Nanomaterials in the Construction Industry: A Review of Their Applications and Environmental Health and Safety Considerations

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ABSTRACT The extraordinary chemical and physical properties of materials at the nanometer scale enable novel applications ranging from structural strength enhancement and energy conservation to antimicrobial properties and self-cleaning surfaces. Consequently, manufactured nanomaterials (MNMs) and nanocomposites are being considered for various uses in the construction and related infrastructure industries. To achieve environmentally responsible nanotechnology in construction, it is important to consider the lifecycle impacts of MNMs on the health of construction workers and dwellers, as well as unintended environmental effects at all stages of manufacturing, construction, use, demolition, and disposal. Here, we review state-of-the-art applications of MNMs that improve conventional construction materials, suggest likely environmental release scenarios, and summarize potential adverse biological and toxicological effects and their mitigation. Aligned with multidisciplinary assessment of the environmental implications of emerging technologies, this review seeks to promote awareness of potential benefits of MNMs in construction and stimulate the development of guidelines to regulate their use and disposal to mitigate potential adverse effects on human and environmental health.

KEYWORDS: concrete · windows · sensor · exposure · bioavailability · toxicity · oxidative stress · industrial ecology · risk assessment · labeling

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The nanotechnology revolution is making a ground-breaking impact on diverse science, engineering, and commercial sectors, including the construction industry. The physical and chemical properties unique to the nanoscale can lead to remarkable efficacy enhancement in (photo)catalysis, (thermal and electrical) conductivity, mechanical strength, and optical sensitivity, enabling applications such as catalysts, electronic and energy storage devices, advanced mechanical materials, and sensors.[1−4]

Tailing after emerging nanotechnology applications in biomedical and electronic industries, the construction industry recently started seeking out a way to advance conventional construction materials using a variety of manufactured nanomaterials (MNMs)[5−7] (Figure 1). Various MNMs can improve vital characteristics of construction materials such as strength, durability, and lightness,[5,8,9] endow useful properties (*e.g.*, heat-insulating, self-cleaning, and antifogging),[10,11] and function as key sensing components to monitor construction safety and structural health.[12,13] Despite the current relatively high cost of nanoenabled products, their use in construction materials is likely to increase because of (1) highly valuable properties imparted at relatively low additive ratios, (2) rapid development of new applications harnessing unique nanoscale properties, and (3) decreasing cost of base nanomaterials as they are produced in larger quantities.[14]

The benefits of incorporating MNMs in construction materials could be offset by concerns about their potential to behave as harmful environmental contaminants after their incidental or accidental release. This underscores the need for proactive risk assessment and regulatory guidelines to ensure the safe use and disposal of products containing MNMs.[15]

Use of MNMs in Construction. A variety of MNMs can have beneficial applications in construction that encompass superior structural properties, functional paints and coatings, and high-resolution sensing/actuating devices (Table 1). Selected current and potential uses of MNMs in construction are described below and illustrated in Figure 1.

Carbon-Based Nanomaterials. Carbon nanotubes (CNTs) as a proxy for polymeric chemical admixtures can remarkably improve mechanical durability by gluing concrete mixtures, that is, cementitious agents and concrete aggregates, and prevent crack propagation.[5,9,16] Incorporation of CNTs as crack bridging agents into nondecorative ceramics can enhance their mechanical strength and reduce their fragility, as well as improve their thermal properties.[17,18] Nano- and microscale sensors and actuators are implanted in construction structures for accurate real-time monitoring of material/structural damage and health (*e.g.,* cracking, corrosion., wear, and stress) and environmental conditions (*e.g.,* moisture, temperature, and smoke).[13,19] CNT/polycarbonate nanocomposite produces momentary changes in the electrical resistance when the device senses strain inputs, providing an early indication on the possible structural damage.[12] An important application is also to exploit the remarkable electron shuttle properties of CNTs and C_{60} fullerenes to boost the performance of fuel and solar cells that harvest renewable energy.[20,21]

