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Nanotechnology risk assessment from a waste management perspective: Are the current tools adequate?

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Abstract

The burgeoning nanotechnology industry is rapidly generating new forms of waste streams generically referred herein as nanowastes. However, little is known about the fate and behavior of these waste streams and their impacts thereof in different ecological systems despite their increasingly widespread dispersion into the environment through production, distribution, handling, and nanomaterials (NMs) incorporation into bulk products processes. In this paper, risk assessment of nanotechnology from a waste management perspective was examined to elucidate potential new forms of challenges nanowastes may likely pose to the current legislative and waste management systems. This was through the identification of several knowledge gaps that merit urgent attention in order to increase our collective understanding of managing nanowastes safely, responsibly, and sustainably. The paper presents the identified gaps and consequently proposes a qualitative risk assessment of nanowastes to address some of the current challenges. The applicability of the proposed model is illustrated through several examples. In addition, the first nanowastes classification protocol presented in this article show that a given nanomaterial may result in generating nanowaste streams of different forms with variant hazard levels ranging from benign to extremely being hazardous waste streams – a dramatic phenomenon from the conventional waste streams due to macroscale chemicals. The study shows that it is in the early days to draw broad generic classification of different nanowastes, and each stream may require their risk profile be assessed on a case-by-case basis. We conclude by presenting several recommendations on what needs to be done in dealing with nanowastes as means of avoiding unintended long-term consequences of nanotechnology.

Keywords

nanowastes, risk assessment, nanotechnology, nanowastes classification, nanoproducts, nanowastes management, nanopollution

Introduction

The 20th and 21st centuries are commonly defined by unrelenting quest for the provision of goods and services to meet human needs, improve the quality of life to mankind, and create wealth. Such quest has caused rapid industrialization, urbanization, extensive agriculture, high energy demand (e.g. evidenced via over-reliance in burning fossils for transportation, domestic and industrial purposes), and rigorous exploitation of natural resources (e.g. destruction of rainforests, drying of water resource systems). Unfortunately, such actions resulted in causing unintended outcomes like high population growth (current global population has exceeded 6.4 billion people), rapid increase in hazardous waste generation, extensive pollution of environmental systems (water, soil and air resources), causation of climate change-inducing effects, and extinction of certain ecological species.

To counter these undesirable impacts, numerous science- and technology-driven solutions namely sustainable development (SD), design for environment (DfE), end-of-pipe treatment, and pollution prevention (PP), just to mention a few, have been advanced as remedies. Recent additional technological solution

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viewed to support sustained current economic growth, exacerbate reduction in raw materials demand, and improve the performance of existing technologies is via the design, manipulation, and fabrication of materials at nanoscale.

Materials production at nanoscale led to the birth of the nanotechnology industry, which has commercially grown from under 30 companies globally in the 1960s to over 1500 companies by early 2000s,[1,2] with more than 600 company-identified products as of February 2008.[3] Now, nanomaterials (NMs) constitute by far the most significant market opportunity in the next coming years. For example, market survey forecasts show that in all likelihood, the industrial sector by 2014 will be nano-influenced especially in the chemicals, electronics, and the pharmaceuticals sectors contributing up to 15% of the global manufacturing output with an estimated economic value of US$2.6 trillion dollars.[2,4]

Nanotechnology involves the manipulation, precision placement, measurement, modeling, or fabricating of matter at nanoscale – with at least one dimension measuring 100 nm or less,[5] and on how to control the formation of two-and three-dimensional assemblies of molecular scale building blocks into well-defined nanostructures.[6] NMs are broadly classified as carbon-based materials (e.g. fullerenes, carbon nanotubes – singe walled carbon nanotubes [SWNCT] or multi-walled carbon nanotubes [MWCNT]) and inorganic engineered nanoparticles (ENPs) fabricated from metal oxides (e.g. zinc oxide, yttrium iron oxide, nickel zinc iron oxide, titanium oxide, indium tin oxide, samarium (III) oxide, erbium (III) oxide, aluminium oxide, etc) and metals (gold, silver, iron, copper, palladium, etc.). Other forms of NMs include semiconductor nanocrystals known as quantum dots (QDs; e.g. cadmium selenide [CdSe], indium phosphide [InP] cadmium telluride [CdTe], zinc selenide [ZnSe], etc). In addition, mixtures of different phases of NMs are also fabricated at laboratory and industrial scales.

Rapid commercialization and application of NMs has led to their continued release into the biological and environmental systems as their terminal sinks and more are expected due to the breadth of current and future anticipated applications. Given the likelihood of exposure, and certain NMs being toxic, necessitates systematic evaluation of their potential advance effects to the biological systems. Presently, there is paucity of scientific data to elucidate the fate, behavior, and interaction of NMs with biological and environmental systems.[7] For instance, research on the ecotoxicity of NMs is at infancy, and only limited scientific findings are available for fullerenes, carbon nanotubes (CNTs), and metal oxides.[8-19]

Likewise, the ecotoxicity data for QDs and polymer nanoparticles are scare in the scientific literature. Clapp et al.[20] reported that the toxicity of CdTe is possibly linked to leaching of toxic heavy metals from the colloidal form and derived from the intrinsic properties of size and surface chemistry of these QDs. Also, ecotoxicological findings of Gagné and co-workers[21] show that CdTe QDs are immunotoxic to the freshwater mussel *Elliptio complanata* and can cause oxidative stress in gills as well as DNA damage. Therefore, because of the breadth on the number of NMs and nano-induced products being fabricated in addition to the anticipated economic size of nanotechnology, industry necessitates urgent systematic assessment of the potential impacts of this technology in the environment. One of the key strategies of reducing the impacts of these materials is through effective waste management of nano-related waste streams.

