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Matters related to the work programme of the Open-ended Working Group for 2018–2019: scientific and technical matters: waste containing nanomaterials

Report on issues related to waste containing nanomaterials and options for further work under the Basel Convention

Note by the Secretariat

As referred to in the note by the Secretariat on waste containing nanomaterials (UNEP/CHW/OEWG.11/8), a report on issues related to waste containing nanomaterials that may be relevant to work under the Basel Convention and options for further work that may be carried out under the Convention related to such waste is set out in the annex to the present note. The present note, including its annex, has not been formally edited.

* UNEP/CHW/OEWG.11/1/Rev.1.

Annex

Report on issues related to waste containing nanomaterials and options for further work under the Basel Convention

Contents

I. Mandate and objectives

1. In paragraph 5 of decision BC-13/17, the Conference of the Parties to the Basel Convention requested the Secretariat to prepare, for consideration of the Open-ended Working Group at its eleventh meeting, a document compiling information on existing activities that address waste containing nanomaterials and identifying issues related to waste containing nanomaterials that may be relevant to work under the Basel Convention and on options for further work that may be carried out under the Convention related to waste containing nanomaterials within the scope of the Convention, avoiding duplication with activities relating to the matter in other forums. The Open-Ended Working Group was mandated to consider further work that may be carried out in relation to waste containing nanomaterials.

2. Pursuant to the above-mentioned decision, the main objectives of this report are to identify issues related to waste containing nanomaterials and their environmentally sound management, to explore possible approaches to addressing these issues and those that may fall within the scope of Basel Convention.

II. Scope of the report

3. The Framework for the environmentally sound management (ESM) of hazardous wastes and other wastes,[1] developed under the Basel Convention, establishes a number of elements that are necessary to ensure that wastes are managed in an environmentally sound manner. These are:

(a) Having a clear picture as to which wastes are arising and the quantities that need to be managed;

(b) Understanding how these need to be managed to ensure ESM;

(c) Having sufficient capacity to manage all waste streams in an environmentally sound manner;

(d) Ensuring that those with a role in the generation and management of wastes understand what they need to do to ensure wastes are managed in an environmentally sound manner;

(e) Having a system that incentivizes compliance;

(f) Monitoring the effectiveness of the system;

(g) Ensuring transboundary movement of wastes is in compliance with the Basel Convention.

4. The report examines the extent to which it is currently possible to fulfill the requirements that are considered necessary to ensure that wastes are managed in an environmentally sound manner in relation to waste containing nanomaterials, in particular the necessity of having a clear picture as to which wastes are arising and the quantities that need to be managed and of understanding how these need to be managed to ensure ESM.

III. Background on nanomaterials

5. This section provides a succinct summary of background information about nanomaterials that is relevant for further discussion of issues related to waste containing nanomaterials.

A. Definitions of nanomaterials

6. Nanomaterials are generally thought of as being particles with a size from approximately 1 to 100 nanometres (nm). Many different definitions of nanomaterials exist in the scientific literature and have been developed for various regulatory purposes and terms such as nanotechnology, nanomaterials and nanoparticles are understood in a variety of ways (Arts et al., 2014; Boholm and Arvidsson, 2016).

7. As an example, the International Organisation for Standardisation (ISO) defines nanomaterial as a material with any external dimension in the nanoscale or having an internal structure or surface structure in the nanoscale (length range approximately from 1 nm to 100 nm) (ISO, 2017). This term is inclusive of nano-objects and nanostructured material. A nano-object is discrete piece of material with one, two or three external dimensions in the nanoscale. Nano-objects are typically described or grouped in terms of the dimensions constrained in the nanoscale: in one dimension (nanoplates); in

[1] UNEP/CHW.11/3/Add.1/Rev.1.

two dimensions (nanofibres, including nanotubes); in all three dimensions (nanoparticles and quantum dots). Nanostructured materials are materials with an internal structure or surface structure in the nanoscale.

8. Nanomaterials can be naturally occurring, manufactured or incidental, i.e., a nano-object generated as an unintentional by-product of a process. A manufactured or engineered nanomaterial (ENM) is a nanomaterial intentionally produced to have selected properties or composition.

9. Most definitions of nanomaterials focus on ENMs. An exception to this rule is the definition adopted by the European Commission (2011) for regulatory purposes with includes natural, incidental as well as manufactured material containing particles. The definition proposed by the European Commission furthermore accounts for the fact that nanomaterials most typically consist of many particles present in different sizes in a particular distribution. Thus nanomaterial means 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 (European Commission, 2011). The definition proposed by the European Commission is currently undergoing a review in order to address challenges identified with practical implementation. Terms such as “particle,” “size” and “external dimension” have been found to leave a lot of room for interpretation and there is a lack of standardized methods to measure particle size distribution (Rauscher et al., 2015).

B. Properties specific to nanomaterials

10. Nanomaterials may have unique chemical, physical, electrical, and mechanical properties that are different to the same material (same elemental or molecular composition) without nanoforms (often called bulk substances). One important aspect in which nanomaterials differ from bulk is that they have a much larger specific surface, i.e. a larger area to volume (or mass) ratio. For instance, 10 g of spherical silver nanoparticles with a diameter of 10 nm have a total surface area of about 570 m^2, whereas a single solid 10 g silver sphere would have a surface area of about 4.7 cm^2. This corresponds to an increase in total surface area of more than 1,200,000 times. This has an impact on the reactivity of nanomaterials since chemical reactions often take place at the surface of materials.

11. A change in size is also associated with changes in a range of chemical and physical properties including melting point, altered crystallographic structure and solubility, photocatalytic activity and optical properties. Some of these properties can be extrapolated from the macroscale, whereas others change drastically or are only observed below a certain size (EASAC-JRC, 2011). Below a few tens of nanometres (less than about 30 nm), considerable changes in fundamental physico-chemical properties such as the catalytic, optical, electrical, and magnetic properties can be observed as a result of quantum confinement of atoms and electrons (EASAC-JRC, 2011).

12. Nanomaterials can vary with regard to not only size and specific surface area but also with regard to shape, surface charge and surface coating (core particles are modified to provide for specific functions) and they can in theory be designed to have any desired property. It is furthermore well-established that nanomaterials can undergo changes that affect their behavior and environmental fate, such as dissolution, aggregation/agglomeration, sorption onto other surfaces and biomodification. The impact of these processes depend on the composition of the nanomaterial as well and the coating of the nanomaterial (Hartmann et al., 2014).

C. Production and use of engineered nanomaterials

1. Production of ENMs

13. Detailed and precise information about the production of ENMs is scarce. It has been estimated that the main categories of ENMs on the market include inorganic non-metallic nanomaterials (e.g., synthetic amorphous silica, aluminium oxide, titanium dioxide), carbon based nanomaterials (e.g., carbon black, carbon nanotubes (CNTs)), metal nanoparticles (e.g., nanosilver) and organic, macromolecular or polymeric particulate materials (e.g., dendrimers) (European Commission, 2012). More than 60 different ENMs are marketed and the ones with the largest production volumes globally are estimated to be carbon black (9.6 million tons) and synthethic amorphous silica (1.5 million tons). Other ENMs on the market are aluminium oxide (200,000 tons), barium titanate (15,000 tons), titanium dioxide (10,000 tons), cerium oxide (10,000 tons), zinc oxide (8,000 tons), CNTs and carbon nanofibres (100-1,000 tons) and silver (20 tons).

14. More detailed information on ENMs put on the market is available from France where it is mandatory to register nanomaterials intentionally manufactured or imported in quantities above 100 grams (Broomfield et al., 2016). Since 2013, about 14,000 registrations of 300 different ENMs were made by 2600 companies, adding up to a total volume of about 500,000 tons. The ENMs with the

largest volumes (above 10,000 tons) are carbon black, silicon dioxide, calcium carbonate and titanium dioxide (see Table A1 in the appendix I). 65 % of registrations were for ENMs produced or imported in volumes of less than 1 ton (Mir, 2015).

15. It is important to note, however, that for a given ENM, a variety of forms can exist and may be tailored for specific uses. For instance, many different forms of titanium dioxide exist and they can have different crystal structure, shape, size and surface coatings, which may affect their properties, fate and effects on human health and the environment. Specific information about the production of the various forms of ENMs is difficult to obtain.

16. Although production of ENMs is predicted to increase, precise information on production trends is not readily available (Broomfield et al., 2016). One estimate is that ENM production across a range of different sectors over the period extending from 2014 to 2020 would increase in the range of 9% to 29% per year (Federal Ministry of Education and Research, 2014).

2. Uses of ENMs

17. ENMs are reported to be used in a wide range of industrial and commercial applications across various industries, for example, in paints and pigments, tyres and rubber, building materials, catalysis, energy generation and storage, water filtration and remediation, food packaging and processing, machinery and wear protection, data storage and electronics, textiles and optics, and diagnostics and medical devices (Royal Society and Royal Academy of Engineering, 2004; European Commission, 2012; Nanowerk, 2018; Danish Environmental Protection Agency, 2015). While it is generally agreed that ENMs are present in a range of consumer products and articles, the types of ENMs present and their concentrations is largely unknown.

18. To collect information on the presence of ENMs in products, several inventories or registers have been established in countries such as Germany, Belgium, France and Denmark (Hansen et al., 2016). In general, these inventories suffer from one or several of the following limitations: they are not continuously updated; they contain a large number products that are no longer on the market; some of them are not fully available to the public; the information is based on claims by manufacturers/importers; they do not always provide detailed and specific information about the ENMs used in the product and/or and the content of ENMs. Figure 1 in appendix I provides a snapshot of the products registered in the registry set up in Denmark which contains information about more than 3000 products on the European market that are claimed to contain ENMs or are claimed to be based on nanotechnology. The most commonly used ENMs are silver and titanium but the ENMs in 60% of products are not specified.

D. Effects of engineered nanomaterials on human health and the environment

19. The properties of ENMs that have spurred their use in a wide range of novel applications are also those that give rise to concerns about potential adverse effects on human health and the environment. Insights about the potential toxicity of nanoparticles and nanotubes have been derived from evidence about the adverse effects of human exposure to airborne particles in ambient air, such as in the case of quartz dusts, asbestos and particulate fraction of air pollution resulting from the burning of fossil fuels (Royal Society and Royal Academy of Engineering, 2004; Scientific Committee on Emerging and Newly Identified Health Risks (SCENIHR), 2006; Health Council of Netherlands, 2006).

20. A fundamental question regarding the toxicology of nanomaterials is whether there are hazards specific to this class of substances. In 2006, SCENIHR of the European Commission concluded that there was insufficient data available to allow the identification of any systematic rules that govern the toxicological characteristics of all products of nanotechnology. Nevertheless, it was also concluded that the safety evaluation of nanoparticles and nanostructures cannot rely solely on the toxicological profile of the equivalent bulk material and nanomaterials need to be evaluated for their risk on a case by case basis for each preparation including the intended use of the material. There is ongoing debate about nano-specific effects of ENMs and the best approach to their testing given the sheer degree of variability of substances that can be engineered (Donaldson and Poland, 2013).