Metal Oxide Nanoparticles. De-icers such as $CaCl_2$ and $MgCl_2$ can penetrate nano- or micropores that concrete develops due to cement hydration, reacting with concrete constituents to weaken the structure. To prevent this, SiO_2 and Fe_2O_3 nanoparticles (NPs) can be used as filling agents to pack the pores and reinforce concrete.[8,9] Their incorporation with fly ash as a cement replacement can also enhance the mechanical properties of concrete.[8]

Incorporation of or coating with SiO_2 and TiO_2 NPs allows supplementary functions for window glass, pavement, walls, and roofs. Silica (nano)layers sandwiched between two glass panels can fireproof windows.[6] Silica NPs on windows control exterior light as an antireflection coating, contributing to energy (air conditioning) conservation.[22] TiO_2 is photoactivated with UV fractions in indoor or sunlight to yield reactive oxygen species (ROS), which enable effective elimination of bacterial films and dirt attached on windows.[10,23] TiO_2 coated on pavements, walls, and roofs also functions as an antifouling agent to keep the surfaces dirt-free under solar irradiation.[7,10] In addition to photoassisted bacterial/viral inactivation, the photoinduced superhydrophilic property of TiO_2 prevents hydrophobic dust accumulation on windows. Light-mediated TiO_2 surface hydroxylation endows window glass with antifogging properties, by decreasing the contact angle between water droplets and the glass surface.[10,24] Flexible solar cells for the purpose of surface coating (referred to as energy coating), including silicon-based photovoltaic and dye-sensitized TiO_2 cells, placed on roofs and windows, produce electricity under sunlight illumination.[7]

Metal Nanoparticles. Addition of magnetic nickel NPs during concrete formation increases the compressive strength by over 15% as the magnetic interaction enhances the mechanical properties of cement mortars.[25] Copper NPs mitigate the surface roughness of steel to promote the weldability and render the steel surface corrosion-resistant.[5] Uniform nanoscale dispersion of metal alloyed with carbon or nitrogen, that is, MX carbonitride (*e.g.,* $M = Cr, Nb, and V; X = C and N$), through the steel matrix strengthens steel against creep by 2 orders of magnitude.[26] Silver NPs (nAg) can be embedded in paint to inactivate pathogenic microbes and provide antimicrobial properties to surfaces (*e.g.*, hospital walls).[11]

Lifecycle Exposure Pathways. MNMs may be accidentally or incidentally released to the environment at different stages of their life cycle (Figure 2). Some MNMs could be considered as potential emerging pollutants[27−29] because their environmental release is currently not regulated despite growing concerns about the associated risks to public and environmental health. Once in the environment, MNMs may undergo diverse physical, chemical, and biological transformations that change their properties, impact, and fate. Thus, a holistic MNM lifecycle exposure profiling is essential to evaluate potential impacts to human and ecosystem health, as well as to mitigate unnecessary risks. This underscores the need for predictive models for multimedia fate and transport of MNMs and analytical methodologies to quantify MNMs (and their form) in environmental matrices. Currently, quantitative information on MNM sources dynamics and exposure pathways remain relatively scarce, and there is concern that the current headlong rush into nanotechnology applications in construction may impede proactive exposure assessment. Albeit, current understanding of construction waste management[30−32] and environmental fate and behavior of MNMs[33−35] can provide valuable insight into likely exposure scenarios.

VOCABULARY: risk assessment – quantitative determination of risk by calculating magnitude of hazard and probability of exposure to that hazard • **industrial ecology** – systems-based, multidisciplinary approach to sustainable industrial processes that shift from linear (open loop) systems, in which resource and capital investments move through the system to become waste, to a closed loop system where waste becomes input for new processes • **structure−activity relationships** – mathematical relationships between a chemical structure and its biological activity • **oxidative stress** – imbalance between the production of reactive oxygen and a biological system's ability to readily detoxify the reactive intermediates or easily repair the resulting damage • **bioavailability** – a measure of the amount of substance/contaminant/drug in a form that produces a biological effect in a target organism

Occupational Exposure. Inhalation of MNMs during coating, molding, compounding, and incorporation can pose a respiratory health risk to workers. A risk assessment worksheet on nano-TiO_2 (released by DuPont)[36] showed that occupational exposure exceeded the acceptable limit only in packaging process. For some MNMs, worker exposure may also occur during production and processing before incorporation into products. Aerosolized carbon NPs can also be generated during aqueous dispersion of fullerenes and CNTs *via* sonication, while airborne particles are emitted during weighing.[37] Therefore, air monitoring during the over-