Nanowastes management

Generically, the new forms of waste streams containing NMs are referred as nanowastes. In this paper, nanowastes refers to waste streams containing engineered nanoparticles, nanomaterials, or synthetic by-products with nanoscale properties, generated either during production, storage and distribution or waste streams resulting from the end of lifespan of formerly nanotechnologically enabled materials and products or waste streams generated through use of NMs to remove pollutants from aqueous and/or gaseous effluents. The objective of assuming broad definition is to aid in developing a holistic approach in addressing the management of nanowastes over the entire NMs lifecycle.

In the context of waste management, it is anticipated that as the production and the number of application for NMs increases, waste streams related to these materials will increase, and possibly become ubiquitous in the environment as a result of poor or inadequate management. Processes where nano-related waste streams can be generated includes; production, distribution, handling, and during incorporation of NMs into bulk products. Most significant risks of nanowastes to the environment can be attributed to spillages during the transportation of engineered NMs from manufacturing facilities to other manufacturing sites, industrial discharges of off-specification products or NMs, intentional releases for environmental applications (e.g. remediation of contaminated soils), and leachate into the underground or surface waters from waste disposal sites. Other sources may include solid wastes and wastewater streams from the manufacturing sites due to cleaning processes, NMs produced in colloidal form and discharged directly into the current waste management systems, or NMs released from nanoproducts through wear and tear during their application phase. During the production phase, nanowastes generation is most unlikely because closed reactors are used under vacuum conditions unless due to the normal accidentals and incidentals of manufacturing processes.

Until now, the capabilities of waste management systems regarding handling, treating, or disposing of nanowastes in environmentally acceptable manner remains unknown and poorly researched. For instance, recent international survey findings of Helland and co-workers[22] showed that companies working with or manufacturing NMs paid minimal or no attention in risk assessment during use and at the disposal phase of nanowastes. Given the increasing likely release of nanowastes into environmental systems as the nanotechnology industry grows merits a critical examination on the adequacy of current technologies and legislative frameworks to handle, treat, and dispose these waste streams adequately.

Therefore, in this paper, threefold objectives are addressed. First, the adequacy of the current waste management technologies and legislative frameworks in managing nanowastes is examined. Secondly, we qualitatively quantify the potential risks of nanowastes to the biological systems and the environment. And finally, we propose a new categorization of nanowastes ranging from benign to high hazardous status based on their constituent intrinsic chemical properties and potential degree of exposure to the ecological systems as a function of the loci of the NMs in the product. Such classification system is useful to waste management industry and regulators to exercise precautionary approach in managing different classes of nanowaste streams.

Nanowastes risk assessment

At the moment, risk assessment of nanowastes is yet to be quantified mainly because of the lack of generic principles that governs risk assessment and characterization of NMs. This means, unless the challenges regarding the response of NMs to organisms and the actual degree of exposure in environment are addressed – at this point – it is difficult to characterize the risks of nanowastes. This is exacerbated by lack of ecotoxicological data to the ecosystems as well as exposure potency of these materials.

For example, very few data exists on NMs regarding their hazard effects, probability of occurrence in diverse environmental systems, and the exposure potency (bioaccumulation and biopersistence). Therefore, it is scarce or highly unlikely to find data for a specific NM on (i) its ecotoxicity to organisms both under laboratory and environmental conditions, (ii) its expected degree of exposure to aquatic and terrestrial organisms in diverse environments (e.g. water and soil), (iii) its exposure potency (e.g. bioaccumulation and biopersistence), and (iv) the precise dose-response relationship between the levels of exposure to the aquatic and terrestrial organisms, and the consequent adverse effects observed. Equally important, even the limited data available is of disjointed nature; consequently, it is inconceivable to develop a robust quantitative risk assessment in any given environmental media.

Other obstacles in developing a quantitative risk assessment for nanowastes include lack of data on the actual concentrations of NMs released, or currently residing in the environment, the relationship between the reported observed toxicity and the physicochemical properties of the NMs, and the likely quantities to be released into the environment intentionally (e.g. through bioremediation of contaminated soils[23]) or unintentionally (via liquid and solid nanowaste streams). Therefore, the absence of quantitative risk assessment of NMs, again, makes it difficult for industries, waste management specialists, and regulators to manage such waste streams adequately. For a start, we present a qualitative risk assessment of NMs in order to identify the streams which merit immediate attention.

In addition, it is unclear how the background NMs due to natural (volcanic eruptions, hydro thermal systems, viruses, forest fires, etc.) and anthropogenic sources (internal engines using fossil fuels, power plants, welding, frying, fumes from incinerators, air jet, etc) would be discriminated from intentional engineered NMs once they are released into the environment. This is because of the potential interaction between the engineered NMs with natural ones, and also, with other chemical pollutants present in the environment which may complicate the quantification of risk assessment for nanowastes in real world environmental scenarios.

For the latter case, the interactions and adsorption of other environmental pollutants by NMs have been reported,[24-27] and clearly will complicate risk assessment of these materials in water and soil environments. In addition, due to the adsorptive capabilities of NMs and the ability to permeate across membranes raises concerns regarding the translocation of toxic bulk chemicals in tissues and cells that previously were unlikely to be affected by the macroscale chemicals. Therefore, this is of interest because though certain NMs may not be toxic, if the nanowaste mixes/interacts with other conventional waste streams containing toxic chemicals, the former may act as a Trojan horse to transport the latter into the cells,[28] which could substantially demand forensic examination of the effectiveness of current waste management systems.