21. Despite the existence of a wide and increasingly large body of research related to the toxicological properties of nanomaterials, much doubt and uncertainty prevails about their effects on human health (Krug, 2014). A number of factors make it challenging to compare results among studies and draw consistent conclusions. These include the diversity of ENMs studied and variability in the characterization and preparation of ENMs used in the studies, in test methods used and end-points examined (Krug, 2014; Maynard and Aitken, 2016). The Organisation for Economic Cooperation and Development has been working on adapting its guidelines for the testing of

chemicals methods to the specificities of nanomaterials and on harmonizing of test methods and approaches used (http://www.oecd.org/chemicalsafety/nanosafety/).

22. Some ENMs have been more thoroughly studied and subject to evaluation by various research agencies and regulatory bodies. For example, the International Agency for Research on Cancer (IARC) has classified a certain group of multiwalled CNTs known MWCNT-7 as "possibly carcinogenic to humans" (Group 2B) (IARC 2017). The Health and Safety Executive (United Kingdom) has recommended a precautionary approach to the risk management of CNTs in view of emerging evidence for lung damage (HSE, 2003). The Scientific Committee on Consumer Safety (SCCS) of the European Commission has provided opinions on the safety of a range of nanomaterials for use in relevant cosmetic product categories, e.g. zinc oxide, titanium dioxide, carbon black and silica (SCCS 2012, 2014a, b, 2015a, b; 2016). The World Health Organization (WHO; Lee et al., 2017) has published guidelines on protecting workers from potential risks of manufactured nanomaterials that includes a classification of hazardous properties of 11 ENMs. Challenges for undertaking hazard and risk assessment of four classes of ENMs (fullerenes, CNTs, metals and metal oxides) have been described (Stone et al., 2010).

23. An increasingly large body of research on the ecotoxicology of ENMs also exists. While a variety of effects have been observed on aquatic and terrestrial organisms for different types of ENMs, significant knowledge gaps and methodological variability among studies make it difficult to integrate their findings (Science for Environment Policy, 2017). Many existing studies has focused on the ecotoxicity of nanoparticles but few environmental risk assessments have been undertaken due to information gaps on environmental levels, behaviour and fate of ENMs in the environment (Kjølholt et al., 2015). Reliable analytical techniques for characterizing and quantifying ENMs in complex environmental matrices, are still under development (Bundschuh et al., 2018).

IV. Waste containing nanomaterials and its quantification

A. Types and sources of waste containing nanomaterials

24. There is no agreed definition at the international level of what constitutes waste containing nanomaterials. Discussions in this report pertain to waste that contain ENMs only. In general terms, waste containing nanomaterials (WCNM) is generated during two phases of the life cycle of products and articles containing ENMs (nano-enabled products): production of ENMs and manufacturing of nano-enabled products; and when nano-enabled products reach the end-of-life. The waste generated falls into three main categories:

(a) Manufacturing waste materials (by-products of the manufacturing process consisting of ENMs as a single fraction);

(b) End-of-life nano-enabled products;

(c) Waste (unintentionally) contaminated with ENMs (e.g. containers for cosmetics) (Boldrin et al., 2014).

25. The quantities of manufacturing waste and waste materials contaminated with ENMs could in principle be measured or estimated by producers of ENMs and manufacturers of nano-enabled products. Such information is currently difficult to access publicly, because in many countries manufacturers do not have any obligation to report on WCNM and reporting on a voluntary basis is often not done in order to protect confidentiality regarding industrial processes. As a result, limited data is available about the amounts of manufacturing waste containing ENMs generated although this may be significantly larger than the amount of ENMs produced (Keller et al., 2013; Boldrin et al., 2014). Examples of some of the available information on the generation rate of WCNM is provided in Table A2 of appendix I.

26. Attempts to estimate the quantities of wastes generated from end-of-life nano-enabled products rely on modelling approaches based on mass balances covering the life-cycle stages of ENMs and nano-enabled products (Adam and Nowack, 2017; Caballero-Guzman et al., 2015; Gottschalk et al., 2009; Sun et al., 2017, 2016, 2015, 2014; Walser and Gottschalk, 2014; Asmatulu et al., 2012; Boldrin et al., 2014; Heggelund et al., 2016). In general, the studies are constrained by the paucity of data on the production and use of ENMs (see section III above) which also limits model validation (Nichols, 2016) and quantitative assessment (Heggelund, 2017).

27. Direct characterization of ENMs in waste can also provide useful information for estimating the quantities of WCNM generated. Such measurements remain challenging because the majority of nano-enabled products are not labelled (Heggelund, 2017) and because the investigation of ENMs in

complex matrices such as solid waste is limited by current analytical capabilities (Reinhart et al., 2010; Part et al., 2015).

28. Several studies have attempted to identify the waste streams that are likely to contain significant levels of ENMs due to the presence of end-of-life nano-enabled products. The results of some of these are shown in Table 1. In addition to these findings, Andersen et al. (2014) identified waste tyres as being of concern due to the large amounts generated and their content of different types of ENMs such as carbon black, highly dispersible silica and nanoclay.

Table 1. Overview of waste streams impacted by the presence of ENMs

Waste streams	ENMs present	End-of-life products	Context	Source
Electronics	silicon-based iron-based	Coatings, solar cells Coatings, electronics	Global	(Keller et al., 2013) (Keller and Lazareva, 2014)
Catalysts	silicon-based aluminum-based	Coatings Catalysts		
Energy and Environment	silicon-based titanium-based	Sensors, coatings, solar cells		
Plastic packaging	silicon-based	Food packaging	European	(Heggelund et al., 2016)
Textile	silver-based	Clothing		
Electronics	titanium-based carbon-based	Household appliances Semiconductors, housings		
Packaging	zinc-based, silver-based	Food packaging	European	(Adam and Nowack, 2017)
Textile	Silver-based	Clothing		
Electronics	carbon-based titanium-based	Electronics, batteries Household appliances		
Construction and demolition waste	titanium-based zinc-based	Paints Glass		

B. Disposal paths and flows of waste containing nanomaterials

29. Information on the disposal paths of WCNM and the magnitude of flows within the waste management system is important for understanding emissions from waste disposal of WCNM and identifying where exposure to ENMs could occur, either in the environment or as a potential occupational hazard (Andersen et al., 2014). Such information is poorly described and has mostly been obtained from modelling exercises, rather than from empirical measurements (German Ministry of Environment, 2015; OECD, 2016). A common approach is to use generic figures for ENMs production, qualitatively assigning these to products and assigning these products to waste streams according to average figures for waste management at the country level. The results of such exercises are associated with significant uncertainty in part due to the approximations made and the paucity of input data.

30. Sun et al. (2014) modelled the concentrations of selected ENMs (titanium dioxide, silver, zinc oxide, fullerenes and CNTs) in environmental and technical compartments in Europe. Higher concentrations of ENMs were estimated for the technical compartments, which included landfilling, waste incineration, sewage treatment and recycling, than for environmental compartments. The highest concentrations are expected in sewage sludge, followed by concentrations in solid waste and waste incineration ashes (fly and bottom ash).

31. The disposal paths of WCNM are largely influenced by how the impacted waste streams are handled in the local or regional waste management system. For example, it was estimated in Denmark that a large proportion of ENMs in construction waste or waste incinerator slag is recycled into construction work. The percentage recycled was 68% for nano-silver and 2% for CNTs. The situation was estimated to be different for Switzerland, where these materials are landfilled and not recycled (Andersen et al., 2014).

32. Table 2 provides an overview of the predicted fate of WCNM, based on various modelling studies. These studies are concerned with the fate of the end-of-life consumer products (typically disposed of as municipal waste), whereas little information is available regarding manufacturing

wastes containing ENMs. A few studies have also attempted to estimate the quantities of ENMs entering into waste disposal processes (see **Error! Reference source not found.**3 in appendix I).

Table 2 – Predicted disposal paths of WCNM present in municipal waste

WCNM disposal paths*	Context	Source	Notes
Recycling: >50% of all ENMs Incineration: 13-38% of all ENMs Landfill: 8-29% of all ENMs	EU	(Boldrin et al., 2016; Heggelund et al., 2016)	
Recycling: 18% of TiO_2 (titanium dioxide), 11% of ZnO (zinc oxide), 36% of Ag (silver), 20% of CNT (carbon nanotube), 51% of fullerene Incineration: 17% of TiO_2, 3% of ZnO, 9% of Ag, 22% of CNT, 20% of fullerene Landfill: 37% of TiO_2, 19% of ZnO, 16% of Ag, 51% of CNT, 24% of fullerene Sludge: 49% of TiO_2, 53% of ZnO, 22% of Ag, 0.4% of CNT, 5% of fullerene	EU	(Sun et al., 2014)	Landfill, sludge and incineration solid residues likely sinks For individual ENMs, values may add up to >100% because of further routing of by-products from waste treatment (e.g. bottom ash to landfill)
Incineration: 3.5% of all ENMs Landfill: 60-86% of all ENMs Sludge: 19% of all ENMs	Global	(Keller and Lazareva, 2014)	
Incineration: 6% of all ENMs Landfill: 63-91% of all ENMs Sludge: 52% of all ENMs	Global	(Keller et al., 2013)	Incineration/WWTP intermediate steps Recycling not considered
Landfill: main	Global	(Reinhart et al., 2010)	
Recycling: most of Ag, Ti, Zn CNT to landfill/incineration	EU	(Adam and Nowack, 2017)	

* estimations refer to the fate of WCNM in the waste system. E.g., >50% means greater than 50% of the WCNM end up in recycling processes.

V. Disposal of waste containing nanomaterials

33. Understanding the fate of ENMs within waste treatment processes is important for determining where releases of ENMs contained in waste could present possible risks of environmental exposure or constitute an occupational hazard.

34. The fate of ENMs within waste treatment processes is dependent on several factors: the physicochemical properties of the ENMs and the matrix in which they are embedded; the behaviour of the ENMs and the matrix during waste processing and the ability of technologies applied in retaining and destroying ENMs.

35. The following sections explore the state of knowledge regarding the extent to which ENMs contained in waste are retained or eliminated by existing waste management processes as well as the potential for environmental release of ENMs from such processes.

A. Recycling of waste containing nanomaterials

1. Fate and behaviour of ENMs during recycling

36. Recycling operations typically involve different mechanical, physical, and chemical processes, such as sorting, washing, crushing, shredding, pulping, melting, extrusion, drying, refining, and reforming. The release of ENMs from the waste matrix during recycling depends on the processes involved, the hardness of the matrix, the temperature reached during the process and the affinity of ENMs towards the air, solid and liquid phases.

37. In the case of the recycling of plastic waste, processes involving size reduction (e.g. grinding, shredding, cutting) could release ENMs to the ambient air. The extent to which this happens is unclear, as various studies provide dissimilar results. Zhang et al. (2016) reported that grinding of CNT-filled polypropylene generated significant releases of nanoscale and macroscale particles, although no free CNTs were found. Conversely, NRCWE (2017) reported very low emissions of ENMs from shredding of polypropylene containing CNT and organic pigments. While plastic is

exposed to relatively high temperature during extrusion and repellitization, the release through evaporation of most inorganic ENMs is considered rather unlikely (Boldrin et al., 2016). In the case of CNT, Zhang et al.(2016) reported particle emissions slightly higher than background when melting and moulding polypropylene filled with CNT.