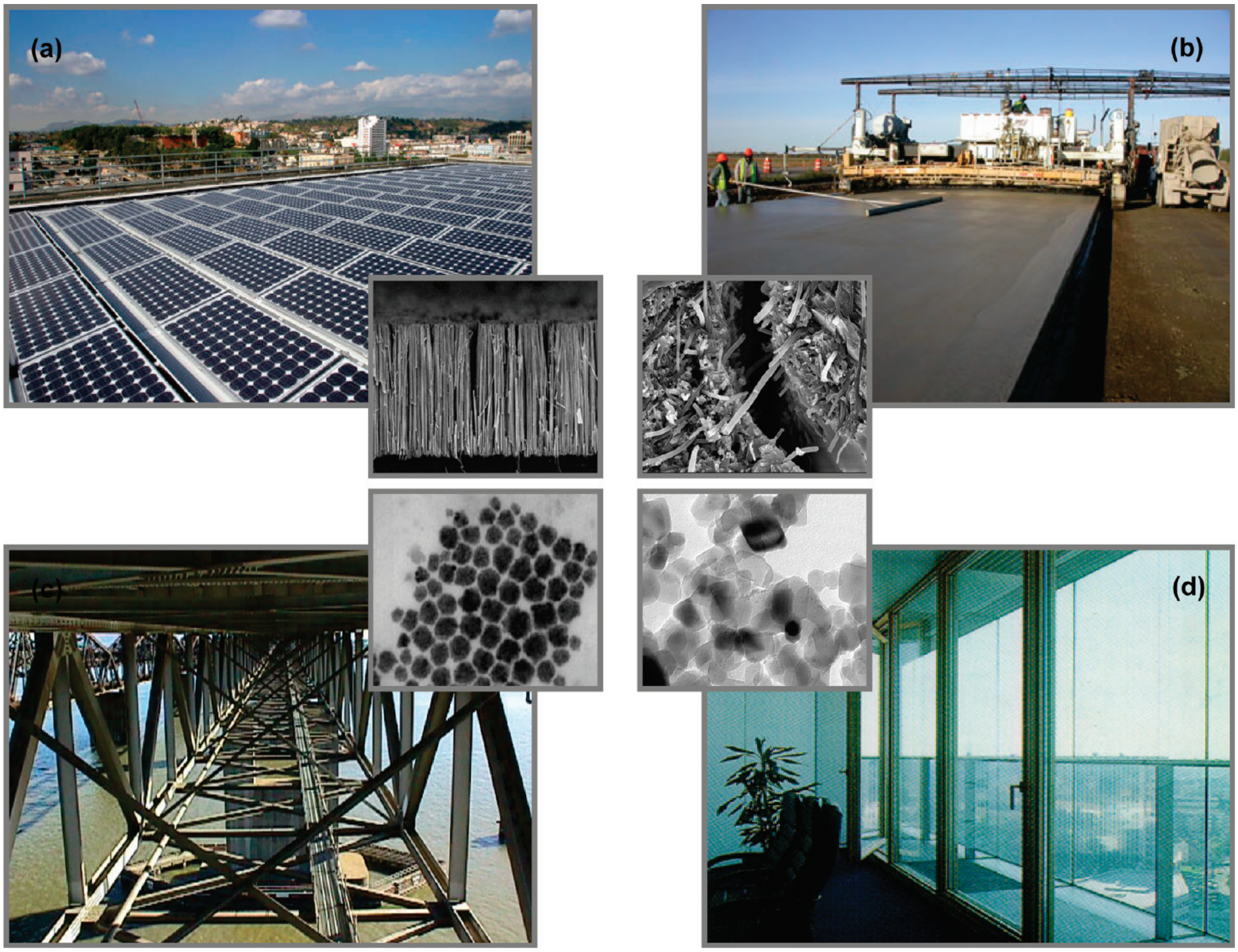

Figure 1. Examples of MNM used by the construction industry. (a) Rooftop solar panel (source: National Renewable Energy Laboratory (NREL)). Inset: Arrays of silicon/TiO_2 nanowires (source: Lawrence Berkeley National Laboratory (LBNL)). (b) Concrete pavement. Inset: Carbon nanofibers (source: U.S. Department of Transportation Federal Highway Administration). (c) Steel bridge (source: California Department of Transportation). Inset: Copper nanoparticles (source: Air Force Research Laboratory). (d) Building window (source: LBNL). Inset: TiO_2 nanoparticles.