Other studies have showed that the sorption of pollutants into NMs[29-31] is mainly due to the large surface area of these materials. Baun and co-workers[32] illustrated the carrier effect of NMs in invertebrates using *Daphnia magna*. The test results showed that the toxicity of methyl parathion was not affected by the presence of fullerenes aggregates, however, a 1.9 times decrease in the toxicity was observed for pentachlorophenol. For phenanthrene, an 85% sorption to the fullerenes aggregates was observed to have increased its toxicity by 60% – attributed to the presence of fullerenes aggregates. The results illustrate that sorbed phenanthrene was made bioavailable to the test organisms.[32]

Thus, attempts to address these challenges underpins the necessity for adopting multidisciplinary approaches through collaborative efforts between biologists, ecotoxicologists, environmental scientists, toxicologists, analytical researchers, and nanoscientists (e.g. physicists, chemists, and materials engineers) to ensure that data gathered from laboratory setups and actual environmental conditions are useful in elucidating the fate and behaviour of NMs in the environment. Clearly, this requires a new paradigm that breaks virtual barriers imposed by distinctive discipline ethos and purported institutional autonomies.

And secondly, multidisciplinary approach will aid in establishing the linkage between the physicochemical properties of NMs and the observed toxicity effects on target test species. For instance, it would be vital for the ecotoxicologists to take into account the NMs chemistry in order to correctly interpret the experimental ecotoxicological data. Also, the exposure environment conditions like the pH, presence or absence of oxidants, complexed ions, zeta potential, effects of macromolecules (e.g. polyelectrolytes or polysaccharides), effect of light, and effect of the media used in performing the toxicity studies[19] should be factored in order to generate useful and practical data.

What novel challenges do nanowastes pose?

Nanotechnology has matured into industrial manufacturing of products and other applications in nanoelectronics, molecular assemblies, tissue engineering, biomedicine, nanocomposites, cosmetics, pharmaceuticals, environmental analysis and remediation, catalysis and materials science, among others. This is because of the ease with which NMs can be prepared and manipulated, their unique physicochemical properties (e.g. high reactivity, large surface area, etc), and the tunable nature of their optical and other properties.[33-35]

Because the biological interactions of nanowastes with ecological systems are dependent on the NMs content, it is important to highlight the unique challenges of dealing with these forms of waste streams from a waste management perspective. First, owing to the lack of data for the exposure potency for numerous NMs (as described in section on nanowastes risk assessment), it is unclear whether these materials partition in the environmental media as is the case with certain macroscale chemicals. Studies on the partition of the NMs in air, water, or soil are yet to be reported, and therefore, it is improbable to develop generic principles for personnel working in the waste industry on how to handle various forms of nanowastes. In the light of these uncertainties, several methods of handling nanowastes have been proposed[36] to prevent their potential adverse effects to the humans and the environment.

For instance, it is known that cosmetics and other personal-care products containing different types of NMs are widely used, and already have entered the aquatic environments – through bathing, sewage systems or showering – and to the municipal waste system (e.g. landfilling) via the household waste. Yet, the bioaccumulation or biopersistence of NMs used in cosmetics and other personal-care products (e.g. zinc oxide, fullerenes, *n*-silver, titanium oxide, iron oxide, *n*-gold, etc.) remains unknown. The present assumption of low or non-existence of exposure potency may influence current waste management practices where such waste streams are assumed to be benign though in the absence of substantive scientific evidence in support of such assumptions. However, the increase in concentrations of NMs in the environment may cause long-term chronic effects through different food chains. In this case, effective nanowaste management is vital to prevent such unforeseen consequences related to nanotechnology.

Secondly, recent studies on macroscale chemicals and hazardous wastes have elucidated the significance of quantifying chemicals or waste streams entering into the ecological systems in order to establish realistic risk assessment of the receptor environment.[37-41] Currently, the quantities or concentrations of NMs in waste streams or in the environment remain unknown – and the estimates provided by Boxall and co-workers[35] are highly hypothetical – and difficult to verify.

Apparently, it may be assumed that the current quantities are low; however, with rapid introduction of new nanoproducts into the market, and discovery of new NMs of unknown impacts to the environment, this scenario is likely to change dramatically. For instance, in the case of macroscale chemicals (without NMs) according to the United States Environmental Protection Agency chemical substances rules[42] – deems the production of less than 4.5 tonnes annually as low, and is presumed to cause minimal or no adverse impacts in the environment. However, if the chemicals are highly persistent[43] irrespective of the quantity produced annually leads to invoking special handling and management protocols throughout their entire lifecycle. Such clear guidelines for the NMs are yet to be developed.

Thirdly, there is paucity of toxicity data and its relationship to the physicochemical properties of NMs, incoherency of few reported toxicity data (see results of Velzeboer et al.[44] and those of Lovern and Klaper[11] for the TiO_2 toxicity to *Daphnia magna*), and lack thereof of universally agreed units of expressing the NMs toxicity. These factors among others earlier mentioned inhibit robust risk assessment of NMs. Consequently, it is improbable to develop estimation models at the moment to predict the toxicity or fate and behavior of NMs of similar structure as is the case for the conventional macroscale chemicals. This further inhibits consistent interpretation of the available data especially in addressing both immediate and long-term complex issues of waste management.

Fourthly, the complexity of managing nanowastes is also due to the dynamic transformation of NMs along their entire lifecycle. Such transformation influences the fate and behavior of these materials in different environments owing to nanostructures intrinsic properties (e.g. surface chemistry, aggregation, agglomeration, adsorption or absorption properties, etc.), and the environmental factors (pH, presence or absence of oxidants, complexed ions, zeta potential, effects of macromolecules, presence of other chemicals, etc). The multidimensionality of the influencing factors makes it a Herculean task in managing diverse nanowastes that are poorly characterized, and this appears to remain a concern in the coming years.

Equally important, the available reported ecotoxicity data according to recent reviews[45-47] is largely based on laboratory setups and may be of limited value in elucidating our collective understanding on the fate and behavior of NMs in actual environmental systems as numerous real-world environmental conditions were not considered in these studies. This implies the available data may be of limited use in terms of aiding the design of systems that can handle the nanowastes sufficiently.