38. Glass waste, when recycled, is either reused as an inert aggregate, or re-melted for the production of new glass products. When reused as an inert aggregate, surface abrasion could result in the release of ENMs into the water phase. Given the resistant nature of glass, this mechanism could be expected to be rather slow. Glass re-melting occurs at high temperatures (e.g. 1400-1600 °C), and evaporation of ENMs could occur, with subsequent release through exhaust gases (Boldrin et al., 2016). The boiling/melting point of the individual ENMs and the removal efficiency of the flue gas cleaning system are decisive factors determining the release of ENMs into the environment (Boldrin et al., 2016). Similarly, metal waste may be processed (e.g. re-melted) in high temperature ovens during the recycling of metal waste. The magnitude of the release of ENMs during this process is largely unknown (TNO, 2014).

39. Paper waste recycling is a series of processes, where waste paper is pulped, de-inked and processed to produce new paper. The process generates solid waste (e.g. sludge) and liquid effluents that could carry a variety of contaminants. Both streams need further treatment and water contamination may be an issue. Chemical emissions to air may occur at different sub-processes of the recycling facility, as for example during chemical processing, requiring the use of air-pollution control systems. Based on an assessment by Pivnenko et al. (2015) on a variety of chemicals, the two main factors potentially affecting the release of chemicals during paper recycling are: (i) affinity for the air, aqueous or solid phase; and (ii) biodegradability (i.e. persistency). ENMs that have limited affinity for the air phase may end-up in the recycled paper products or in the solid and liquid wastes. ENMs that are not biodegradable (such as inorganic ENMs) may accumulate at each cycle of paper recycling.

40. Construction and demolition (C&D) waste is recycled and used in many applications, for example as aggregate in sub-base for roads, for backfilling of excavations, and as a filler in asphalt concrete. A significant share of C&D waste is hard materials (i.e. concrete, tiles, mortar), some of which may contain ENMs. During recycling of C&D waste, ENMs may become airborne during the crushing, shredding and milling activities (Boldrin et al., 2015; OECD, 2016). When C&D waste is used as aggregate in e.g. road construction, ENMs may be released into leachate when this is formed in presence of water.

41. Few empirical studies have examined the release of ENMs during recycling processes. Preliminary assessments based on the limited data available point to several possible pathways of occupational exposure to ENMs (Struwe and Schindler, 2012). For instance, fine or ultrafine dust containing free ENMs could be released during transport, sorting, shredding, grinding of WCNM and during thermal processes (heating, welding, pyrolysis) when occupational controls are insufficient. An overview of experimental data on release of ENMs during recycling operations is provided in **Error! Reference source not found.**A4 of appendix I.

42. ENMs that are not released from the waste matrix during recycling may end up in the recycled products or materials. A study which looked at the recycling of specific ENMs in different product categories, based on a probabilistic mass flow modelling of ENMs in recycling processes, concluded that less than 10% of the ENMs contained in WCNM will be cycled back to the production and manufacturing chain (Caballero-Guzman et al., 2015).

43. Destruction of ENMs during recycling is an aspect which has not been well explored. It can be speculated that ENMs can undergo either thermal destruction if exposed to sufficiently high temperatures or chemical destruction if necessary chemical conditions exist in the process. Destruction of organic ENMs could hence be expected in glass/metal smelting which occur at rather high temperatures.

2. Release of ENM from the recycling of WCNM

44. Releases of ENMs to the environment from recycling facilities may occur as a result of thermal processes involving high temperatures such as the smelting of metals and re-melting of glass. The boiling/melting point of the individual ENMs and the removal efficiency of the flue gas cleaning system are decisive factors determining the release of ENMs into the environment (Boldrin et al., 2016). Shredding, milling and size reduction of hard materials (e.g. C&D waste, glass) are likely to be associated with dust formation and subsequent airborne release of ENMs.

3. Effects on recycling processes

45. There is currently little evidence that the presence of ENMs in WCNM can significantly affect recycling processes (Boldrin et al., 2016; UniHB, 2016; Zhang et al., 2016). This may be because recycling processes involve mainly mechanical and thermal treatments rather than complex chemical transformations that could be affected by the presence of ENMs and levels of ENMs in recycled materials are at present relatively low. However, the presence of ENMs may involve restrictions and specific safety procedures if environmental and human exposures are recognized as being critical, thereby requiring changes in the management of recycling facilities (Boldrin et al., 2016).

B. Incineration of waste containing nanomaterials

1. Fate and behaviour of ENMs during incineration

46. During incineration, and once released from the waste matrix, ENMs can be destroyed or can undergo a number of transformation processes which will influence their properties. If the matrix is combustible, ENMs have higher chances of being liberated and be present in the gas phases.

47. The combustion temperature and melting/boiling points of ENMs affect the distribution of ENMs between the solid and gaseous phases and determine whether the ENMs are destroyed due to complete combustion (Mueller et al., 2013). Thus, it can be speculated that CNTs undergo complete combustion, silver could be expected to enter the gas phase, whereas ENMs such as zinc oxide, titanium dioxide, cerium dioxide are likely to end up in the bottom ash (Boldrin et al., 2016). Chemical composition, size and oxidation state of the ENMs are other determinants of the fate of the ENMs during incineration. For example, if temperature is high enough, reduced particles (e.g. aluminium) may undergo combustion to an extent that depends on their size and aggregation state (Holder et al., 2013). Conversely, particles that are already oxidized and have high melting points (e.g. cerium dioxide) may exit the combustion zone essentially unchanged.

48. ENMs that escape destruction during incineration of WCNM may be captured by the flue gas treatment system and end up in the fly ash or other residues (e.g. bottom ash). Inorganic ENMs will mostly end up in bottom ash (Andersen et al., 2014; Baran, 2016; UniHB, 2016; Walser et al., 2012), possibly in some aggregated and more stable form as a result of chemical reactions with other compounds. Non-negligible amounts of ENMs – especially metal ones - can be expected to be found in fly ash and other flue gas cleaning residues.

49. The few studies on the incineration of WCNM indicate that CNTs (and possibly other organic ENMs) are likely to be destroyed during combustion if temperatures are sufficiently high at all times. Complete destruction cannot however be ensured (Health Council of the Netherlands, 2011; Mueller et al., 2013; UniHB, 2016; Vejerano et al., 2014); CNTs that are not destroyed are likely to end up in bottom ash (Andersen et al., 2014; Mueller et al., 2013; Sotiriou et al., 2016).

50. ENMs that are not destroyed can undergo various transformation processes. They may react with other substances to form new particles, as in the case of silver in biosolids which is transformed to silver-sulphur species during incineration (Impellitteri et al., 2013). Larger nanoparticles may decompose into smaller particles while ENMs may agglomerate to form bigger particles thereby losing their nanoform.

51. Because of the complexity of the factors that influence the behaviour of ENMs during incineration and the difficulties in sampling and analysis of WCNM, the fate of ENMs during incineration is not well described (Sotiriou et al., 2016; Wiesner and Plata, 2012). Studied under realistic conditions (i.e. in pilot- or full-scale facilities) have been conducted only for cerium dioxide, titanium dioxide and barium sulphate. An overview of the partitioning of ENMs during these tests is provided in **Error! Reference source not found.**A5 in appendix I. The results of these studies suggest that most of the inorganic ENMs contained in the WCNM end up primarily in the bottom ash (Andersen et al., 2014; Ounoughene et al., 2015; Sotiriou et al., 2016) and that a small, but non-insignificant share of ENMs is routed into fly ash (Andersen et al., 2014; Buha et al., 2014). The results of the few studies undertaken so far cannot be extrapolated to all ENMs and all types of installations, as conditions among them may differ significantly.

2. Release of ENMs from incineration of WCNM

52. The environmental release of ENMs from incineration facilities is in part determined by the efficacy of the air pollution control (APC) system in removing ENMs from the raw flue gas. An overview of the ENMs removal rates in different parts of APC systems typically installed in incineration plants is provided in Table A6 in appendix I. Existing studies do not provide a clear and consistent picture about the efficiency of the APC system in capturing ENMs: some studies indicate

that electrostatic precipitators and wet scrubbers could effectively remove most ENMs from the flue gas, as in the case of CeO_2 (Walser et al., 2012), whereas other studies conclude that up to 20% of the ENMs could pass through these systems, in which case additional solutions are needed (Andersen et al., 2014; Roes et al., 2012). The transformation of ENMs and their interaction with other substances in the flue gas are additional factors that affect the removal efficiency in the APC system (Holder et al., 2013).

53. The formation of fine and ultrafine particles is a well-known phenomenon occurring as a result of the high temperature combustion processes. Experimental data indicate that the addition of nano-enabled products to the waste feedstock does not significantly increase the emissions of ultrafine particles from the stack (Quicker and Baran, 2016), unless the amount of ENMs in the feedstock is significantly higher than the typical range that would be expected in waste (Baran, 2016).

54. According to OECD (2016), the use of state-of-the-art technology in the APC system of incineration facilities can capture a significant proportion of ENMs released from WCNM during incineration. “State-of-the-art technology” is understood in the context of “Best available techniques (BAT)”, defined as “the most effective and advanced stage in the development of activities and their methods of operation which indicates the practical suitability of particular techniques for providing the basis for emission limit values and other permit conditions designed to prevent and, where that is not practicable, to reduce emissions and the impact on the environment as a whole” (Gleis, 2012). The list of technologies defined as BAT changes over time with innovation and technological development. If BAT are applied, the environmental release of ENMs in the clean flue gas could be expected to be minimal (Mueller et al., 2013; Quicker and Baran, 2016; Roes et al., 2012; Walser et al., 2012). However, attention should be placed on medium scale plants (below 1 mega watt), where efficient flue gas cleaning systems may not be installed (Foppiano et al., 2018).

3. Management of residues from incineration

55. When ENMs are not completely combusted, they will likely end up in incineration slag (i.e. bottom ash) or the solid/liquid residues from the APC system. Ashes from incineration plants can either be deposited by special waste management (i.e., contained in big bags in indoor storage facilities) (Flyvbjerg and Hjelmar, 1997), landfilled (Hjelmar, O. & van der Sloot, 2010) or recycled in construction work (e.g. road sub-base) (Danish Ministry of the Environment, 2010). When recycled, bottom ash is often mechanically processed to recover metal fractions and/or to achieve desired material properties (e.g. grain size) which can result in environmental releases of ENMs. If bottom ash is sent for final disposal in landfills, release of ENMs to landfill leachate could occur (Reihlen and Jepsen, 2015); the extent to which this happens is poorly studied.

56. Liquid effluents from incineration plants (e.g., from scrubbers) are often sent to wastewater treatment plants (WWTPs) which may result in the presence of ENMs in output sludge and further environmental dispersal if such sludge is not properly managed (see section V.D. below).

4. Effect of ENMs on the incineration process

57. A few studies have looked at the consequences of the presence of ENMs on incineration processes (Baran, 2016; UniHB, 2016; Ounoughene et al., 2015). Although municipal solid waste typically has a heterogeneous composition, carrying a variety of compounds and chemicals, modern incineration facilities can be managed to run under steady conditions. Considering the current state of knowledge and the fact that ENMs are generally present in trace concentrations in municipal waste, it is unlikely that the presence of ENMs could have any effect on combustion processes. However, ENMs can potentially affect the production and/or destruction of hazardous pollutants during combustion (Andersen et al., 2014; Boldrin et al., 2016). An example is the de-novo formation of PCDD/F, which is catalysed by copper and zinc.