all manufacturing processes needs to be periodically conducted over entire operation areas. Fabrication of nanomaterials in sufficient amounts that can be used for construction purposes requires significant scale up and potentially different controls and backups. The lack of material descriptors (*e.g.*, Material Safety Data Sheets (MSDS) for MNMs) further limits the development and enforcement of handling and safety standards.

Some nanomaterials may display different material forms during their lifecycles, which affect the potential for occupational exposure. For example, sepiolite clay (used by Dupont as a nanofiller for nanocomposite ap-

TABLE 1. Examples of MNMs Used in Construction

MNMs	architectural/construction materials	expected benefits	refs
carbon nanotubes	concrete	mechanical durability; crack prevention	5, 9, 16, 114
	ceramics	enhanced mechanical and thermal properties	17, 18
	NEMS/MEMS	real-time structural health monitoring	12
	solar cell	effective electron mediation	7, 20
SiO_2 nanoparticles	concrete	reinforcement in mechanical strength	5, 8, 9, 114
	ceramics	coolant; light transmission; fire resistant	115, 116
	window	flame-proofing; anti-reflection	6, 22
TiO_2 nanoparticles	cement	rapid hydration; increased degree of hydration; self-cleaning	114
	window	superhydrophilicity; anti-fogging; fouling-resistance	7, 10, 23, 24
	solar cell	non-utility electricity generation	7
Fe_2O_3 nanoparticles	concrete	increased compressive strength; abrasion-resistant	9, 114
Cu nanoparticles	steel	weldability; corrosion resistance; formability	5
Ag nanoparticles	coating/painting	biocidal activity	11

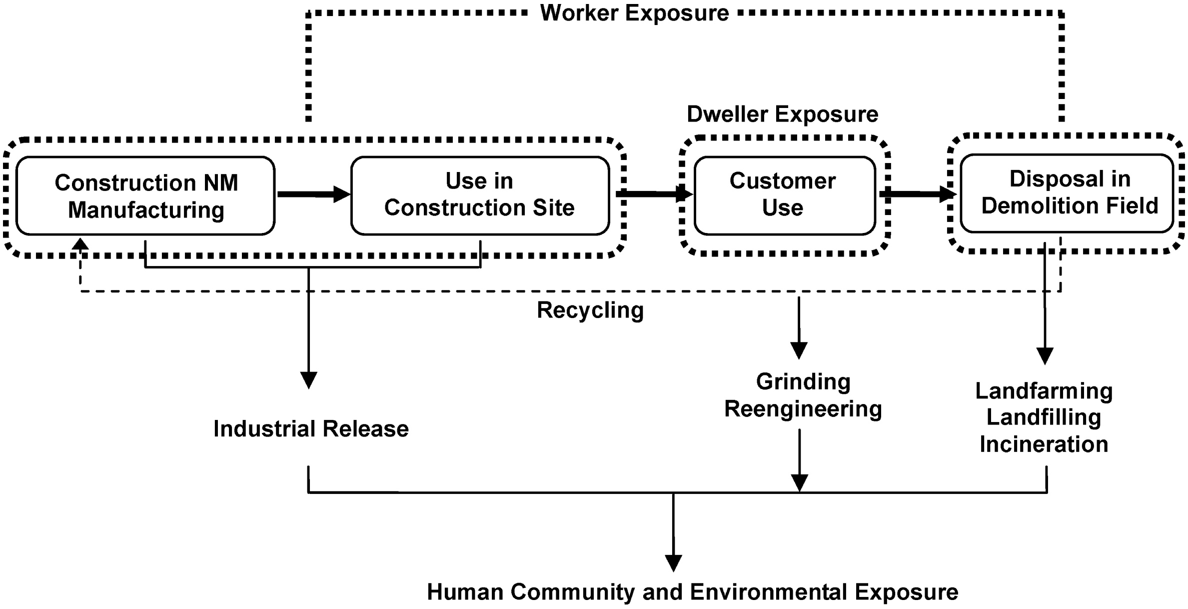

Figure 2. Possible exposure scenarios during the lifecycle of MNMs used in construction.