Fifthly, the large number of companies ranging from small start-ups to global corporate entities[1] led to the production of diverse NMs in thousands as evidenced by huge databases of international patents.[48,49] This renders nanowastes management quite challenging task – and unless universal principles and technologies of managing these wastes are developed urgently – a case-by-case approach recommended presently may prove uneconomically viable, laborious, and even impractical considering the number and types of NMs as well as the nanoproducts. To put our argument into perspective, assume for a given NM (*e.g.* MWCNT) has 10 major types, *and* can be produced using five different fabrication techniques where some types may contain varying degrees of impurities. In addition, the nanostructure sizes of this NM under question – ranges from few to hundred nanometers, can be purified using three different purification techniques, and there are 10 possible surface coatings to maintain their nanoscale properties during their application phase.

Evidently, this results in a combinatorial problem with numerous possibilities of distinctive nanowaste streams from a single material. Hence, it strengthens the call for urgent development of practical methods and tools to manage nanowastes before they become extensively ubiquitous in the environment, and possibly render nanotechnology a malevolent technology of the 21st century. If decisive action in dealing with nanowastes is delayed, the consequences thereof could be in similar magnitude and global scope as those of 14 case studies recently explored in the European Environment Agency Report.[50]

Under each case, it is evident that failure to heed early warnings in terms of gathering information that guides taking the right actions and corrective measures to remedy any potential dark side of a given technology and innovation with an endeavor to protect the environment and ecosystems that are dependent on it resulted in costly consequences through loss of human lives, extensive pollution of ground and surface waters, and even causing extinction of certain ecological species. Similar early warnings for nanotechnology have been raised by Hansen and co-workers[51] and should be viewed as sound basis to interrogate not only the novel benefits of nanotechnology but also examine the potential threats of this technology to the current waste management systems (e.g. the microbial populations useful in wastewater treatment plants).

Sixthly, the development of nanoproducts has outpaced the technological advancement to detect NMs in environmental systems particularly in the soil system. This makes it improbable to detect, monitor, and develop remediation protocols to mitigate possible nanopollution in the soil environments. It is not surprising that one of the global grand challenges of addressing environmental-related aspects of nanotechnology identified urgent development of metrology to aid in detecting and measuring NMs in the soil systems.[52]

In view of the above-discussed technologically-oriented challenges of nanowastes – both directly and indirectly – have induced new legislative and regulatory hurdles in dealing with these new forms of waste streams. Emergent of nanowastes has revealed cracks in terms of the inadequacy of the existing legislations governing their handling, treatment and disposal. The reason being, existing legislative waste management frameworks were developed based on mass as a determinant of regulatory coverage, with no anticipation of waste streams whose impacts on the receptive environments and organisms are a function of novel properties owing to size, size distribution, shape, structure, microstructure, surface chemistries (e.g. capping agents, co-solvents or surfactants), and homogeneity of the constituent chemicals. Presently there are debates on whether these regulatory frameworks are effective in addressing potential nanopollution due to nanowastes.[53-55]

Davies[56] proposed fundamental changes to the Toxic Substances Control Act (TSCA) and the cosmetics, food additive and food packaging provisions of the Federal Food, Drug, and Cosmetic Act (FFDCA) that would enable Environmental Protection Agency and the Food and Drug Administration, respectively, to consider the novel qualities and effects of nanomaterials when evaluating risk assessment of waste streams. To contextualize the limits of the current legislations in dealing with nanowastes, generally consumer waste is presumed to be non-hazardous, and therefore, any household waste containing NMs should be exempted from hazardous waste regulations. However, owing to the transformative character of NMs throughout the entire lifecycle, this could have serious long-term implications to the environment – again showing the inadequacy of the current legislative frameworks in addressing the handling, storing, treating, and disposing of waste streams containing materials fabricated at nanoscale even of the same chemicals.

Qualitative risk assessment of nanowastes

The qualitative characterization of specific nanowastes at the disposal phase is dependent on the expected hazard of the constituent NMs and the likelihood of their exposure to the receptor organisms in the environment. To characterize the hazard, data reported on the toxicity of different NMs in the scientific literature were used. A large database of ecotoxicity data for species (e.g. *Bacillus subtilis, Daphnia magna, Oncorhynchus mykiss, P. subsapiata, Micropterus salmoides,* etc.) likely to be exposed to NMs in environmental systems was compiled from the available scientific literature. On the other hand, the possible degree of exposure was estimated through examining the loci of NMs in a given nanoproduct or state of the medium containing the NMs during the application phase that could give rise in generating nanowastes.

Nanomaterials hazard characterization

Different NMs induce a wide breadth of ecotoxicity effects to different receptor organisms. By applying the precautionary principle, and assuming that all organisms in the environment have equal probability of being exposed to NMs from a given nanowaste, the highest acute toxicity value was used. That is, if a particular NM has varied toxicity values in different

Table 1. Qualitative quantification of toxicity levels of different NMs based on the currently available ecotoxicity data

NMs type	Examples	Hazard (toxicity)[a]
Carbon based	Fullerenes	High
	Singled-walled carbon nanotubes (SWCNT)	High
	Multi-walled carbon nanotubes (MWCNT)	High
Metal oxides	Zinc oxide (ZnO)	Medium
	Titanium oxide (TiO_2)	Low
	Aluminium oxide (Al_2O_3)	Medium
	Yttrium iron oxide ($Y_3Fe_5O_{12}$)	Low
	Silicon dioxide (SiO_2)	Low
	Iron oxide (Fe_2O_3)	Medium
Metals	Silver (Ag)	Medium
	Gold (Au)	High
	Silica (Si)	Low
Quantum dots	Cadmium-selenide (CdSe)	High
	Cadmium telluride (CdTe)	High
Others	Silicon nanowires	Low
	Nanoclay particles	Low
	Dendrimers	Medium

Abbreviation: NMs, nanomaterials.