C. Landfilling of waste containing nanomaterials

1. Fate and behaviour of ENMs during landfilling

58. During landfilling, ENMs released from the waste matrix can enter landfill leachate, which forms when water infiltrates in landfills and passes through the waste. Leachate is loaded with different organic and inorganic compounds and tends to deposit at the bottom of the landfill. Factors influencing the release of ENMs include the location of the ENMs in the nano-enabled product, the degradability of the matrix and landfill conditions. (Reinhart et al., 2010). ENMs present on the surface of waste, such as nano-enabled textile waste, are in direct contact with the surroundings and more likely to be released (Heggelund, 2017) as are ENMs in liquid suspensions.

59. ENMs released from the waste matrix can also end up in landfill gas. Given the slow nature of the degradation processes occurring in a landfill and the relatively low prevailing temperature, it is considered unlikely that significant amounts of ENMs could be carried by the landfill gas. However this is an aspect that has been poorly studied.

60. Destruction of ENMs in WCNM disposed in landfills is not likely to occur, at least within short timeframes. ENMs could undergo a change in structure and/or bind to other substances present in landfill leachate, which would change their properties and mobility in landfill leachate. These processes are influenced by landfill conditions such as pH and the presence of other substances. For example, typical landfill conditions – where organic matter and divalent cations are present – could enhance agglomeration and reduce the mobility of ENMs in leachate (Andersen et al., 2014). Adsorption or complexation of ENMs with the natural organic matter was suggested to occur to a significant extent for titanium and silver in aerobic landfilling (Yazici Guvenc et al., 2017).

2. Release of ENMs from landfilling of WCNM

61. In engineered landfills, liners are placed at the bottom and on the side of the landfill to prevent the flow of leachate out of the landfill. The efficacy of liners to contain ENMs present in leachate has not been widely investigated. Two studies (Siddique, 2013; Zuin et al., 2013) suggest that advanced membrane liners may be capable of limiting the dispersion ENMs. While more studies involving a wide variety of ENMs, nano-enabled products as well as types of liners are needed, it should be also be kept in mind that liners typically last no longer than 50 years (Christensen et al., 2010), meaning that a risk of ENMs release may exist in the long-term. In the absence of a landfill liner and a leachate collection system, ENMs contained in landfill leachate may contaminate the surrounding environment.

3. Treatment of landfill leachate and risk of exposure

62. In the case of engineered landfills, leachate is collected treated before discharge to the environment. The impact of leachate treatment technologies on ENMs has not been well studied except in the case when leachate undergoes biological processing in WWTP. The outputs of leachate treatment in WWTP are sludge and "clean" waste water. The way in which these outputs are further managed will influence environmental releases of ENMs, as for example, when water from WWTP is discharged into surface waters or sprayed on soil surfaces (Danish Ministry of the Environment, 2007) and sludge is applied on land (see section V.D. below).

4. Effect of ENMs on the landfilling process

63. Some ENMs may have an inhibitory effect on the degradation processes occurring in landfills (Boldrin et al., 2016), as in the case of nanosilver, which is one of the most common ENMs in WCNM and has biocidal properties. The few experimental results available (see Table A7 in appendix I) suggest that the presence of ENMs in waste does not induce significant inhibitory effects on degradation processes in landfills. This may be due to the low concentration of ENMs as a result of dispersion processes (Bolyard et al., 2013), or to the occurrence of adsorption and complexation of ENMs with natural organic matter (Yazici Guvenc et al., 2017). These results do not exclude that higher concentrations of ENMs could have an inhibitory effect.

D. Biological treatment of waste containing nanomaterials

64. Composting and anaerobic digestion are the most commonly used biological processes for treatment of solid organic waste originating from industries and municipal/urban activities. Among urban organic waste streams, the important ones are household organic waste, garden/park waste, and sludge from WWTPs. Significant levels of ENMs are not expected in household organic waste (Adam and Nowack, 2017; L. Heggelund et al., 2016) but may occur in sewage sludge (see Table A3 in appendix I).

1. Fate and behaviour of ENMs during biological treatment

65. No studies have specifically investigated the partitioning of ENMs in biological processes for solid waste. During both composting (Boldrin et al., 2010) and anaerobic digestion (Møller et al., 2010), inorganic elements are conserved through the process and appear in the final outputs. This is likely to be the case for inorganic ENMs (e.g., titanium dioxide, silver, iron oxide) or those that show a low biological degradability (e.g. CNT) within the short timeframe of biological waste treatment processes (Nguyen, 2013; Kaegi et al., 2011; Lombi et al., 2013, 2012; Ma et al., 2014). Release of ENMs into liquid media can be expected to be low, considering the levels reported for many other compounds (Boldrin et al., 2010; Møller et al., 2010) and the results of studies on this topic (see Table AA8 in appendix I)**Error! Reference source not found.**.

66. Inorganic elements are not destroyed during biological waste treatment processes but are likely to undergo transformation processes such as complexation and aggregation with other compounds. For example, silver and zinc oxide are transformed during biological treatment into different and more stable forms (see Table A9 in appendix I).

2. Release of ENMs from biological treatment of WCNM

67. Given that the release of ENMs is expected to be limited during biological treatment processes, the solid outputs (i.e., compost, digestate) of these processes could become a source of emission of ENMs if they are applied to soil. The characteristics of ENMs (e.g., shape, size, surface charge) and soil (e.g., organic matter, pH, ionic strength) influence the behaviour (e.g., dissolution, agglomeration, and aggregation) and hence their mobility and bioavailability to soil organisms (Rajput et al., 2018). High concentrations of ENMs have been found to have negative impacts on ecosystems (Rajput et al., 2018, 2017; Sillen et al., 2015; Tourinho et al., 2012; WANG et al., 2017). In some cases, the presence of nanoparticles had positive effects on specific soil properties, for example, the use of iron oxide was reported to enhance the availability of nutrients in saline sodic soils (Ghodsi et al., 2015).

3. Effect of ENMs on biological treatment processes

68. The presence of ENMs can have beneficial or detrimental effects on anaerobic digestion of different organic substrates. The effect and its magnitude are influenced by the type of ENM and its concentration in sludge (see Table A10 in appendix I). In several studies, ENM concentrations associated with reported effects on the functioning of biological treatment processes were significantly higher than those that can be expected in WCNMs entering these processes.

E. Other waste treatment technologies that may potentially be applied to dispose of waste containing nanomaterials

69. Various technologies for the recovery of ENMs from waste are under development (some examples are provided in **Error! Reference source not found.**11 in appendix I) and are mainly based on technologies established within the metallurgic industry. The majority these of are still being tested at laboratory scale and not applicable at industrial scale. They may be more suited for the treatment of manufacturing waste rather than end-of-life nano-enabled products because of the diversity and complexity of the latter (Myakonkaya et al., 2010).

VI. Summary of issues related to waste containing nanomaterials

A. Hazardousness of engineered nanomaterials and waste containing nanomaterials

70. The unique properties of ENMs that explain their use in a wide range of novel applications may also lead to adverse effects that are different those of their bulk forms. Although a large body of scientific research addressing the health and environmental effects of ENMs has been undertaken over the past few decades, it has been difficult to integrate the body of data and draw coherent conclusions due to the wide heterogeneity of ENMs studied and a number of methodological limitations. Some ENMs have been more thoroughly studied than others and assessments of a limited number of ENMs have been undertaken by regulatory or technical advisory bodies in some countries. Significant uncertainty remains as to the effects of ENMs on human health and the environment.

71. The classification of wastes as hazardous is often based on legislation governing chemicals (for example, the Regulation on the classification, labelling and packaging in the European Union) or the hazardous characteristics of the waste constituents (such as the characteristics listed in Annex III to the Basel Convention). Efforts to find appropriate ways to address the potential risk posed by nanomaterials within regulatory frameworks governing the production and use of chemicals are ongoing in a number of countries and regions. There is regulatory uncertainty as to whether nanoforms of chemicals fall within the scope of existing regulations pertaining to their bulk forms. Additionally, whether existing regulatory and risk assessment frameworks, which were developed based on the properties and behavior of bulk chemicals, can adequately address the potential risks posed by nanoforms of such chemicals, is a subject of debate (Milieu Ltd. and AMEC Environment & Infrastructure UK Ltd.2011; German Environment Agency, 2016). Given the uncertainty regarding the adverse effects of ENMs and their categorization, WCNM may not yet be considered as hazardous under the domestic legislation of many countries.

72. Classification of wastes as hazardous triggers specific requirements for their handling and management, including under the Basel Convention. The prevailing scientific and regulatory uncertainty regarding the hazardousness of WCNM currently limits the scope for preventative action.

In light of this situation and the predicted rise in the production and use of ENMs which could result in increased environmental emissions at various stages of the life-cycle of ENMs, it has been proposed that policies and measures for the regulation of ENMs and WCNMs should be based on the precautionary principle (Health Council of Netherlands. 2011; German Ministry of the Environment, 2015; CIEL, 2016).

B. Quantification of waste containing nanomaterials and their flows

73. Having a clear picture of the types of waste and the quantities entering the waste management system is a foundation for environmentally sound management. In the case of WCNM, precise information about the amount of WCNM entering the waste management system or accurate estimates thereof are generally lacking.

74. The information needed to estimate these amounts and the flows of WCNM to different waste management processes using modelling approaches is difficult to obtain. In the case of end-of-life nano-enabled products, the information gaps pertain to the production volume of the ENMs and the identity and content of ENMs in products. Measures to increase transparent communication of the content of ENMs in products would facilitate the characterization of WCNM, exposure and risk assessment, the development of separate sorting and collection schemes for end-of-life products containing ENMs and their safe disposal according to specific procedures.

75. The lack of mandatory requirements to report on use of ENMs for most applications is a limitation to any effort to obtain precise information on the presence of ENMs in consumer products. Several countries have established registration systems for ENMs being placed on the market but the resulting registries have yet to be sufficiently comprehensive and transparent to yield the information necessary to estimate the volumes of WCNM generated and their flows. Labelling is another approach that has been recommended for increasing transparency about the presence of ENMs within the product supply and use chains (SAICM, 2012; Hansen et al., 2016).

76. While empirical data from sampling and analysis of WCNM could provide information on their content of ENMs and help validate modelling approaches that have been applied to estimate the flows of WCNM within the waste management system, techniques for such measurements are not yet mature and standardized. There is a pressing need for the further development of methods and capabilities for analyzing ENMs in complex media, including WCNM.

C. Disposal of waste containing nanomaterials

77. A first step towards understanding how WCNM need to be managed to ensure ESM is to assess whether their disposal in existing waste treatment processes is adequate for reducing environmental emissions of ENMs to levels that protect human health and the environment from potential adverse effects. Available studies addressing the fate of ENMs in waste treatment processes provide a fragmented and incomplete picture. Some types of ENMs (e.g., silver, titanium oxide, zinc oxide, cerium oxide, CNTs) have been more extensively studied, whereas information is missing for many others. Only a limited number of studies have been undertaken under realistic conditions or in full-scale facilities and findings about the fate and behavior of a given type of ENM cannot be generalized. Information on the presence of ENMs in various outputs and releases from waste treatment processes is not accurate and exhaustive enough to allow reliable predictions about the environmental compartment where ENMs could accumulate, nor the levels at which they would be found. Considering the large diversity of ENMs present in waste, uncertainties about the composition of waste and variations in conditions encountered in waste treatment facilities, it is not as yet possible to draw a definitive conclusion as to whether existing waste treatment processes are capable of preventing potential harm from ENMs contained in WCNM.

