental media will vary depending on several factors such as the chemical species and state of the released NMs, weather conditions, and the structure and composition of the location of the accident site.

46. The existence of NMs in the environment and their effects have been identified by a number of published literature. However, the presence of NMs in the environment does not necessarily mean that these adverse effects will occur there. These effects are highly material- and site-dependent and closely connected to the dose and chemical speciation (bioavailability) of released NMs. Their environmental fate is strongly related to their stability, mobility and transformation/dissolution properties. Some metals are also essential, and several metals are naturally occurring minerals of largely varying local background concentrations.

47. No studies have been found on the environmental impact of NMs leaked in large quantities due to accidents. Even if the accident situation is not assumed, it is possible to indirectly assess the impact of accidental leakage through existing studies on this topic. Their effects on the ecosystem can be categorised into three environmental media: soil, aquatic (including sediment) and atmospheric environment (EPA, 2017[18]; Sajid et al., 2014[62]; Lead et al., 2018[63]; Turan et al., 2019[64]):

- Selected effects on soil environment
    - NMs released into the soil can affect microorganisms, small animals (macrofauna) and plants on the ground (Mishra, Singh and Yang, 2019[65]).
    - The bactericidal effect of Ag NPs on two common soil bacteria (*Bacillus cereus* and *Pseudomonas stutzeri*) was identified (Fajardo et al., 2014[66]).
    - Ag NPs showed an effect on the growth rate and population of earthworms (*Lumbricus rubellus*), and long-term (10 months) exposure to high concentration (154 mg Ag/kg soil) of Ag NPs resulted in complete juvenile mortality (van der Ploeg et al., 2014[67]).
    - The study on the effect of CeO_2 NPs on wheat growth showed that they caused biochemical changes such as decreased chlorophyll content and increased activities of two enzymes, and physiological changes such as microstructure changes in root and leaf cells and delayed flowering (Du et al., 2015[68]).
- Selected effects on the aquatic environment
    - NMs in water may pose a risk to the aquatic environment: plants and algae; bacteria and aquatic microbes; and; aquatic animals (Turan et al., 2019[64]).
    - ZnO NPs affect the growth rate of algae and suggested that the ZnO NPs were more toxic to the marine algae than bulk ZnO (Manzo et al., 2013[69]).
    - Coatings on iron oxide NPs cause different toxic effects which were linked to decreasing colloidal stability, the release of ions from the core material or the ability to form reactive oxygen species in daphnids (Baumann et al., 2014[70]).
    - TiO_2 NPs have been shown to cause mortality, reduced growth and negative impacts on cells and DNA of aquatic organisms (Haynes et al., 2017[71]).
    - It has been identified through experiments on *Chironomus tentans* that NMs above a certain threshold concentration have the potential to adversely affect the survival and behaviour of benthic organisms (Oberholster et al., 2011[72]).
    - Carbon fullerenes (C_{60} fullerenes) prepared as colloidal aggregates in aqueous solutions are stable for months to years, allowing for chronic exposure to biological and environmental systems (Hegde et al., 2015[73]).

- Selected effects on atmospheric environment
    - The surface of TiO_2 and ZnO NPs and photosensitive fullerenes can facilitate atmospheric photochemical reactions by generating reactive oxygen species (ROS), and these reactions potentially change the chemical balance of the atmosphere (John et al., 2017[74]).
    - In contrast, other NMs (e.g. cerium oxide ENMs) can scavenge superoxide (Heckert et al., 2008[75]).
    - It was shown that Ag NPs could absorb SO_2 on their surface and catalyse the reduction of NO under anhydrous conditions (Patakfalvi et al., 2007[76]).

48. Although many research findings are available and new studies are in progress on this issue, it should be remembered that there are still uncertainties in the potential risks of NMs to the environment, especially for metal and metal oxide NMs, due to limited experience in standardised sample preparation and dosimetry, knowledge on transformation dynamics, and lack of chronic studies (Lead et al., 2018[63]). Another reason for the uncertainties is the lack of nanospecific consideration in some of the current standardised test guidelines that were used for previous data collection. To address this, the OECD Programmes on Manufactured Nanomaterials and on Test Guidelines are conducting several projects to develop standardised test methods for NMs (OECD, 2021[77]) in close collaboration with EU's Gov4Nano[12] and NanoHarmony[13] Programmes.