[a] Measure of ecotoxicity to different test species. According to Globally Harmonized System,[57,58] aquatic toxicity can be expressed in five classes namely extremely toxic (<0.1 mg/L); very toxic (0.1-1 mg/L); toxic (1-10 mg/L); harmful (10-100 mg/L); and none toxic (>100 mg/L), which were reduced into the three classes (high, medium, and low).

organisms – the value expressing the highest toxic effect was selected as representative of the overall hazard of that given NM – in the event of its release into the environment. For example, Lovern and Klaper[11] showed that fullerenes are very toxic to the *Daphnia magna* as 100% mortality was achieved at a concentration of 0.88 mg/L. However, Oberdörster et al.[12] findings of similar range of fullerene concentrations showed no toxic effect on *Pimephales promelas* and *Oryzias lapties* species. Thus, in this case, fullerenes were assumed to be very toxic in the environment because of the reported high toxic effects in *Daphnia magna* species.

Similar methodology was applied to other forms of NMs in the database. Generally, the data reported for NMs like SWCNT, MWCNT, fullerenes, quantum dots, certain metal oxides like zinc and silver had higher toxicity ratings to different organisms in comparison to those of titanium oxide and yttrium iron oxide. A summary of qualitative hazard characterization for few NMs are presented in Table 1.

Exposure potency

The exposure potency aids in assessing possible impacts due to the release of chemicals in different environmental systems (water, air, or soil). Exposure potential is a function of numerous inter-linked and complex factors like persistence, bioaccumulation, solubility, biodegradability hydrolysis, and photolysis. As mentioned earlier, unlike in the case of macroscale chemicals, there is paucity of data for all these factors with respect to NMs. Therefore, in this study, the exposure potential of NMs to the ecological systems was estimated based on their loci in the nanoproducts. This is because the locus of nanostructures in a product, or their carrier media during the application phase (free or bound), strongly influences the ultimate degree of bioavailability to the receptor organisms.

Hansen et al.[59,60] identified the NMs hazards depending on their loci in the nanoproduct, namely (i) enclosed in the bulk part of the product, (ii) on the surface of the product, or (iii) as free or as suspended particles in a product. Therefore, following the Hansen et al.[60] proposed formalism, the possible exposure potential of NMs in nanowaste streams are summarized in Table 2. In order for the exposure assessment to be complete, it is crucial to quantify the level of exposure. However, currently it is difficult to quantify the NMs entering into environmental systems (water or soil) due to limited data on the quantities of nanowastes generated, modes of disposal used by the industries and research laboratories, and the concentration of the NMs in the waste streams. As earlier mentioned, the highest release of NMs is expected during the disposal phase of the

Table 2. Nanostructures loci identification in nanoproducts based on Hansen et al.[60] classification protocol, and postulated potential levels of exposure

NMs types	Possible categories	Description	Anticipated exposure levels
Free-bound	Solid-bound	The NMs are fixed on a solid structure. However, the NMs can be released easily from the surface if the nanoproduct is exposed to considerable degree of mechanical stress or via wear and tear processes	Low-to-medium exposure
	Liquid-suspended	The NMs are suspended in liquid and can easily get into contact with living organisms like mammalian and aquatic systems. Constitutes the largest class of nanomaterials found in numerous nanoproducts[60]	Highly likely
	Solid-suspended	The NMs are encapsulated in a solid matrix to strengthen the supporting material or for applications like drug delivery. Exposure to the environment is feasible after matrix or coating falls off or through wear and tear processes	Low to high depending on coating stability, immediate environment conditions, etc.
Surface-bound	Surface-bound nanostructures	The NMs are bound on the surface of a solid matrix. Their release into the environment is dependent on strength of mechanical stress to set them free from surface or through normal wear and tear processes	Very low to medium
Bulk-bound	Bulk-material bound nanostructures	The NMs are bound inside the bulk part of the nanoproducts. Exposure in the environment is highly unlikely or very low unless the nanoproduct is exposed to extreme mechanical force to break it up though it may not imply that the NMs will be free to cause a considerable degree of exposure to the organisms	Very low to low

Abbreviation: NMs, nanomaterials.

nanoproducts; therefore, to prevent widespread nanopollution, waste management of nanowastes should receive high priority.

Therefore, for estimation purposes on the quantity of the NMs entering into the environmental systems, it can be assumed that these quantities are equivalent to those contained in the nanoproducts that have expired in addition to those intentionally introduced to remediate contaminated soils. The limited data on the products containing NMs, and the concentrations of NMs contained in these products, affects the accuracy of the exposure approximations considerably. This knowledge gap needs urgent attention in order to provide regulators and industry with information to undertake risk assessment of these materials.

Risk characterization

In this section, we present risk characterization of different NMs in different nanoproducts during their disposal phase of the nanoproducts. Risk is a function of both the hazard and the exposure potency. Results of several products containing different NMs are presented in Table 3 derived from published nanoecotoxicological data. The findings show that a given nanoproduct may pose a range of risk profiles depending on the constituent NM because different NMs have different toxicities. For instance, the risk associated with sunscreens lotions at disposal phase ranges from low to high because of different toxicity profiles of titanium oxide, zinc oxide, and fullerenes. From a waste management perspective, this implies that a single nanoproduct at disposal phase may require to be disposed of through different technologies owing to the breath of toxicity profiles of different NMs used for fabricating the same product. This not only would be costly – but almost practically unfeasible because segregating waste streams of the same product is laborious, complex, and to a large extent impractical.