78. Recycling of WCNM comprises a variety of processes, which are typically specific for the waste material being handled. Releases of ENMs to the environment and risk of occupational exposure may arise from shredding, milling and size reduction of hard materials and inefficient flue gas cleaning systems applied to recycling processes involving high temperature. ENMs that are not released during recycling may contaminate secondary materials and end up in products made from such materials. The distribution of ENMs in recycling processes and the factors affecting such partitioning for different materials should be further investigated. Information on releases of ENMs as airborne particles during recycling processes is needed for assessing exposure and associated risks.

79. During incineration of WCNM, ENMs that are not destroyed will be released as airborne emissions or accumulate in residues including fly ash and bottom ash. A limited number of studies suggest that that most of the inorganic ENMs contained in the WCNM primarily end up in the bottom ash and that a small, but non-insignificant share of ENMs is routed to fly ash. The extent of release of ENMs to air depends on the efficiency of air pollution control systems. Early findings suggest that, in

modern incineration facilities where state-of-the air pollution control systems are installed, direct release of ENMs into the environment from WCNM incineration is limited. Further studies are needed, covering a larger range of waste materials and ENMs, conducted at full-scale facilities or in realistic process conditions. Attention should be devoted to the further treatment of solid residues from incineration, where ENMs contained in WCNM are likely to accumulate.

80. Landfilling is the main route of disposal for WCNM in many countries. It is not only the means of disposal for end-of-life products containing ENMs but also the final sink for residues from other waste treatment processes such as ashes from incineration plants and sludge from WWTPs. Based on currently available information, it cannot be concluded that landfilling is a safe option for disposal of WCNM. ENMs from WCNM that are disposed in landfills can be released into landfill leachate or gas. Release of ENMs may be more relevant in the case of ENMs suspended in liquids than those embedded in solid matrices. It is not yet clear whether landfill liners that are used in engineered landfills are effective in preventing contamination of the surrounding environment by ENMs present in leachate. Moreover, in many countries waste is disposed in uncontrolled landfills that are not lined. When landfill leachates are treated in WWTPs, the resulting water and sludge may still contain ENMs and pose a risk of environmental exposure if applied to land. Areas that require further investigation include the release of ENMs from waste to leachate and gas during landfilling, using a variety of test methods, and the efficacy of landfill liners in preventing environmental dispersion of ENMs, including in the long-term.

81. Sewage sludge may contain significant amounts of ENMs and is typically subject to biological treatment in WWTPs. While most ENMs are likely to undergo transformation during such treatment, significant shares of ENMs are likely to end up in compost or digestate which should be safely managed. The fate and effects of ENMs released to soil as a consequence of agricultural application of sludge, digestate and composts should be further investigated either through modelling and possibly full-scale investigations.

82. The application of BAT currently appears to be effective in minimizing environmental releases of and associated risks related to ENMs contained in waste. They are therefore important for preventing workplace exposure to ENMs (e.g., personal protective equipment) and the containment of ENMs within waste disposal processes (e.g., filters, liners). It is not clear how efficient sub-standard installations are in protecting workers and preventing environmental releases. In terms of having sufficient capacity to manage WCNM in an environmentally sound manner, it is noteworthy that waste disposal facilities that apply BAT are not widely available in all countries.

83. The impact of ENMs contained in waste on the efficacy of waste treatment processes has also been invoked as a source of concern. While some ENMs with biocidal properties have been reported to interfere with biological processes taking place in landfills and WWTPs, severe effects would currently not be expected of the low concentrations of ENMs that can be expected in WCNM. This situation may change in the future and need to be further investigated.

VII. Existing activities that address waste containing nanomaterials

84. Although the importance of addressing potential risks posed by ENMs during the waste disposal stage of the life-cycle of ENMs and products containing ENMs has been widely recognized, relatively few activities have so far been undertaken in that direction. The table in appendix II provides an overview of some existing activities that address WCNM. These belong to two main categories:

(a) Activities and studies aimed at understanding and addressing potential risks associated with WCNM;

(b) Activities aimed at understanding and addressing potential risks associated with nanomaterials throughout the whole life-cycle, with some attention paid to the end-of-life stage. Issues related to WCNM are generally not addressed in detail due to the broad scope of these studies.

85. Information on existing activities that address waste containing nanomaterials and issues related to such wastes that was provided to the Secretariat by Parties and others is available on the website of the Basel Convention.[2]

[2] http://www.basel.int/?tabid=7621.

VIII. Options for further work under the Basel Convention related to waste containing nanomaterials

86. Taking into account the issues summarized in section VI above and the activities undertaken in other fora and at the national level as described in section VII above, options for further work that may be carried out under the Basel Convention related to WCNM, within the scope of the Convention, are set out below, for consideration by the Open-ended Working Group.

A. Classification of WCNM

(a) Consider whether WCNM fall under the scope of the Basel Convention. For example, a number of metals and metal compounds listed in Annex I to the Convention or as constituents of wastes listed in Annex VIII to the Convention could exist in the bulk and in the nanoform;

(b) Consider whether WCNM or wastes containing specific ENMs should be brought within the scope of the Basel Convention. This could be achieved by the placement of new categories of waste in Annex I, II or VIII to the Convention. Despite the uncertainty surrounding the health and environmental effects of ENMs in general, significant amounts of information exist about the hazards of some ENMs such as CNTs;

(c) Consider how the activities mentioned in paragraphs (a) and (b) should be undertaken. A group of experts with the relevant expertise could be established for that purpose or the mandate could be added to that of the Expert Working Group on the Review of Annexes.

B. Information needed to develop strategies for the ESM of WCNM

(a) Encourage Parties and others to undertake further research and develop other measures as appropriate to generate the information needed to better understand the potential risks posed by WCNM and, if necessary, facilitate the development of strategies for the ESM of WCNM;

(b) Encourage Parties to develop strategies for the ESM of WCNM that systematically anticipate, identify and prioritize issues that need to be addressed by compiling baseline information on a variety of waste-related aspects including:

(i) Types and quantities of wastes generated;

(ii) Potential for waste prevention and minimization;

(iii) Actual or potential risks posed to human health, worker safety and the environment;

(iv) Available infrastructure and capacity to manage wastes;

(c) Consider whether it would be necessary to provide guidance to Parties and others on the aspects on which to focus efforts for generating information and on measures that could be implemented to obtain such information. A significant obstacle to decision-making on the issue of WCNM is not only a paucity of information but also the fragmented nature of the body of knowledge which makes it difficult to reach conclusions on the bigger picture;

(d) Consider the means for the development of the guidance mentioned in (c), if deemed necessary. A working group could be established for that purpose or the activity could be added to the mandate of an existing group such as the Expert Working Group on Environmentally Sound Management.

C. Minimizing exposure to ENMs during the handling and disposal of WCNM

(a) Provide guidance to Parties and others on approaches and tools that can be applied to identify potential sources of exposure to ENMs during the handling and disposal of WCNM and measures that can be applied to minimize such exposure. In the absence of conclusive evidence about the hazardousness of specific ENMs, general measures to minimize exposure to ENMs in the course of handling and disposal of WCNM could provide protection from as yet undefined adverse effects of ENMs. Such tools and measures may be more suited to situations where worker exposure to high levels of ENMs is likely and the ENM content of waste is known such as in facilities that handle wastes from the manufacture and processing of ENMs.

D. Awareness raising and information exchange about WCNM and related issues

(a) Develop activities aimed at raising awareness and promoting information exchange, at the national and international levels, about issues related to WCNM and their management. While there is increasing awareness about the potential risks associated with nanotechnology, the attention paid to this issue has focused more on the production and use stages than on the waste stage of the life-cycle of ENMs. Enhancing awareness about issues related to WCNM can stimulate dialogue among stakeholders about the potential risks arising from the disposal of WCNM and increase opportunities for the development of policies and technologies to address such risks;

(b) Invite Parties and others to make available to the Secretariat information related to activities aimed at addressing the issues related to WCNM, including case studies and best practices about the management of WCNM, and request the Secretariat to disseminate this information;

(c) Request the Secretariat to raise awareness and promote information exchange about issues related to WCNM by including relevant activities in its technical assistance programme and through its work to enhance cooperation and coordination within the chemicals and wastes cluster and with other international bodies.

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Appendix I

(ENMs may be referred to by their chemical formulas and abbreviations. Full names may be obtained by consulting resources such as the ChemSpider database (http://www.chemspider.com/Default.aspxhttps://iupac.org/what-we-do/periodic-table-of-elements/))

Table A1 – Types of ENMs produced or imported in quantities larger than 100 ton in France in 2017 (from MEEM, 2017)

Nanomaterial	Amount [ton]
Carbon black	>10'000
Silicon dioxide	>10'000
Calcium carbonate	>10'000
Titanium dioxide	>10'000
Boehmite (AL(OH)O)	~10'000
Silicic acid, magnesium salt	1'000-10'000
Vinylidene chloride copolymers	1'000-10'000
Polyvinyl chloride	1'000-10'000
Aluminium oxide	1'000-10'000
Calcium 4-[(5-chloro-4-methyl-2-sulphonatophenyl)azo]-3-hydroxy-2-naphthoate	1'000-10'000
Mixture of cerium dioxide and zirconium dioxide	1'000-10'000
Iron oxide isostearate	100-1'000
Food texturizer	100-1'000
Food acidifier	100-1'000
Cerium dioxide	100-1'000
Iron hydroxide oxide	100-1'000
Di-iron trioxide	100-1'000
Food preservatives	100-1'000
Amino acids	100-1'000
3,6-bis-biphenyl-4-yl-2,5-dihydropyrrolo[3,4-c]pyrrole-1,4-dione	100-1'000
Salicylic acid, Sodium aluminosilicate	100-1'000
Iron and cerium oxide isostearate	100-1'000
Food aromas	100-1'000
Salicylic acid, Aluminium magnesium sodium silicate	100-1'000
29H,31H-phthalocyaninato(2-)-N29,N30,N31,N32 copper	100-1'000
Aluminium hydroxide	100-1'000
3-hydroxy-N-8o-tolyl)-4-[(2,4,5-trichlorophenyl)azo]naphtalene-2-carboxamide	100-1'000
3,6-Bis(4-tert-butylphenil)-2,5-dihydropyrrolo[3,4-c]pyrrole-1,4-dione	100-1'000
4,4'-diamino[1,1'-bianthracene]-9,9',10,10'-tetraone	100-1'000
2-Propenoic acid, 2-methyl-methyl ester, polymer with 1,3-butadiene, butyl 2-propeonate and ethenylbenzene	100-1'000
2,2'-[(3,3'-dichloro[1,1'-biphenyl]-4,4'-diyl)bis(azo)]bis[N-(2,4-dimethylphenyl)-3-oxobutyramide]	100-1'000

Table A2 – Examples of WCNM generation rate during the manufacturing of ENMs and nano-enabled products