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[12] https://www.gov4nano.eu

[13] https://nanoharmony.eu/

Part III. Review of Prevention, Preparedness and Response Measures

Q.8 - Is it necessary to implement measures to prevent chemical accidents involving nanomaterials in addition to the existing safety protocols?

49. No specific rules or regulations have been identified regarding preventive measures against accidents involving NMs. Moreover, few papers or reports have studied the need for additional regulation on this subject. Some of the relevant research findings and government decisions are presented below:

> *Insufficient fundamental data are at present available on the fire and explosion properties to enable final general conclusions to be drawn. The knowledge gained to-date does not indicate any need for specific regulations for nanomaterials under the Ordinance on Protection against Major Accidents (of Switzerland) (Steinkrauss et al., 2010[44]).*
>
> *The UK line on both these points (one point is accident hazards of certain NMs) is that other legislation already adequately covers these issues (UK Parliament, 2011[78]).*
>
> *The same principles applying to the management of fine powders, dusts or dusty materials should be considered for NOAAs, with particular care taken in the case of easily oxidizable metallic dust. However, the effectiveness of methods for NOAA fire, explosion and catalysis prevention and control is yet to be evaluated (ISO, 2018[35]).*

50. Particular attention should be paid to safety measures, as these can contribute considerably to accident prevention (Krug et al., 2013[45]; Nowack et al., 2014[46]). Downstream users also need to know and follow the safety measures. Whereas chemical production and manufacturing sites have to comply with existing high safety standards, the handling of NMs in manufacturing and processing of the final products is typically much less controlled and can result in a much higher possibility for release (Som et al., 2010[79]; Kuhlbusch and Nickel, 2010[80]). An essential step in this context is employee training. In general, the safe handling of NMs does not require more action than that needed to handle powders and conventional chemicals.

Structural measures

51. Structural measures are vital for the safe handling of NMs. The established safety procedures used in the chemical industry are deemed to be sufficient for accident prevention (Krug et al., 2013[45]; Nowack et al., 2014[46]), but the effectiveness of these procedures for the prevention and control of accidents involving NMs has not yet been evaluated (ISO, 2018[35]; Osman, 2019[81]). Key structural measures include:

- the presence of a detention basin during production, manufacturing, and storage of suspended NMs;
- rooms without any direct connection to the sewer system or, where a connection is present, it should be equipped with a possibility for closure during an accident;
- configuration of ventilation systems and the building envelope to prevent nanomaterial release to the wider environment;
- fire prevention measures such as fire doors, separate storage rooms for organic solvents, and separate fire compartments.

Technical measures

52. Various technical measures can prevent or restrict an accident (Krug et al., 2013[45]; Nowack et al., 2014[46]), including:

- sprinklers in storage rooms;
- pressure-controlled equipment, and;
- disconnection of ventilation in case of an accident.

53. These measures are not nano-specific but target the accident prevention of easily flammable compounds, which are stored in the same room. If these conventional measures are adopted consistently, they are also effective for NMs.

54. Additional workplace procedures to reduce the possibility of a dust explosion (SWA, 2013[22]; Bouillard, 2015[82]; Nazneen, Wang and Kay O'Connor, 2019[25]) include:

- the use of wet processes allowing staff to work with NMs in an agglomerated state or dispersion;
- working in well-ventilated workspaces that provide efficient exhaust with particle filtration;
- the use of effective dust capture methods for collection of the dangerous sized particles;
- elimination of ignition sources such as flames of direct heat, hot work, incandescent material, hot surfaces, electrostatic, electrical and friction sparks, self-heating and lighting;
- a confined process. It may include the incorporation of a protection barrier such as venting systems to reduce the severity of incidents or a prevention barrier to reduce the probability of incidents;
- an inert process (i.e. a process that does not build an explosive dust/air mixture or a process that does not have ignition sources).

55. To reduce the risks of fire and deflagration, it might prove necessary to use controlled-atmosphere production and storage processes using carbon dioxide, nitrogen or other inert gases. However, this could introduce further hazards into the system, notably the risk of asphyxiation.