plications) can be found as free powder as received from suppliers, as slurries prior to polymerization, and as pellets encapsulated in the PET poly(ethylene terephthalate) resins in commercialized products.[38] Potential occupational exposure to sepiolite (and the associated health risks) is higher for the earlier processing steps and decreases after incorporation into the polymer resin. The DuPont risk analysis for sepiolite[38] reported that clay mines treated the nanoclays as nuisance dust, while full exposure controls were used at the DuPont factory. Thus, environmental health and safety controls that are used within a company may not be consistently applied across the industry.

Engineering control (*e.g.*, ventilation systems and dust collectors) and personal protective equipment (*e.g.*, masks, coveralls, and gloves) should also be provided for enclosed manufacturing facilities, along with personal monitoring and medical check-up on dermal, respiratory, and optical exposure. Since construction activities predominantly occur in outdoor environments, construction personal shielding devices such as air filter masks, gloves, safety goggles, and visors may be appropriate.

Community Exposure. Construction, repair, renovation, and (mainly) demolition activities could result in the release of some construction MNMs. Standard demolition procedures[31] recommend hazardous materials disposal (*e.g.*, asbestos cement, lead-based paint, and some persistent residues) prior to demolition, which is compulsorily assigned to a specialist team. Along similar lines, some nanoenabled construction products such as coated windows and sensor devices may have to be cautiously removed prior to demolition.

Environmental Release. Solid MNM wastes from manufacturing processes or construction and demolition activities are transported to permitted disposal sites. Prior to the disposal, these wastes likely undergo crushing. Subsequent landfarming, landfilling, and incineration could be the prevalent routes for the environmental release of construction MNMs. Aerosolization of MNMs, wastewater effluents from manufacturing processes, and construction-related work, as well as adhesive wear, abrasion, and corrosion of buildings/civil infrastructures could also result in MNMs' release to the environment. While it is argued that MNMs embedded in composites will not be significantly released or reactive in the environment, leaching of hazardous materials from various commercial products has been previously reported, including lead from paint,[39] organo-tin from ship hull paint,[40] Ni−Cd from batteries,[41] asbestos from tiles,[42] bisphenol A from food containers,[43] phthalates from plastics,[44] and PBDEs from fabrics.[45] Assessing environmental exposure to MNMs on a long-term basis is a major challenge due to analytical limitations that preclude broad multiphase monitoring of their transport, transformation, and fate in the environment.

Potential Adverse Impacts and Toxicity Mechanisms. The unique properties that make MNMs in construction so promising may also produce unforeseen environmental and human health impacts. MNMs released from nanoenabled construction materials could pose a toxicological risk to microorganisms (which provide valuable ecosystem services including primary productivity, nutrient cycling, and waste degradation) as well as to higher organisms *via* multiple mechanisms. These include cell wall disruption (*e.g.*, single-walled nanotubes, SWNTs), DNA/RNA damage (*e.g.*, multiwalled nanotubes, MWNTs), direct cell membrane oxidation (*e.g.*, aqueous C_{60} aggregates), dissolution of toxic metal components (*e.g.*, quantum dots (QDs)), and ROS-induced oxidative stress (*e.g.*, TiO_2) (Table 2 and Figure S1 in Supporting Information).