ENM type	Product manufactured	Process	WCNM type	WCNM generation	Notes	Source
Al2O3	Dielectric films	Atomic layer deposition (ALD) process	Trimethyl Aluminium [Al2(CH3)6]	0.98 g/gproduct	Disposal unknown	(Yuan and Dornfeld, 2008)
Ag	Polyester textile	Synthesis	Ag	5% of input	95% internally recycled	(TNO, 2014)
		Extrusion		negligible		(TNO, 2014)
		Tailoring		Few %		(TNO, 2014)
	Ag-ENM	Synthesis	Ag+ in H2O solution	0.43 g/gproduct	Probably discharged as wastewater	(Tolaymat et al., 2010)
Au	Au-ENM	Purification	Thiol solvent	15 L/gproduct	Disposal unknown	(Dahl et al., 2007)
CNT	CNT-ENM	Vapour grown	Carbon soot	2-9 g/gproduct	Disposal unknown	(Khanna et al., 2007)
	CNT-ENM	Various synthesis	Carbon soot	2-33 g/gproduct	Disposal unknown	(Zhang et al., 2011)
	CNT-ENM	Synthesis	Carbon soot	9 g/gproduct	Disposal unknown	(Seager et al., 2008)
	CNT-ENM	Arc ablation (ARC) synthesis	Carbon soot	21.2 g/gproduct	Disposal unknown	(Isaacs et al., 2009)
	CNT-ENM	Chemical vapour deposition (CVD) synthesis	Carbon soot	31.9 g/gproduct	Disposal unknown	(Isaacs et al., 2009)
	CNT-ENM	High pressure carbon monoxide (HiPco) synthesis	Carbon soot	1250 g/gproduct	Disposal unknown	(Isaacs et al., 2009)
	PTFE membrane	Purification after ARC synthesis	PTFE scrap membrane	11.91 g/gproduct	Disposal unknown	(Healy et al., 2008)
	PTFE membrane	Purification after CVD synthesis	PTFE scrap membrane	6.17 g/gproduct	Disposal unknown	(Healy et al., 2008)
	PTFE membrane	Purification after HiPco synthesis	PTFE scrap membrane	5.73 g/gproduct	Disposal unknown	(Healy et al., 2008)
Fullerene	Fullerene-ENM		Carbon soot	0.9 g/gproduct	Sent to landfill	(Royal Commission on Enviromental Pollution, 2008)
	Fullerene-ENM	Pyrolysis, plasma RF/Arc	Carbon soot	7.22–25.6 g/gproduct	Disposal unknown	(Anctil et al., 2011)
TiO2	TiO2-ENM	Altair(nano) hydrochloride process	Mix of ilmenite, iron powder, HCl	1.33 g/gproduct	Disposal unknown	(Grubb and Bakshi, 2011)

Table A3 – Examples of quantitative estimates of flows of ENMs to waste disposal processes (n.s.= not specified)

ENMs	Context	Amount (ton/year) Recycling	Incineration	Landfill	WWTP	Notes	Source
All	Global, 2010	-	n.s.	203900	n.s.	Recycling not considered	(Keller et al., 2013)
ZnO	Global, 2010	-	3400	21100	11700	Recycling not considered. Landfill receives some ENMs from incineration and WWTP	(Keller et al., 2013)
CNT		-	200	2700	200		
TiO2		-	8700	32600	47700		
SiO2		-	1200	7000	81200		
Al2O3		-	1400	23600	8300		
Fe		-	3000	25700	13500		
Clay		-	900	8400	1500		
CeO2		-	300	8200	1100		
Ag		-	61	200	200		
Cu		-	7	150	37		
All	Global, 2010	-	8600	189200	47300	Recycling not considered. Landfills receive ENMs from incineration and WWTP	(Keller and Lazareva, 2013)
Ag	EU 28 + NO + CH, 2015	12	4.0	3.5	-	WWTP not considered	(Adam and Nowack, 2017)

Table A4 – Examples of empirical studies on the release of ENMs during recycling operations

Material	ENM type	Process	Findings	Source
Polypropylene	Organic pigment, 0.2% wt	Cutting Shredding, pilot scale	• Low levels of airborne release of ENMs • Cutting: <0.22 µg/min • Shredding: 0.41 µg/min • Insignificant exposure level	(NRCWE, 2017)
Polypropylene	CNT, 2.5% wt	Cutting Shredding, pilot scale	• Low levels of airborne release of ENMs • Cutting: <0.22 µg/min • Shredding: <0.26 µg/min • Insignificant exposure level	(NRCWE, 2017)
Concrete bricks	TiO_2	Shredding, pilot scale	• Low levels of airborne release of ENMs, no concern of exposure	(NRCWE, 2017)
Coated tiles	TiO_2	Shredding, pilot scale	• Low levels of airborne release of ENMs, no concern of exposure	(NRCWE, 2017)
Concrete bricks	TiO_2	Milling, lab	• Airborne release of ENMs: 5-16% of input	(Boldrin et al., 2015)
Coated tiles	TiO_2	Milling, lab	• Airborne release of ENMs: 5-16% of input	(Boldrin et al., 2015)
Coated glass	ZnO	Milling, lab	• Airborne release of ENMs: 7-47% of input	(Boldrin et al., 2015)
Polypropylene	Organic pigment, 0.2% wt	Injection moulding, industry	• Airborne release of particles: 1.4×10^{-3} cm^2/g, i.e. 1/100 of NOEL for biopersistent materials	(NRCWE, 2017)

Material	ENM type	Process	Findings	Source
Polypropylene	Montmorillonite nanoclay, 5% wt	Shredding, pilot scale	• Airborne release of particles: 4280 particles/cm^3, or 8.5 µm^2/cm^3, but no nanoclay ENM liberated. Presence of nanoclay has no additional risk	(Raynor et al., 2012)

Table A5 – ENMs partitioning during incineration in full-scale facilities (n.s.= not-specified).

ENM	Experiment scale	Dosage	Mass partition (%)				Mass recovery (%)	Ref.
			Bottom ash	Fly ash	Quench water	Clean flue gas		
CeO	Full	Sprayed on waste	~81	~19	0.02	0.0001	~100	[1]
	Full	Injected into furnace	~53	~45	1.7	0.0004	~100	[1]
	Full	Not specified		10.6	68.7	0.1	~79	[2]
	Lab	Spiked waste, 10%	82	n.s.	n.s.	0.0023	~82	[3]
TiO_2	Full	Not specified	89.9	10.7	n.s.	n.s.	~100	[2]
	Lab	Spiked waste, 0.1%	5.8	n.s.	n.s.	0.19	~6	[3]
	Lab	Spiked waste, 1%	11	n.s.	n.s.	0.0044	~11	[3]
	Lab	Spiked waste, 10%	75	n.s.	n.s.	0.0035	~75	[3]
	Lab	Paint, 6%	~100	<0.001% in raw flue gas			~100	[4]
$BaSO_4$	Full	Suspension on waste	59.1	5.8	n.s.	3.2	~68	[2]
Ag	Lab	Spiked waste, 0.1%	26	n.s.	n.s.	2.1	~28	[3]
	Lab	Spiked waste, 1%	24	n.s.	n.s.	0.13	~24	[3]
	Lab	Spiked waste, 10%	29	n.s.	n.s.	0.044	~29	[3]
NiO	Lab	Spiked waste, 0.1%	62	n.s.	n.s.	2.4	~64	[3]
	Lab	Spiked waste, 1%	77	n.s.	n.s.	n.s.	~77	[3]
	Lab	Spiked waste, 10%	110	n.s.	n.s.	n.s.	~110	[3]
Fe_2O_3	Lab	Spiked waste, 0.1%	32	n.s.	n.s.	n.s.	~32	[3]
	Lab	Spiked waste, 1%	67	n.s.	n.s.	n.s.	~67	[3]
	Lab	Spiked waste, 10%	100	n.s.	n.s.	n.s.	~100	[3]
	Lab	Polyethylene, 4%	~100	0.025% in raw flue gas			~100	[5]
CNT	Lab	Polyurethane, 0.09%	0	n.s.	n.s.	0	~100	[5]
Carbon black	Lab	Polyurethane, 0.09%	0	n.s.	n.s.	0	~100	[5]
Org. pigment	Lab	Polyethylene, 2%	0	n.s.	n.s.	0	~100	[5]

[1] (Walser et al., 2012); [2] (Baran, 2016); [3] (Vejerano et al., 2014); [4] (Massari et al., 2014); [5] (Sotiriou et al., 2016)

Table A6 - Removal rates of ENMs in different parts of the air pollution control (APC) system of incineration plants

APC technology	ENMs type	ENMs size	Efficiency	Reference
Fabric filter	Generic	<100 nm	<80 %	(Roes et al., 2012)
	TiO_2	<100 nm	99.99%	(Baran, 2016)
	$BaSO_4$	<100 nm	99.9%	(Baran, 2016)
	Generic	>100 nm	~99-100%	Roes et al. (2012)
Wet scrubber	CeO_2	80 nm	99.9%	Walser et al. (2012)
	Generic	<50 nm	50%	(Bologa et al., 2009)
	Generic	<100 nm	65%	Bologa et al. 2009)
	Generic	<100 nm	80%	(Zeuthen et al., 2007)
ESP	CeO_2	80 nm	99.995%	Walser et al. (2012)
	CeO_2	<100 nm	99.99%	(Baran, 2016)
Two-stage ESP	Generic	<100 nm	65-95%	(Huang and Chen, 2002)

APC technology	ENMs type	ENMs size	Efficiency	Reference
Single-stage ESP	Generic	<100 nm	90-100%	(Huang and Chen, 2002)

Table A7 – Effects of ENMs on landfilling processes

Material	ENM type	Process	Conclusion	Source
Municipal solid waste (MSW) leachate	ZnO, TiO_2	Aerobic/anaerobic	No inhibition	(Bolyard et al., 2013)
MSW (of which 62% organic)	Ag, TiO_2	Pilot-scale, aerobic, 250 days	No inhibition	(Yazici Guvenc et al., 2017)
MSW	Ag	Lab-scale, anaerobic, 250 days	1 mg/kg: no inhibition 10 mg/kg: inhibition	(Yang et al., 2012b)
MSW (of which 52% organic)	ZnO	Lab-scale, anaerobic (conventional + bioreactor), 300 days	100 mg/kg: 15% lower biogas production	(Temizel et al., 2017)

Table A8 – Release of ENMs into liquid media during aerobic processing (composting) of WCNM.

ENM type	ENM size [nm]	Concentration of ENMs	Feedstock type	Process	Temp. [°C]	Incubation time [day]	Amount of ENM in leachate	Source
PVP coated AgNPs	12.3	2 mg/kg ww	Food waste	Rotating drum, continuous aeration	50	60	Not significant	(Gitipour et al., 2013)
Ag-TiO_2	8	Ag: 5-50 mg/kg OM Ti: 5-50 mg/kg OM	Grass, leaves, wheat straw, sawdust, food	In-vessel, continuous aeration	38	21	1.2-14% of initial	(Stamou and Antizar-Ladislao, 2016)
Ag	15	5-50 mg/kg OM	Grass, leaves, wheat straw, sawdust, food	In-vessel, continuous aeration	38	21	1.4-4.4% of initial	(Stamou and Antizar-Ladislao, 2016)

Table A9 –Transformation processes undergone by ENMs during biological treatment of WCNM

ENM type	Feedstock type	Process	Transformation of ENMs	Source
Ag	Sludge	Anaerobic digestion	Stabilization into Ag_2S	(Lombi et al., 2013)
	Sludge	Anaerobic digestion	Stabilization into Ag_2S	(Ma et al., 2014)
	Sludge	Composting	Ag_2S remains stable	(Lombi et al., 2013)
	Sludge	Composting	Ag_2S remains stable	(Ma et al., 2014)
	Sludge	Anoxic aging	Stabilization into Ag_2S	(Impellitteri et al., 2013)
	Sludge	Short aerobic incub.	Stabilization into Ag_2S	(Kaegi et al., 2011)
	Food waste	Composting	Ag remains in metallic form in low Cl conc., possibly transformed to $AgCl_2$ in high Cl conc.	(Gitipour et al., 2013)
Zn	Sludge	Anaerobic digestion	Complexation with phosphate	(Lombi et al., 2012)

ENM type	Feedstock type	Process	Transformation of ENMs	Source
	Sludge	Anaerobic digestion	Complexation with S, Fe, P	(Ma et al., 2014)
	Sludge	Composting	Oxidation of ZnS to Fe oxy/hydroxides	(Lombi et al., 2012)
	Sludge	Composting	Oxidation of ZnS to Fe oxy/hydroxides	(Ma et al., 2014)

Table A10 – Effects associated with the presence of ENMs on anaerobic digestion processes. Partly based on (Demirel, 2016; Ganzoury and Allam, 2015).