56. More generally, it is also recommended that appropriate steps should be taken to minimise worker exposure by developing a risk management programme and implementing an exposure measurement and control strategy (NIOSH, 2013[83]). Exposure should be controlled by applying protection measures appropriate to the activity and consistent with the 'hierarchy of control' (BSI, 2007[47]). The hazard controls in the hierarchy are, in order of decreasing effectiveness: elimination; substitution; engineering controls; administration controls, and; PPE (Personal Protective Equipment). It means that lower hierarchy measures are to be adopted when no other higher hierarchy means are available. For example, among the measures presented above, PPE should be considered a last resort.

Organisational measures

57. Simple but effective organisational measures (Krug et al., 2013[45]; Nowack et al., 2014[46]) include:

- appropriate access restrictions;
- training of all employees on the hazards of working with NMs, the risks they pose, and the precautions that should be taken to avoid or minimise release and exposure;
- provision of PPE to employees;
- regular cleaning of the workplace to prevent nanomaterial build-up;
- procedures to ensure that control measures are effective and are adhered to by employees.

58. The installation/facility's fire brigade or the local fire brigade should also be informed about the presence of NMs and should be trained in suitable firefighting procedures (Krug et al., 2013[45]; Nowack et al., 2014[46]).

Packaging & Labelling

59. Another critical aspect of preventing the release of NMs or exposure to NMs, particularly during storage and transport, is appropriate packaging and labelling. It has been recommended to store dispersible NMs, whether suspended in liquids or dry particle form, in closed (tightly sealed) containers whenever possible (NIOSH, 2012[84]). Containers should be unbreakable and labelled to indicate the chemical content and form of the NMs. Secondary containment (i.e. double bagging or containment) should also be used.

60. Similarly, transport of NMs should be in sealed, robust, labelled containers inside a secondary containment capable of withstanding foreseeable impacts (e.g. bottles inside strong plastic outer containers) (HSE, 2013[85]), and precautions should be taken during transport to prevent accidental spillage. For shipping, NMs should be packaged, marked, labelled and shipped using approved packaging/containers and in accordance with the relevant technical instructions and transport/shipping regulations (BSI, 2012[86]).

Additional resources

61. Dust explosion protection is of central importance for the safety of a plant dealing with NMs. However, the practical and technical details of the safety measures are not included in this paper. Please refer to the easily accessible guidance on this topic below.

- Safe handling of combustible dust: Precautions against explosions (HSE, 2003[87])
- Combustible dust in Industry: Preventing and Mitigating the Effects of Fire and Explosions (U.S. OSHA, 2005[88])
- Hazard Communication Guidance for Combustible Dusts (U.S. OSHA, 2009[89])
- Firefighting Precautions for Facilities with Combustible Dust (U.S. OSHA, 2013[90])

Q.9 - Considering current knowledge and information, what needs to be done to prepare for and respond to chemical accidents involving nanomaterials?

Preparedness

62. Careful planning and thorough preparedness are prerequisites for an effective response to a chemical incident. The overarching preparedness measures for incidents involving chemicals and public health at both the national and regional levels can be considered to apply equally to NMs (IPCS, 1999[91]). These include:

- setting up multi-disciplinary public health working arrangements;
- networking with all interested parties;
- conducting a risk assessment;
- drawing up a public health chemical incident plan;
- establishing access to a variety of information sources, databases, and experts;
- pursuing measures to reduce the probability of incidents and the health effects of incidents.

63. Given the remaining uncertainties regarding health risks that may be associated with NMs, it has been suggested that a preventative approach based on the ‘precautionary principle’ should be applied (IRSST, 2009[92]; NIOSH, 2009[38]). This principle stipulates that a precautionary approach should be adopted when faced with a high degree of scientific uncertainty. Moreover, the possible negative impacts need to be reduced by minimising occupational exposure, among other factors. For most processes and job tasks, the control of airborne exposure to NMs can be accomplished using a variety of engineering controls similar to those used in reducing exposure to conventional aerosols (NIOSH, 2009[38]).

64. Implementing a risk management programme in workplaces where exposure to NMs may exist can help minimise nanoparticle release and exposure (ISO, 2012[93]). Elements of such a programme should include the following:

- identifying the hazards and assessing the risks;
- deciding what precautions are needed;
- preventing or adequately controlling exposure;
- ensuring that control measures are used and maintained;
- monitoring the exposure;
- carrying out appropriate health surveillance;
- preparing plans and procedures to deal with accidents, incidents and emergencies;
- ensuring employees are properly informed, trained and supervised.