TABLE 2. MNM Toxicity to Microorganisms, Laboratory Test Mammals, and Human Cell Lines

MNMs	toxicological impacts	refs
carbon nanotubes	antibacterial cell membrane damage apoptosis/necrosis inhibit respiratory functions mitochondrial DNA damage induce granulomas and athereoschlerotic lesions inhibit bacterial clearance from lung tissues	46, 47, 51, 96, 103, 117−122
C_{60} (water-stable colloid)	antibacterial cytotoxic to human cell lines taken up by human keratinocytes stabilizes proteins lipid peroxidation	54, 56, 57, 59, 60, 62, 123−130
C_{60} derivatives	bactericidal for Gram-positive bacteria oxidative cytotoxicity apoptosis/necrosis accumulation in liver induces gliomas, sarcomas in mice and human cells	63, 64, 123, 126, 128−131
Quantum dots	bactericidal toxicity from metal release particle uptake oxidative damage to DNA accumulation of metals in kidneys cytotoxic due to oxidative damage to multiple organelles	83, 87−90, 92−95, 132−136
TiO_2	acute lethality growth inhibition bactericidal for Gram-positive bacteria suppression of photosynthetic activity oxidative damage due to ROS	75, 76, 80, 96, 137, 138
SiO_2	mild toxicity due to ROS production toxic to marine algae apoptosis up-regulation of tumor necrosis factor - alpha genes inflammatory and immune responses	79, 80, 139−142
nCu/nCuO	toxic to freshwater algae toxic to yeast DNA damage (single strand breaks) lipid peroxidation acute toxicity to liver, kidney, and spleen	96, 97, 104, 137, 138, 143

Carbon nanotubes (SWNTs and MWNTs) of respirable sizes pose a potential hazard[46] because they exert pulmonary toxicity, such as inflammation, fibrosis, and epithelioid granulomas in mammals.[47−49] Both SWNTs and MWNTs can also exhibit antibacterial properties. The mechanism of microbial toxicity of SWNTs appears to be direct damage to cell walls,[50,51] while MWNTs cause toxicity *via* oxidative stress.[52,53]

C_{60} fullerene's water-stable aggregates (referred to as nC_{60}[54]) display broad antimicrobial activity independent of the preparation method, that is, solvent-mediated, sonicated, or prolonged stirring in water.[55−57] Recent studies confirmed that nC_{60} toxicity to bacteria was due to direct oxidation of the cell upon direct contact rather than by ROS-dependent oxidative stress.[58,59] Oxidative stress exerted by nC_{60} leads to lipid peroxidation, which is also responsible for cytotoxicity in eukaryotic organisms.[60−62] C_{60} derivatives such as fullerol and carboxyfullerene, designed to enhance its aqueous availability, are capable of puncturing the cell membrane[63] and behaving as oxidizing agents in biological systems.[64]

TiO_2 irradiated with UV light or sunlight produces ROS, which cause inflammation, cytotoxicity, and DNA damage in mammalian cells.[65−72] TiO_2 morphology, which can differ significantly, affects uptake through cell membranes and stimulation of phagocytosis cells,[73] as well as endogenous ROS generation as immune response within the cell matrix.[69] Solar irradiation enables the antimicrobial activity of TiO_2 toward various bacteria, including *Escherichia coli*, *Micrococcus luteus*, *Bacillus subtilis*, and fungi, such as *Aspergillus niger*.[74−76]

SiO_2 NPs have been reported to exert carcinogenic activity.[77] Exposure to nanosized SiO_2 triggers lipid peroxidation and membrane damage on human lung cancer cells[78] and induces tumor necrosis genes in rats.[79] Nanosized silica is also hazardous to bacteria *via* ROS generation.[80]

TABLE 3. 12 Principles of Ecologically Responsible Construction Nanotechnology Adapted from Anastas and Zimmerman (2003)[99]

1: inherent rather than circumstantial (use raw materials and elements that are inherently nonhazardous if dissolved or otherwise released)
2: prevention rather than treatment (contain and minimize exposure using appropriate coating; design away hazardous features without impacting useful properties)
3: design for separation and purification of nano construction wastes (take advantage of magnetic properties for separation/stabilizing coatings that can be intentionally removed after use to coagulated and precipitate MNMs/introduce surface properties to enable facile aggregation after environmental release)
4: maximize mass, energy, space, and time efficiency (use multifunctional MNMs, quality > quantity, need > greed, enough > more, long-term > short-term)
5: "out-pulled" rather than "input-pushed" through the use of energy and materials (drive manufacturing reactions to completion by removing products rather than increasing inputs of materials or energy, according to Le Châtelier's Principle)
6: find opportunities for recycle, reuse, or beneficial disposition (*e.g.*, nontoxic construction MNMs that, when present in waste sludge that is land-applied, enhance nutrient or water retention and soil fertility)
7: target durability rather than immortality (avoid indefinite persistence)
8: need rather than excess - do not design for unnecessary capacity - avoid "one size fits all" (avoid adding excess MNMs in construction nanoproducts)
9: minimize MNM diversity to strive for material unification and promote disassembly + value retention
10: integrate local material and energy flows (holistic life cycle perspective, look for interconnectivity, system of systems)
11: design for performance in a commercial "afterlife" (enable recycling, remanufacturing, and/or reuse opportunities and for beneficial disposition)
12: use renewable and readily available inputs through life cycle (minimize carbon, land use, and water footprint)