On the other hand, though some nanoproducts are incorporated with NMs that are highly toxic (e.g. fullerenes, SWCNT, MWCNT, etc) such as memory chips, the overall risk is likely to be low. This is because the probability of exposure for these NMs into diverse environmental components e.g. soil, water, or sediments is highly improbable as the nanostructures are firmly embedded on the bulk matrix of the product.

Nanowaste classification

In this paper, we propose the first classification of nanowaste streams viewed as significantly important to aid in isolating nanowaste classes in terms of the degree of attention required to manage them effectively. The author is not aware of such classification, and this can form basis for informed debate in identifying the most effective strategies to deal with emerging and rapidly increasing nanowastes. Such action can aid in eliminating or minimizing expansive and unintended long-term adverse effects of nanoproducts during their disposal phase in case of toxic NMs resulting into different environmental systems.

Secondly, such classification allows effective evaluation of most appropriate modes of disposal for different types of nanowastes. And thirdly, it can aid the regulatory authorities in drafting of permits for companies manufacturing products or applying technologies that could lead to the generation of nanowastes. As is the case with hazardous waste streams, permits for nanowastes should specify its "class" as such information has direct influence on the set of actions required to prevent undesirable long-term effects in the environment. Therefore, based on the protocols for nanowaste hazard characterization and the exposure potency described in previous sections on hazard characterization and exposure potential, respectively, nanowastes were broadly classified into five categories as summarized in Table 4.

From a practical point of view, it is improbable to accurately categorize nanowaste streams in specific classes due to factors like the nature of the nanoproducts under question, types of NMs contained in the nanowastes or nanoproducts, possibility of nanostructures aggregation and agglomeration, high variance of micro- an macro-environmental factors, and methods of NMs production at the industrial level. Paucity of data to elucidate the relationship between each of these factors to the resulting forms of nanowastes impedes their accurate classification – which in turn renders effective management of nanowastes both in the short- and long-term a difficult task.

For the purpose of clarity, salient characteristics of each of the five nanowaste classes are summarized.

- *Class I nanowastes*. Under this category, the nanowastes have very low or no toxic effects in humans and other ecological systems owing to non-toxic constituent NMs. In this case, the exposure potency is deemed to have no influence in the overall hazardousness of the nanowaste whether the NMs are bound on the surface or inside the bulk part of the product. Examples of such nanowastes are likely to include those generated from

Table 3. Risk characterization of nanoproducts and/or applications using different NMs during the disposal phase

Application	NMs	Hazard	Exposure potency	Risk at disposal
Sports equipment	SiO_2	Low	Low	Low
	Ag	Medium	Low	Low
	SWCNT	High	Low	Low
	MWCNT	High	Low	Low
Personal-care products	Ag	Medium	High	Medium
	Fullerenes	High	High	High
	Fe_2O_3	Medium	High	Medium
	TiO_2	Low	High	Low
Food/beverages	TiO_2	Low	Medium	Low
	ZnO	Medium	Medium	Medium
	Fullerenes	High	Medium	High
	Dendrimers	Medium	Medium	Medium
Sunscreen lotions	ZnO	Medium	High	Medium
	TiO_2	Low	High	Low
	Fullerenes	High	High	High
	Dendrimers	Medium	High	Medium
Automobile parts	SWNCT	High	Medium	Medium
	MWNCT	High	Medium	Medium
	Nanoclays	Low	Medium	Low
	Fullerenes	High	Medium	Medium
Solar panels	CdSe	High	High	Medium
	TiO_2	Low	High	Low
	Fullerenes	High	High	Medium
	Silicon nanowires	Low	High	Low
Memory chip	SWNCT	High	Low	Low
	CdSe	High	Low	Low
	Silicon nanowires	Low	Low	Low
	Fullerenes	High	Low	Low
Pesticides	Fullerenes	High	High	High
	Fe_2O_3	Medium	High	Medium
Paints/coatings	TiO_2	Low	Medium	Low
	SiO_2	Low	Medium	Low
	CdSe	High	Medium	Medium
Food packaging	Ag	Medium	High	Medium
	Nanoclays	Low	High	Low
	TiO_2	Low	High	Low
Agrichemicals	SiO_2	Low	High	Low
Polishing agents	TiO_2	Low	High	Low
	ZnO	Medium	High	Medium

Abbreviations: NMs, nanomaterials, SWCNT: singled-walled carbon nanotubes, MWCNT: multi-walled carbon nanotubes.

display backplane in television screens, solar panels, or memory chips containing silicon nanowires though the exposure levels may range from low to high during the disposal phase – if the NMs break away or leach out.

- *Class II nanowastes*. These are nanowastes likely to exert harmful or toxic effects on humans and other organisms because the constituent NMs exhibits toxicity that can be ranked as low to high. Based on the results obtained from the matrix developed to derive the nanowastes classes, the overall waste risk was established to be strongly linked to the exposure potency due to nanostructures embedded on the surface or inside the bulk part of the nanoproduct. If the exposure potency is low or unlikely, such wastes may be handled as non-toxic though they contain highly toxic materials. Examples include nanowastes generated after the lifespan expiry of display backplane and memory chips. Both nanoproducts contain

Table 4. Nanowastes classification based on the toxicity and the loci of the nanostructures in the nanoproducts