65. The knowledge gaps concerning the health hazards of new NMs introduce significant uncertainty into any risk assessment. In general, the greater the gaps in knowledge, the more cautious the control strategy should be. In the absence of knowledge, it is inappropriate to assume that a nanoparticle form of a material has the same hazard potential as it has in the larger particulate form (ISO, 2012[93]). Concerning fire and explosion hazards, in the absence of specific information, it has been suggested that dust clouds of all NMs should be considered to present an explosion hazard (SWA, 2013[22]).

66. Another essential element in preparedness is the Safety Data Sheet (SDS). SDS facilitates the consideration of measures to prevent accidents because it is a well-accepted and effective method for providing workplace health and safety information. As uncertainties remain regarding the potentially hazardous properties of NMs, SDS for NMs must reflect as best as possible current knowledge in the field. In the EU, compiling SDSs for NMs became mandatory from January 1, 2021 (EUON, 2020[94]).

Response

67. Specific response approaches for accidents involving NMs have not been proposed to date. However, in responding to an incident involving NMs, the general principles in dealing with chemical incidents are relevant (IPCS, 1999[91]). These include:

- activating the public health management team;
- alerting secondary health services;
- conducting the best outcome assessment;
- advising public, media and first responders on:
    - personal protection;
    - decontamination;
    - restrictions;
    - evacuation / safe re-entry.

68. Emergency responders should be provided with specialist information regarding NMs hazards and risks. This could be aided by providing an SDS which includes nano-specific information (discussed further in the 'Preparedness' section above).

69. In the event of a fire, selecting an extinguishing agent should take into account the compatibility or incompatibility of the nanomaterial with water (BSI, 2007[47]). Some metallic dusts react with water to form, among other things, hydrogen, which ignites very easily. Chemical powders are available to extinguish burning metallic dust powders, though this has the effect of putting the metallic dust in suspension, thereby increasing the risk of deflagration (ISO, 2012[93]).

70. Guidance on the clean-up and disposal of NMs has been published (BSI, 2007[47]; NIOSH, 2009[38]; HSE, 2013[85]), although this is generally aimed at dealing with small-scale laboratory spills and contaminated surfaces. It is recommended that clean-up should be performed in a manner that prevents or limits worker exposure. In addition, only trained competent personnel who are authorised to deal with spillages and accidental release of nanoparticles should enter the affected area.

71. Clean-up of potentially contaminated surfaces and spills should be performed using either a HEPA-filtered vacuum cleaner or wet-wiping (using a damp cloth or wetting the materials before wiping) or both. It is important to note that a vacuum cleaner should be explosion-proof (e.g. ATEX certified) and meet the safety requirement of activities in the field (Baron et al., 2015[23]). If NMs are cleaned by wet-wiping, adequate and non-reacting wetting agents should be used. It is advised that energetic cleaning methods such as dry sweeping or the use of compressed-air hoses should be avoided or only used with precautions (BSI, 2007[47]). A method for surface decontamination of carbon-based NMs using solvent cleaning and wipes was also published (Su et al., 2014[95])

72. It is considered essential that employers have documented policies and procedures in place which cover both more minor and more significant events as far as possible. In the absence of specific information, it would be prudent to base strategies on current good practice, together with information on exposure risks, including the relative importance of different exposure and release routes (NIOSH, 2009[38]).

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Annex A. Technology readiness level (TRL) of 25 selected NMs

73. The technology readiness level (TRL) in Table A.1. below is an adapted version (three-level metric) of what was originally developed as a nine-level metric by U.S. NASA in the 1980s (Janković and Plata, 2019[14]). The table shows the count of application areas for each NM by technology maturity: commercial; demonstration, and; applied research and development (R&D). It also highlights where the 25 NMs are being commercially used.