Quantum dots contain toxic heavy metals such as cadmium, lead, and zinc in core/shell configurations.[81] The release of core metals has been accepted as the predominant mechanism of QDs toxicity toward mammalian cells[82−87] as well as bacteria.[88,89] While surface coatings attenuate core decomposition and the resulting heavy metal dissolution, some coating materials themselves may also be toxic to mammalian cells.[90−92] Also, some coatings are readily hydrolyzed resulting in the release of toxic metal ions.[88] The internalization or membrane association of QDs in eukaryotic cells caused oxidative stress, nucleic acid damage, and cytotoxicity.[93−95]

Copper or copper oxide NPs induce oxidative stress and DNA damage in bacteria, algae, yeasts, mice, and human cells.[66,96−98]

Mitigation of Public and Environmental Health Impacts. Whether nanoenabled construction materials could be designed to be "safe" and still display the properties that make them useful is an outstanding question. Adopting principles of industrial ecology and pollution prevention (Table 3) should be a high priority to prevent environmental pollution and associated impacts by MNMs.[99] Some substances can be re-engineered to create safer, greener, and yet effective products. Recent examples include the substitution of branched alkylbenzene sulfonate detergents, which caused excessive foaming in the environment, with biodegradable linear homologues,[100] as well as the replacement of ozone-depleting chlorofluorocarbons by less harmful and less persistent hydrochlorofluorocarbons.[101] Thus, it is important to discern the molecular structures and associated properties that make NMs harmful and determine which receptors might be at higher risks. However, detoxification could result in loss of useful reactivity, and focusing on exposure control (*e.g.*, by using appropriate durable coatings during manufacturing, improving matrix stability to minimize MNM leaching, and adopting controlled construction and careful disposal practices) rather than suppressing intrinsic reactivity that contributes to toxicity might be appropriate in many cases, as discussed below.

Manufacturing. At the outset, robust chemical structure−activity relationships that elucidate how particle properties determine environmental behavior of MNMs are urgently needed. These will provide a foundation for controlling hazard as well as exposure pathways. Structural properties relevant to MNM's tendency to aggregate or disperse, dissolve or partition, will directly bear on bioavailability, bioaccumulation, and toxicity.[102] Research on the toxicity mechanisms of MNMs may reveal information useful for designing environmentally benign nanocomposites. For example, SWNTs display antimicrobial activity by damaging bacterial cell walls upon contact.[51] Similarly, SWNTs interact with alveolar tissues to inhibit inflammatory responses.[103] Thus, construction and transportation applications using SWNTs must ensure that SWNTs are suitably encapsulated in polymer resins or other materials to prevent leaching or loss during abrasion. Similarly, CuO toxicity is due to released Cu^{2+} ions.[104] Both of these MNM classes will benefit from durable coatings that are resistant to weathering.

Establishing a systematic understanding of structure−reactivity relationships and their correlation to immunology and toxicity is a priority research area. Such research should not only consider acute toxicity and mortality, which have been historically the focus of nanotoxicology, but also address sublethal chronic exposure and impact on the behavior of organisms. Materials that have the potential for bioaccumulation and trophic transfer, leading to biomagnification; for example, Cd, Pb in QDs should be capped and used only if alternatives are not available.