ENM type	ENM size [nm]	Concentration of ENMs	Feedstock type	Temperature [°C]	Incubation time [day]	Effect on methane/biogas production	Source
CuO	37	1.4 mg/l	AGS	30	83	-15% methane	(Otero-González et al., 2014a)
	5	15 mg/l 120 mg/l 240 mg/l	Cattle manure	36	14	No effect -19% biogas -60% biogas	(Luna-delRisco et al., 2011)
	30	15 mg/l				-30% biogas	(Luna-delRisco et al., 2011)
	40	1500 mg/l	AGS	30	Max. BMP	-87% acetoclastic MA No effect on hydrogentrophic MA	(Gonzalez-Estrella et al., 2013)
ZnO	15	120 mg/l 240 mg/l	Cattle manure	36	14	-18% biogas -72% biogas	(Luna-delRisco et al., 2011)
	50–70	120 mg/l				-43% biogas	(Luna-delRisco et al., 2011)
	140	1 mg/g-TSS 30 mg/g-TSS 150 mg/g-TSS	WAS	35	105	No effect -18% methane -75% methane	(Mu and Chen, 2011)
		10 mg/g-TSS 50 mg/g-TSS 100 mg/g-TSS 200 mg/g-TSS	AGS		8	No effect No effect -25% methane -43% methane	(Mu et al., 2012)
	<100	0.32 mg/l 34.5 mg/l	Sludge	30	90	Slight decrease in methane Complete inhibition	(Otero-González et al., 2014b)
	850	10 mg/l 1000 mg/l	Sludge	30	40	-8% biogas -65% biogas	(Nguyen, 2013)
	<100	6 mg/g TSS 30 mg/g TSS 150 mg/g TSS	WAS	35	18	No effect -23% methane -81% methane	(Mu et al., 2011)
	10–30	1500 mg/l	AGS	30	TMMP	-53% acetoclastic MA to -75% hydrogentrophic MA	(Gonzalez-Estrella et al., 2013)
	120-140	6 mg/g TS 30 mg/g TSS 150 mg/g TSS	Sludge	30	8	No effect -21% biogas -76% biogas	(Zheng et al., 2015)
TiO_2	<25	6, 30, 150 mg/gTSS	WAS	35	Multiple tests	No effect	(Mu et al., 2011)
	25	1500 mg/l	AGS	30	TMMP	No effect	(Gonzalez-Estrella et al., 2013)
	7.5	1120 mg/l	WWTP sludge	37 and 55	50	+10% biogas	(García et al., 2012)
	185	150 mg/gTSS	WAS	35	105	No effect	(Chen et al., 2014)
	150-170	6, 30, 150 mg/g TSS	Sludge	30	8	No effect	(Zheng et al., 2015)
Al2O3	<50	6, 30, 150 mg/ g TSS	WAS	35	Multiple tests	No effect	(Mu et al., 2011)
	<50	1500 mg/l	AGS	30	TMMP	No effect on acetoclastic MA -82% hydrogentrophic MA	(Gonzalez-Estrella et al., 2013)

ENM type	ENM size [nm]	Concentration of ENMs	Feedstock type	Temperature [°C]	Incubation time [day]	Effect on methane/biogas production	Source
ɤ-Al2O3	20–50	100 g/l	Granular sludge	27	17	-60% decrease	(Alvarez and Cervantes, 2012)
SiO2	10–20	6, 30, 150 mg/g TSS	WAS	35	Multiple tests	No effect	(Mu et al., 2011)
	10–20	1500 mg/l	AGS	30	TMMP	No effect MA	(Gonzalez-Estrella et al., 2013)
Mn2O3	–	1500 mg/l	AGS	30	TMMP	-52% acetoclastic MA -63% hydrogentrophic MA	(Gonzalez-Estrella et al., 2013)
CeO2	50	1500 mg/l	AGS	30	TMMP	-80% acetoclastic MA -82% hydrogentrophic MA	(Gonzalez-Estrella et al., 2013)
	<25	5, 50, 150 mg/g VSS	GS, FS	35	6	No effect	(Ma et al., 2013)
	12	640 mg//l	Sludge	37 and 55	50	-90% biogas	(García et al., 2012)
	192	10 mg/l 1000 mg/l	Sludge	30	40	+11% biogas -35% biogas	(Nguyen, 2013)
	30-50	10 mg/L 100 mg/L 500 mg/L 1000 mg/L	Sludge	40	30	+11% biogas -32% biogas -32% biogas -35% biogas	(Nguyen et al., 2015)
Fe	9	20 mg/l	Manure, slurry	37	40	+50% biogas, +67% methane	(Abdelsalam et al., 2016)
Fe3O4	7	100 ppm	Sludge	37	60	+180% biogas, +234% methane	(Casals et al., 2014)
	7	20 mg/l	Manure, slurry	37	40	+70% biogas, +160% methane	(Abdelsalam et al., 2016)
	20	0.5% wt 1% wt	Sludge	37	12	+26% methane -12% methane	(Suanon et al., 2016)
NZVI	20	0.1 wt%	WAS	37	17	+30.4% biogas, +40.4% methane	(Su et al., 2013)
	55	1, 10 mM 30 mM	Sludge	37	14	-20% methane -70% methane	(Yang et al., 2013)
	ZVI <212	30 mM				+10% methane	(Yang et al., 2013)
	46–60	1500 mg/l	AGS	30	TMMP	-85% acetoclastic MA -91% hydrogentrophic MA	(Gonzalez-Estrella et al., 2013)
	50	0.5% wt 1% wt	Sludge	37	12	+46% methane -30% methane	(Suanon et al., 2016)
Ag	<100	1500 mg/l	AGS	30	TMMP	No effect	(Gonzalez-Estrella et al., 2013)
	21	1 mg/kg 10 mg/kg	MSW	37	250	-10% methane	(Yang et al., 2012b)
	29	10 mg/l 40 mg/l	Digested sludge	37 22	14	No effect	(Yang et al., 2012a)
	30	170 mg/l	Sludge	37 and 55	50	No effect	(García et al., 2012)
	40 nm	6.3, 77, 184 mg/kg	Waste sludge	36	38	No effect	(Doolette et al., 2013)
Au	20 nm	100 mg/l	WWTP sludge	37 and 55	50	No effect	(García et al., 2012)
Cu	40–60	1500 mg/l	AGS	30	TMMP	Completely inhibition	(Gonzalez-Estrella et al., 2013)
Co	28	0.5 mg/l 1 mg/l 2 mg/l	Manure, slurry	37	50	+36% biogas +64% biogas -5% biogas	(Abdelsalam et al., 2017)
	28	1 mg/l	Manure, slurry	37	40	+70% biogas, +100% methane	(Abdelsalam et al., 2016)
Ni	17	0.5 mg/l 1 mg/l 2 mg/l	Manure, slurry	37	50	+46% biogas +72% biogas +74% biogas	(Abdelsalam et al., 2017)
	17	2 mg/l	Manure, slurry	37	40	+80% biogas, +117% methane	(Abdelsalam et al., 2016)
Pt/SiO2	–	10^{-5} mol/l	–	55	–	+7% methane	(Al-Ahmad et al., 2014)
Co/SiO2	–	10^{-5} mol/l	–	55	–	+48% methane	(Al-Ahmad et al., 2014)
Ni/SiO2	–	10^{-5} mol/l	–	55	–	+70% methane	(Al-Ahmad et al., 2014)

ENM type	ENM size [nm]	Concentration of ENMs	Feedstock type	Temperature [°C]	Incubation time [day]	Effect on methane/biogas production	Source
Fe/SiO2	–	10 - 5 mol/l	–	55	–	+7% methane	(Al-Ahmad et al., 2014)
Fullerene (C60)	0.321, 8.6, 3000, 5000 mg/kg	–	WWTP sludge	Ambient	90–150	No effect	(Nyberg et al., 2008)

Table A11 – Overview of recovery processes for ENMs (partly adapted from Dutta et al., 2018)

ENM	Waste	Process	Source
SnO2	Industrial electroplating sludge	Selective crystallization and growth	(Zhuang et al., 2012)
Au	Artificial nanowaste comprised of citrate-reduced gold nanoparticles	Host–guest inclusion complex formation using α-cyclodextrin	(Pati et al., 2016)
CdS, ZnS	Microemulsions	Thermo-reversible liquid-liquid phase transition	(Myakonkaya et al., 2010)
Ag	Environmental waters	Cloud point extraction	(Liu et al., 2009)
SiO_2	Solutions	Cloud point extraction	(Mustafina et al., 2011)
Au, Pd	Aqueous media	Cloud point extraction	(Nazar et al., 2011)
Several	Printed circuit boards	Cryo-milling	(Tiwary et al., 2017)
ZnO	Batteries	Hydrometallurgy-precipitation and liquid-liquid extraction	(Deep et al., 2011)
Zn	Batteries	Hydrometallurgy	(Qu et al., 2015)
Polyaniline/graphite nanocomposites	Spent battery powder	Oxidative polymerization	(Duan et al., 2016)
Co Ferrites	Li ion batteries	Combined sol-gel and hydrothermal method, co-precipitation	(Guo-xi, 2008)
Cu	Automobile shredder	Hydrometallurgy	(Singh and Lee, 2016)
CNT	Supercapacitor	Extraction, filtration	(Vermisoglou et al., 2016)
Pb	Printed circuit boards	Vacuum separation, dynamic inert gas	(Zhan et al., 2016)
Al_2O_3	Aluminium electrolytic solution	Co-precipitation	(Wu and Chang, 2016)
Pd	Spent catalyst Hydrometallurgy	Hydrometallurgy	(Zhou et al., 2016)
Fe_3O_4	Pickling waste	Co-precipitation and sonication	(Tang et al., 2009)
$MnFe_2O_4$, $CuFe_2O_4$	Pickling waste liquor and electroplating wastewater	Co-precipitation	(Chen et al., 2016)