Table A.1. Technology readiness level of 25 selected NMs (as of 2015)

Name	**Commercial application**			**Demon-stration**	**Applied R&D**	**Total**
	(Application area)		(count, A)	(count, B)	(count, C)	(D= A+B+C)
Silicon dioxide	Rubber and plastic additives Coating additives Cosmetics additives Fillers in nanocomposites	Structural adhesives Automotive tire additives Cement additives	7	3	1	11
Titanium dioxide	Photovoltaics (dye-sensitized solar cells) Sunscreens & cosmetics	Photocatalytic self-cleaning coatings	3	3	4	10
Clays	Barrier films in packaging Automotive composites Flame retardant plastic additives	Automotive tire additives Rheology modifiers	5	2	2	9
Zinc oxide	Sunscreens & cosmetics UV absorbers for paints, coatings, plastics/synthetics & textiles	Antimicrobial and bacteriostatic agent Adhesives Electrically conductive applications	5	-	-	5
Aluminium Oxide	Anti-wear coatings Nanofillers for polymer composites Catalysts supports Heat transfer fluids Conductive coatings Propellants	Polishing additives Paint additives Filtration membranes Speciality fibres Lubricants	11	3	2	16
Zirconium oxide	Resins for optics Thermal barrier coatings Ceramics additives Refractory products	Cement additives Catalysts Oxygen sensors	7	4	1	12
Cerium oxide	Polishing slurries UV absorbers	Fuel additives Catalysts	4	2	6	12
Carbon nanotubes	Anti-static composites & films for electrostatic painting and static dissipation Marine coatings Battery additives Data cables & power transmission lines De-icing coatings Thermoset composites, thermoplastics, and rubber additives Fuel system components (EMI) composites & coatings	Conductive additive in composites and pastes Electromagnetic Interference Shielding Sporting goods composites Aerospace composites Filtration membranes Microscopy (TEM grids, SPM tips, AFM tips) EMI, ESD and antistatic, shielding coatings & composites TCF additives	16	15	8	39

Name	Commercial application			Demon-stration (count, B)	Applied R&D (count, C)	Total (D= A+B+C)
	(Application area)		(count, A)			
Cellulose	Cement additives Printing paper Polymer composites in plastics packaging Rheology modifiers	Transparent barrier films in food packaging Paper composites Hygiene products Filter media	8	12	7	27
Copper oxide	Industrial catalysts	Semiconductor additives	2	7	5	14
Fibres	Air/liquid filtration membranes Medical textiles (hydrogel dressings)	Bone/skin regeneration	3	5	1	9
Silver	Antimicrobial wound care Antimicrobial medical devices Textiles Antimicrobial coatings	Cosmetics & personal care additives Conductive inks & films Food packaging Water filtration & purification	8	2	1	11
Antimony Tin oxide	Anti-static coatings		1	8	7	16
Fullerenes	Lubricant additives Whitening and anti-aging cosmetics	Drug delivery	3	6	4	13
Bismuth oxide	Ceramics		1	5	8	14
Magnesium oxide	Catalysts Flame retardants	Refractory material in furnace linings	3	8	5	16
Diamonds	Lubricants Polishing slurries	Anti-friction & wear coatings Thermal compounds (pastes) for electronics	4	3	2	9
Iron oxide	Magnetic storage media MRI contrast agents	Polishing media	3	9	2	14
Cobalt oxide	Magnetic fluids	Catalysts	2	3	4	9
Nickel			-	5	3	8
Manganese oxide			-	6	5	11
Graphene	Antistatic coatings Battery additives Sporting goods Tires Oilfield chemicals Water filtration membranes Electron microscopy sample supports	Polymer composites Conductive inks Conductive additives for Displays Humidity sensors Inks & 3D printed materials EMI shielding	13	16	6	35
Gold	Biosensors	MRI contrast agents	2	5	-	7
Dendrimers	Antimicrobial agents in sexual health Cosmetics Antibody reagents	Medical imaging Inkjet inks Water repellent coatings	6	5	7	18
Quantum dots	Edge optic LCDs in TVs On surface LCDs in TVs Medical contrast agents	Security inks & tags Image sensors	5	7	5	17

Notes: **Commercial application**: fully tested, in operation;
Demonstration: field-tested, basic prototype, final prototype;
Applied R&D: proof of concept, lab-tested;
Count A, B, and C show the number of application areas of each TRL. Specific application areas of Demonstration and Applied R&D stages are not provided here. Please refer to the Electronic Supplementary Information of Janković and Plata (2019[14]).

Source: (Janković and Plata, 2019[14])