Application. Consideration should be given to conditions encountered during the lifetime of the nanoenabled product. While "virgin" MNMs might be safe and effective, they may undergo physical, chemical, and/or biological transformations (*e.g.*, deposition, adsorption, aggregation, oxidation/reduction, and biotransformation) that change their properties. Thus, it is important to discern the effects of environmental factors (*e.g.*, pH, salinity, microbes, and natural organic matter) on the reactivity, mobility, bioavailability, and toxicity of MNMs. To minimize exposure, NM-containing materials and components should be precast or preassembled off-site under controlled conditions. For specific applications, MNMs should be selected based on their stability under conditions encountered. QDs used in solar cells should maintain their optical properties as well as integrity of coatings at the temperatures reached in photovoltaic cells. Similarly, TiO_2 formulations in self-cleaning exteriors and pavements should be strongly bound to the matrix and prevented from dispersing in the air or entering stormwater streams.

Recycling and Disposal. Although many countries have frameworks to regulate hazardous solid waste disposal, none specifically address MNM disposal. If a MNM designated as hazardous is embedded in a product that could be recycled, there will be special considerations for waste disposal and recycling companies. These range from special handling, processing for MNM recovery, and even decisions against recycling if negative impacts and energy consumption outweigh the benefits of recycling. Thus, guidelines and possibly product labeling are needed to safely and responsibly dispose and recycle the waste products that contain MNMs and waste MNMs themselves. Following disposal, appropriate interception and remediation approaches may need to be developed depending on the MNM source and release scenario.

Concluding Remarks and Perspectives for the Future. The application of nanotechnology in construction presents a myriad of opportunities and challenges. The use of MNMs in the construction industry should be considered not only for enhancing material properties and functions but also in the context of energy conservation. This is a particularly important prospect since a high percentage of all energy used (*e.g.*, 41% in the United States)[105] is consumed by commercial buildings and residential houses (including heating, lighting, and air conditioning). Opportunities for energy savings (other than using MNMs to harvest solar or other forms of renewable energy) include improved thermal management by using silica NPs in insulating ceramics and paint/coating that enable energy conservation and solar-powered self-cleaning nano-TiO_2-coated surfaces. Additional opportunities include the use of QDs and CNTs to improve the efficiency of energy transmission, lighting, and/or heating devices,[106,107] as well as incorporation of fullerenes and graphene to enhance energy storage systems such as batteries and capacitors that harvest energy from intermittent, renewable sources (*e.g.*, solar and wind).[108,109] Furthermore, MNMs that extend the durability of structures (*e.g.*, through enhanced resistance to corrosion, fatigue, wear, and abrasion) also contribute indirectly to saving energy that would otherwise be used to repair or replace deteriorated infrastructure.

MNMs can also contribute to a greener construction industry when used as substitutes for materials that can become harmful environmental pollutants, such as lead and mercury. In addition to prevention of potential exposure and resulting hazardous impacts, such replacement facilitates handling and waste management. MNMs as proxy additives include iron oxide NPs for lead (as pigment) in paint[110] and silica NPs for polychlorinated biphenyl (PCB) insulators in electrical devices.[111] Contamination due to disposal of mercury-containing devices, such as fluorescent bulbs, flow meters, pressure gauges, and thermostats, can be mitigated by using QD-based light-emitting diodes (LEDs)[106] and CNT or ZnO nanowire-based sensors.[112,113]

As new materials are designed and brought into use, it is important to understand their potential mobility and impacts in and across air, water, soil, and biota. Advanced analytical capabilities are among the first priorities to detect and characterize MNMs (released from or incorporated into construction materials) at environmentally relevant concentrations within the complex environmental and biological matrices. Environmentally responsible lifecycle engineering of MNMs in construction also needs to be prioritized. Overall, beyond the current excitement about the possibilities of MNMs to enhance our infrastructure, there are reasonable concerns about unintended consequences. This underscores the need to support research into safe design, production, use, and disposal practices and associated recycling, reuse, and remanufacturing initiatives that enhance the sustainability of both the nanotechnology and construction industries.

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Supporting Information Available: Figure S1 summarizes possible toxicity mechanisms exerted by nanomaterials to (a) prokaryotic and (b) eukaryotic cells. This material is available free of charge *via* the Internet at http://pubs.acs.org.

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