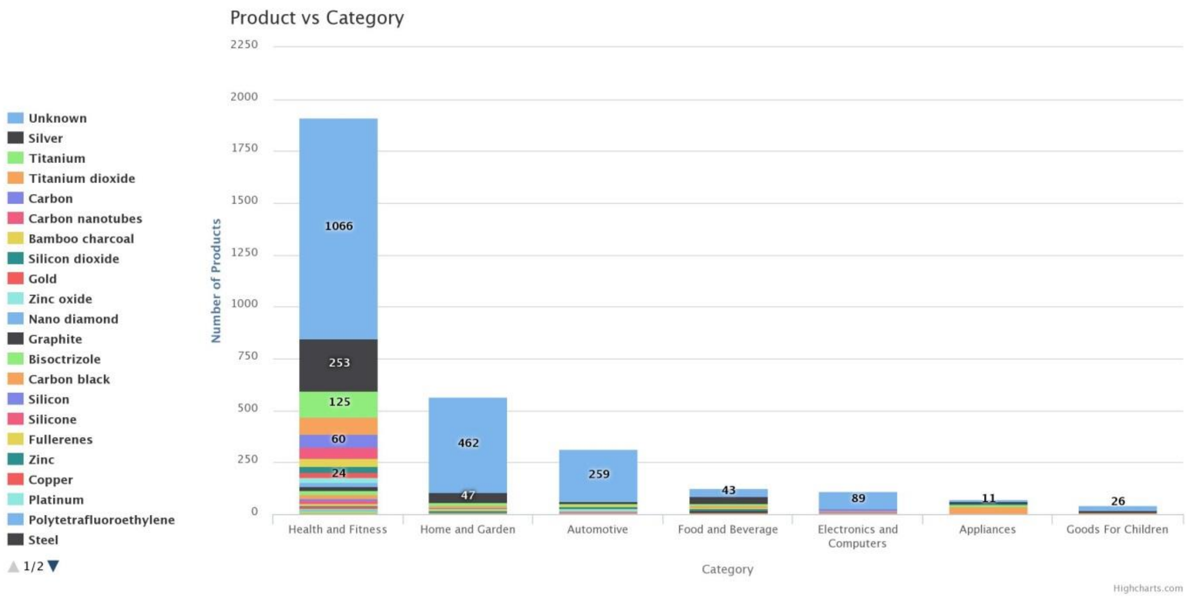

Figure 1. Overview of product categories containing ENMs on the European market (Nanodatabase; www.nanodb.dk)

Appendix II

Overview of some of the existing activities addressing waste containing nanomaterials

Entity	Initiative and duration	Scope	Main outcomes and conclusions
Danish Environmental Protection Agency	Better control of nano; (2012-2015)	• To create an overview of the possible risks of using nanomaterials; • Study on nanomaterials in waste: Overview of the present knowledge and knowledge gaps in relation to nanomaterials and waste (identifying general safety and technical issues)	Nanomaterials in waste (2014): (https://www2.mst.dk/Udgiv/publications/2014/10/978-87-93283-10-7.pdf) ○ The majority of inorganic nanomaterials examined end up in the slag during incineration. There is the potential for occupational and environmental issues arising from the recycling of the slag (e.g. leaching of nanomaterial from slag used in road construction). ○ Landfilling of waste containing nanomaterial my result in nanomaterials in leachate, however conditions in landfills typically promote agglomeration. ○ Recycling of waste containing nanomaterials is associated with several issues namely occupational health concerns during the recycling process, treatment of residues from recycling processes and introduction of nanomaterials in recycled material. ○ Identified a number of areas for further studies including on the characterization and leachability of nanomaterials from various waste types and residues and evaluation of their migration through landfill liners.
German ministry of environment	Expert dialogue on the topic “Nanotechnologies and Waste”. 2014-2015 (http://m.bmu.de/fileadmin/Daten_BMU/Download_PDF/Nanotechnologie/nanodialog_4_fd3_bericht_en_bf.pdf)	Discuss the potential opportunities of using nanotechnologies in the waste treatment sector and the potential risks from the content of nanomaterials in wastes	• Safe disposal of hazardous nanowaste (wastes from the manufacture and processing of nanomaterials) is possible when information on the specific properties of the nanomaterials are available, and modern state of the art waste treatment technologies are used. • Lack of information on the nanomaterials content of end-of-life products hampers their safe disposal. The information gap could be addressed by establishing notification requirements and product registers. • Overall risk posed by nanomaterials in waste cannot be estimated due to a lack of information on the content of nanomaterials in waste and emissions of nanomaterials from disposal processes. • Several examples of possible precautionary measures for the handling and disposal of waste containing nanomaterials are presented.

Entity	Initiative and duration	Scope	Main outcomes and conclusions
Health Council of the Netherlands	Horizon-scanning report Nanomaterials in waste (2011) (https://www.gezondheidsraad.nl/sites/default/files/Nano_waste_201114E.pdf)	Examines the fate of nanomaterial-based products in the disposal phase and raise awareness of the issues related to nanomaterials in waste	• The quantities and types or nanomaterial present in Dutch solid and residual waste is unknown. • Reliable methods to measure specific types of nanomaterials in environmental and complex media are lacking, impairing risk research and risk management • Nanomaterial waste is being disposed of with ordinary residual waste, as there are no facilities for separate collection. • A proactive approach is recommended to monitor issues related to nanomaterials in waste. • Emphasis should be placed on minimizing waste generation by encouraging industry to adopt smart design and production techniques. • Further research is needed into new waste treatment technology for waste containing nanomaterials and methods to measure the presence of nanomaterials in complex matrices.
Swiss Federal Office for the Environment's (FOEN)	Synthetic nanomaterials Action Plan. 2008-2019	Development of tools aimed at taking proactive and responsible steps for the safe handling of nanomaterials, including disposal of industrial nanowaste. Preparation of an exploratory study to be used as the basis of enforcement guidelines for the environmentally sound and safe disposal of waste resulting from the production, and industrial and commercial processing, of synthetic nanomaterials: • Provides recommendations on the handling of commercial/industrial waste containing free or releasable nanomaterials and helps determine the correct methods of disposal. • Identifies knowledge gaps and areas requiring further research.	Draft conceptual study: Environmentally compatible and safe disposal of waste generated by the manufacture as well as the industrial and commercial processing of synthetic nanomaterials (2010): (https://www.bag.admin.ch/bag/en/home/themen/mensch-gesundheit/chemikalien/nanotechnologie/sicherer-umgang-mit-nanomaterialien/entsorgung-von-industriellen-nanoabfaellen.html) ○ Manufacturers of nanomaterials must implement self-regulation measures to assess if these materials pose any risk to human health and the environment at any stage of their lifecycle. ○ Specifies conditions under which nanowastes are to be categorized as special wastes and subject to the relevant regulations, including when owing to their nanospecific characteristics, effects on health, safety or the environment cannot be excluded, or the effects are unknown. ○ Recommends use of the Precautionary matrix for synthetic nanomaterial to assess the need for action concerning disposal of nanowastes. ○ Provides general principles for the disposal of nanowastes and recommendations on possible disposal procedures. ○ The conceptual study is to be subjected to a practical test which would also gather additional information from companies concerned with nanotechnologies.

Entity	Initiative and duration	Scope	Main outcomes and conclusions
Organisation for Economic Co-operation and Development, Working Party on Resource Productivity and Waste	Waste containing nanomaterials 2011-ongoing	Understand the emerging issue of waste containing nanomaterials and attract attention to the potential risks that are linked to the presence of nanomaterials in waste treatment processes	• OECD Workshop on Safe Management of Nanowaste, May 2012, Munich, Germany • OECD Workshop on Recent Scientific Insights into the Fate and Risks of Waste Containing Nanomaterials, November 2016, Paris France – Agenda • Report "Nanomaterials in Waste Streams - Current Knowledge on Risks and Impacts", 2016: (http://www.oecd.org/chemicalsafety/nanomaterials-in-waste-streams-9789264249752-en.htm) o Highlights clear lack of information on the type and quantities of engineered nanomaterial in waste streams o Best available technologies appear best most effective minimizing risk. However significant amounts of emissions are still likely passing through state of the art treatment processes. o Engineered nanomaterials can negatively impact certain waste treatment processes.
International waste working group	IWWG Task Group on Engineered Nanomaterials in Waste. 2015-ongoing	Develop guidance on the appropriate end-of-life management strategies for these ENM-containing products and/or waste streams.	• Organized workshops and published joint reports to create and spread best practice waste management strategies for WCNM. (https://www.tuhh.de/iue/iwwg/task-groups/engineered-nanomaterials-in-waste.html)
SAICM (http://www.saicm.org/Implementation/EmergingPolicyIssues/Nanotechnology/tabid/5475/Default.aspx)	Emerging policy issue – Nanotechnologies and Manufactured nanomaterials	Carry out work to enable countries and governments to better understand the hazards associated with ENMs and how to manage them.	• 2008, adopted the Dakar statement manufactured nanomaterials, focused on ENM safety and recommended the application of the precautionary principal to these. • 2009, ICCM2 adopted resolution II/4-E encouraging "governments and other stakeholders to assist developing countries and countries with economies in transition to enhance their capacity to use and manage nanotechnologies and manufactured nanomaterials responsibly, to maximize potential benefits and to minimize potential risks"

Entity	Initiative and duration	Scope	Main outcomes and conclusions
			• To better implement this resolution UNITAR and OECED worked together to coordinate SAICM activities. Numerous projects have been carried out. • Resolution III/2-E adopted in 2012 and incorporated 13 activities linked to nanotechnologies in the Global Plan of Action, a guidance document to assist stakeholders achieve the objectives of the strategic approach. The 113 activities are found in Annex II of the ICCM3 meeting report (SAICM//ICCM.3/24, http://www.saicm.org/Portals/12/documents/saicmtexts/ICCM3-Annex-II-EN.pdf). Appendix 1 to table B of the Global Plan of Action pertains to work activities relating to nanotechnologies and manufactured nanomaterials. Activity 11 calls for the promotion of producer responsibility for providing appropriate guidance on safe use of manufactured nanomaterials throughout the supply chain, including the waste stage.
UNITAR	Chemicals and waste management-Nanotechnology	Development of international guidance and training material for the sound management of manufactured nanomaterials.	• 2011: UNITAR published "Guidance for Developing a National Nanotechnology Policy and Programme" (http://cwm.unitar.org/publications/publications/cw/Nano/UNITAR_nano_guidance_Pilot_Edition_2011.pdf) • Organized regional nanosafety workshops. (http://www.unitar.org/pillars/planet/nanotechnology) • 2016: held the 10th International Nano-authorities dialogue. Group worked to update and supplement "Nano Roadmap 2020" • Coordinated e-learning course "introduction to Nanomaterials Safety"
G20 Insights	Platform that offers policy proposals to the G20	Policy brief	Nanowaste: Need for Disposal and Recycling Standards (2017) http://www.g20-insights.org/policy_briefs/nanowaste-need-disposal-recycling-standards/
European Commission	7th Research framework programme FP7. 2007-2013	Funding of several projects addressing the safety of nanomaterials throughout their life-cycle including:	Various reports and tools Scientific publications Expert meetings Conferences

Entity	Initiative and duration	Scope	Main outcomes and conclusions
		Life Cycle of Nanoparticle-based Products used in House Coating (NanoHouse) Development of sustainable solutions for nanotechnology-based products based on hazard characterization and Life cycle analysis (NanoSustain) Assessment and mitigation of nano-enabled product risks on human and environmental health: Development of new strategies and creation of a digital guidance tool for nanotech industries (GUIDEnano)	