Nanowaste classes	Description	Possible WM protocol requirements	Comments/observations
Class I	NT: non-toxic; Loci: surface or bulk (low to high exposure levels).	No special or cautionary measures required in handling such waste stream. Current WM systems may be appropriate though no scientific studies have been reported to verify this observation.	Concerns on waste management may only arise if the bulk parent materials can cause toxicity to humans and environment after accumulating beyond a certain limit. Otherwise, nanowaste can be handled as benign/safe. No special disposal requirements.
Class II	NT: Harmful or toxic, Loci: films or bulk (low exposure level-firmly bound).	Caution is essential/ necessary. Check plausibility of low exposure to diverse ecological systems to determine the level of precautionary measures required. Nanowastes may exhibit certain hazardous characteristics to warrant some degree of caution.	Toxicity due to the NMs may warrant establishing potential acute or chronic effects to determine the most suitable and optimal management approach during handling, transportation or disposal processes.
Class III	NT: Toxic to very toxic; Loci: surface or bulk (low to medium exposure-firmly boound).	Nanowastes likely to be hazardous and caution is essential at various phases of WM. If highly toxic NMs present treat the entire waste stream as hazardous.	Protocols appropriate for managing hazardous waste streams in the entire waste management chain are desirable/ recommended.
Class IV	NT: Toxic to very toxic; Loci: free bound (liquid- or solid-suspended hence medium to high exposure).	Nanowastes are highly hazardous and treatment technologies for hazardous waste streams should be applied. However, the success of such technologies is yet to done and published in scientific journals.	Waste streams should be disposed only in specialized hazardous wastes designated sites. Inadequate WM could lead to serious threats to humans and environmental systems.
Class V	NT: Very toxic to extremely toxic; Loci: surface or free (medium to high exposure).	Nanowastes are extremely hazardous, requires efficient treatment techniques before disposal. Only to be disposed in designated waste disposal sites that are specially designed.	Should be disposed only in specialized hazardous waste streams designated sites. Poor WM leads to causing extensive pollution to diverse ecological, water systems, and severe consequences to human health.

Abbreviations: NT: nanostructure toxicity, WM: waste management.

SWCNT and according to the findings of Blaise et al.[18] and Roberts et al.,[61] these NMs are harmful or toxic to organisms (e.g. *Daphnia magna* or *rainbow trout*), and therefore, are likely to cause adverse effects if released into the environment.

However, because the nanostructures in these nanoproducts are firmly bound on the products, the overall risk to the environment may range from very low to medium after being disposed of. Therefore, in class II nanowastes, the exposure potential strongly influences the level of risk for the nanowaste stream under question. It is therefore recommended that great care be exercised in choice of disposal techniques adopted because of the likelihood for the degradation of the nanowastes, consequently, leading to the release of toxic NMs into the environment.

- *Class III nanowastes*. A nanowaste stream is classified as Class III type if its toxicity can be categorized as toxic to very toxic accompanied by low to medium potential exposure during the disposal phase. For instance, currently zinc oxide-engineered nanoparticles are being applied for manufacturing food additives. Findings of Adams et al.[9] have shown that zinc oxide is very toxic to

Daphnia magna. On the other hand, the exposure of the NMs in food additives is expected to be moderate during the disposal phase. Therefore, the resultant waste stream is likely to have medium risk potential to the ecological systems and should be handled as a hazardous waste.

- *Class IV nanowastes*. Toxicity hazard of NMs in this category ranges from toxic to very toxic, and the exposure potential ranked as medium to high because the NMs in the nanoproduct are anticipated to be freely bound on the nanoproducts (in liquid- or solid-bound form). Considering the toxic nature and high expected degree of exposure renders the waste streams to be regarded as highly hazardous. Therefore, such waste streams require specialized handling and should be treated adequately either by immobilizing or neutralizing the NMs – before they are disposed of.

For instance, nanowaste streams of paints and coatings containing CdSe could be highly hazardous. This is because CdSe quantum dots are highly toxic and expected exposure during the disposal phase is moderately high. Therefore, such waste streams should be handled with great care to avoid or minimize their long-term effects into the environment.

- *Class V nanowastes*. Nanowastes in this category are extremely hazardous as the constituent NMs hazard ranges from very toxic to extremely toxic, and the degree of exposure is high. Such waste streams require specialized handling, effective treatment, and must be disposed of in well-designed designated disposal sites. Continuous monitoring of the sites is recommended to ensure that the leachates from the disposal site are adequately managed. Among the most suitable technologies for treating such wastes includes immobilization and neutralization processes. For illustrative purposes, assume that an expired pesticide needs to be disposed of and contains fullerenes suspended in a colloidal solution. The waste stream is not only extremely toxic but also likely to have very high exposure potential when released into the environment because it is in liquid form, which potentially promotes easy interactions with environmental organisms.

In summary, the nanowaste classification presented in this paper is hinged on two assumptions. First, the NMs contained in the waste streams do not react with macroscale chemicals that could transform some of the current known benign wastes into highly hazardous – rendering the later species readily bioavailable to the ecological systems. The converse also may be true where antagonism (masking or inhibition effect) can occur, however, due to limitation of data for either case, such scenarios were not accounted for in the present classification paradigm. Secondly, the quantities of NMs contained in the waste streams and released into the environment were assumed to be of sufficient doses to generate toxic effects in the receptive organisms. Because of limited or non-existence of data on quantities of various NMs released to different nanowaste streams into the environment and concomitant to limited laboratory data elucidating the dose-response of these nanostructures made it improbable to take dose-response function into account in this study.

And finally, it is likely that one type of NM may constitute different waste streams at the disposal phase of the lifecycle ranging from benign to extremely hazardous. This implies that nanotechnology may introduce new complex challenges to the already muddy field of waste management. Clearly, this points to the need of taking urgent measures in terms of considering both short- and long-term potential impacts of nanotechnology to the waste management systems. Also, this leads to an open question, are the current legislative instruments being able to deal with nanowaste streams adequately? This will become clearer as data is generated from the scientific community and experiences begin to emerge from the waste management practitioners and specialists in the field. This underpins the importance of adequate waste management concerning the rapidly emerging nanowaste streams as means of promoting safe, responsible, and sustainable development of nanotechnology industry.

Conclusions and recommendations

Conclusions

Design and development of effective waste management systems for industrial, commercial, or household waste streams are strongly influenced by an understanding on the fate, behavior, and impacts of constituent chemicals or components to different ecological systems. Due to recent birth of the nanotechnology industry, there is paucity of data elucidating how different NMs interact with biological systems, their full extent of environmental impacts, key influencing factors on their fate and behavior in the environment, lack of technologies to detect and quantify them easily in various environmental components (soil or water), and the inability to model their behavior. Because of these challenges, among others, makes it difficult currently to state which methods are most effective in handling, storing, or treating various classes of nanowastes.

Because of high reactivity of NMs, especially due to their size, it is likely that many will aggregate and agglomerate to form bigger particles, and thus, loose their inherent nano properties. However, this may not hold for certain NMs, and this should form the basis for a search of treatment technologies that can deal with such nanowaste streams to prevent large-scale nanopollution. At present, research in this field is lacking and would require multidisciplinary approach to address the numerous factors that need to be considered in order to develop robust nanowaste treatment systems. In this paper, it has been shown that nanowastes may pose new forms of challenges to both current legislative frameworks and waste management systems. Furthermore, the results from our study strengthen the call from the scientific community for careful consideration of the entire lifecycle of nanoproducts in order to effectively manage their potential effects to humans and the environment – including the disposal phase.[22,61,63]

For a start, we have examined qualitatively the potential risks posed by different nanoproducts, and this led to proposing new classification formalism for the wastes generated from nanotechnology-related manufacturing activities and end of lifespan waste streams. This would make it possible to isolate and focus on nanowaste streams more likely to cause expansive adverse environmental effects within short- to long-term timeframes. Currently, no such classification has been developed despite high nanotechnology commercial activity globally.

Interestingly, in undertaking nanowaste classification, it became apparent that a single NM may constitute nanowaste streams of different classes, ranging from benign to highly hazardous. This has serious implications to the waste management as currently known because it may mean that risk profile for each nanowaste stream has to be assessed on case-by-case per given NM. Definitely, such approach would prove to be laborious, cumbersome, and costly to undertake owing to large number and quantities of nanowastes anticipated in the coming years as the nanotechnology-based manufacturing capabilities increase. The solution here lies in intensifying the understanding of the fate and behavior of NMs in the environment in order to develop more robust nanowastes risk assessment tools.

Recommendations

To address some of the knowledge gaps identified in this paper, several recommendations on possible intervening measures are proposed. These include:

- Well-designed research protocol to aid in the development of practical methods and tools of handling nanowaste streams. Currently, it is assumed that present systems (for handling, transportation, treatment and disposal) can handle nanowaste streams, though no scientific proof has been presented to support such claims. In addition, the research potentially will elucidate modifications that may be necessary to meet specific requirements of handling nanowaste streams effectively.
- Both at national and international levels of governance, there is need for the development of legislative framework governing NMs (nanowaste streams as well) because present statues only focuses on macroscale chemicals, and therefore, are to a certain extent inappropriate for the nanoscale materials. Though such a recommendation may appear to be a departure from the current lobbies advocating less legislative framework on businesses, it should be taken into account that, health and environmental effects of chemicals take a long time to manifest and unless well managed now may lead to NMs causing serious adverse implications to future generations and other diverse ecosystems as well.
- Currently, it is difficult to detect NMs except through use of highly sophisticated laboratory equipment under well-characterized media. However, it is impossible to detect them in soil and water environment systems. Because these materials cannot be detected in such systems, the provisions of current environmental laws are inoperable under nanowastes regime. Thus, there is urgent need to develop metrology that can easily detect NMs in different environmental media.
- Presently, a standardized measure of environmental pollution owing to NMs is yet to be established. The key shortcoming is the lack of agreed units of expressing the ecotoxicity and

toxicity of NMs in ecological systems. Therefore, there is need for rigorous research to establish practical units of toxicity (mg/L has been found to be of limited value for NMs), which in turn can be used as the basis for assessing the effectiveness of nanowaste treatment technologies similar to the current practices in dealing with macroscale chemicals waste streams. For example, studies should establish metrics of ecotoxicity based on physicochemical properties of NMs like surface area, surface chemistry, and number of particles per unit volume, which have direct link to the nano properties of NMs.

- Studies are urgently required to establish quantities of NMs that may cause an observable effect in the environment (organisms) as current data falls outside the limits set by present regulations such as TSCA of USA and in other countries as well.
- The lack of quantitative data impedes effective risk assessment of nanowastes in the environment despite their dramatic increase in different environmental systems (air, water, and soil). Therefore, for new nanoproducts, it should be made a requirement for the companies to carry out rigorous risk assessment evaluation of products including at the disposal phase prior to their introduction into the markets.
- The waste management industry should begin to pay attention to the increasing nanowaste streams as they may impact negatively already to the existing and functional effluent treatment systems. For instance, the antibacterial properties of many metal NMs may considerably affect the current biological-based effluent treatment systems. Such a scenario can only be avoided if the question of holistic waste management of nanowaste streams is addressed right from the infancy stage of the nanotechnology industry.
- The total absence of chronic toxicity effects, bioaccumulation, and biopersistence data of NMs currently makes it improbable to design and develop robust nanowaste management systems. Therefore, these research and knowledge gaps merit urgent attention to improve our capability to manage nanowaste streams effectively.
- There are numerous factors that directly or indirectly influence the fate and behaviour of NMs in the nanowaste streams once released into the environment. These comprise of environmental factors, NMs physicochemical properties, diversity of the NMs production techniques, large suite of nanoproducts with different loci of NMs, among others. Currently, there is lack of unified conceptual framework to elucidate the interaction of these factors with respect to influencing the classification and management of diverse nanowaste streams. Therefore, it is recommended that such framework needs to be developed in order to promote long-term safe and responsible management of nanowaste streams.

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