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THE ROLE OF SURFACE CHEMISTRY IN THE TOXICITY OF MANUFACTURED
CERIUM DIOXIDE NANOMATERIALS TO CAENORHABDITIS ELEGANS

THESIS

A thesis submitted in partial fulfillment of the
requirements for degree of Master of Science in the
College of Agriculture, Food, and Environment
at the University of Kentucky

By

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Lexington, Kentucky

Director: Dr. Jason Unrine, Assistant Professor

Lexington, Kentucky

2014

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ABSTRACT FOR THESIS

THE ROLE OF SURFACE CHEMISTRY IN THE TOXICITY OF MANUFACTURED CERIUM DIOXIDE NANOMATERIALS TO CAENORHABDITIS ELEGANS

Manufactured CeO₂ nanomaterials (CeO₂-MNMs) are used for a wide variety of applications including diesel fuel additives and chemical/mechanical planarization media. To test the effects of CeO₂-MNM surface coating charge on to model organism *Caenorhabditis elegans*, we synthesized 4 nm CeO₂ with cationic (DEAE-), anionic (CM-), and neutral (DEX) coatings. In L3 nematodes exposed for 24 hours, DEAE-CeO₂ induced lethality at lower concentrations than CM- or DEX-CeO₂. Feeding slightly decreased CeO₂ toxicity, regardless of coating. In L2 nematodes exposed for 48 hours with feeding, DEAE-CeO₂ caused lethality at the lower concentrations as compared to CM- and DEX-CeO₂. Sublethal effects were measured by observing reproduction and oxidative/nitrosative protein damage. Low concentrations of DEAE-CeO₂ induced similar reductions as CM- and DEX-CeO₂ that were two orders of magnitude higher. Using immunochemical slot blots to explore oxidative/nitrosative stress, no treatments produced significant changes in protein carbonyl or 3-nitrotyrosine formation; however, the statistical power of our assay was low. All treatments caused large but not statistically significant increases in protein carbonyl levels. DEAE-CeO₂ exposure caused a significant reduction in 4-hydroxy-2-nonenol levels. This research suggests that cationic coatings render CeO₂ significantly more toxic to *C. elegans* than neutral or anionic coatings.

KEYWORDS: ceria nanoparticle, nanotoxicology, ecotoxicology, model organism, redox chemistry

Emily Kay Oostveen

20 June 2014

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ACKNOWLEDGEMENTS

Many people have been instrumental in guiding and supporting me through my graduate studies. First, I want to thank my major advisor, Dr. Jason Unrine. I am grateful he saw potential in me and chose to help me develop as a scientist. He has been an incredible teacher. Likewise, I want to thank Dr. Olga Tsyusko. She was always available to help, whether it involved research, classes, or life outside of higher education. I'm equally fortunate to have worked with the people in this research group; they are all intelligent, friendly people that I am honored to call colleagues. I especially want to thank Daniel L. Starnes for regularly assisting with the nematodes and listening as I worked through various aspects of this research aloud. I would like to thank Dr. D. Allan Butterfield for allowing me access to his laboratory for a significant portion of this work; his assistance was vital to completing this research. Specifically, I want to thank Dr. Butterfield's graduate research assistant, Judy Triplett, for her assistance while I worked in his laboratory. Also, thank you to Dr. Uschi Graham for providing generous nanomaterial synthesis and characterization advice and for providing a high resolution transmission electron microscopy image. Furthermore, I want to thank my family for their support. Despite repeatedly telling me they do not understand exactly what I research, their boundless ability to let me share it with them anyway was the best help they could have given me. Lastly, I want to thank the organizations that financially supported me: University of Kentucky's Plant and Soil Science Department, Kentucky Opportunity Fellowship, and U. S. EPA Science to Achieve Results (STAR) Grant (# 834857). Without their assistance, I could not have pursued higher education and am indebted greatly to them.

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Chapter 1: Literature Review

1.1 Introduction

In recent years, manufactured nanomaterials (MNMs) have come to the forefront of technology. The American Standard Testing Methods (ASTM) defines MNMs as materials with at least one dimension in the range of 1-100 nm [1]. Between 2005 and 2009, more than 1,000 consumer products containing MNM-materials were available for purchase with more applications expected each year [2-4]. These products include semiconductors, catalysts, pigments, biomedical applications, textiles, and cosmetics to name a few [2, 5-8]. Because nanotechnology is consistently growing, intentional or accidental environmental release of MNMs is inevitable [5, 9]. The increase of the inclusion of MNMs in everyday products and the possibility of MNM exposure for humans and other organisms has led to an increase in the need for toxicological information [10].

Physiochemical properties of materials at the nano-scale may be significantly different than the same materials at the bulk scale (>100 nm). Likewise, because MNMs are <100 nm in at least one dimension, MNMs have greater surface area to volume ratio as when compared to their bulk counterparts. This exposes more atoms on MNM surface, implying the possibility of size-dependent characteristics [11, 12]. As more atoms are exposed, the likelihood of defects in crystal faces increases. This can enhance a MNM's reactivity. Additionally, the amount of reactive functional groups located on MNM surface potentially increases as particle size decreases [13]. As particle size decreases, the band gap between the valence and conduction bands also decreases [14]. Vossmeier et al. found that as CdS quantum dots decreases in size from 39\AA to 13\AA , the band gap decreases from 4.5

to 2.5 eV [15]. Additionally, the melting point changes from 400°C to 1600°C. Likewise with decreasing particle size, CeO₂ MNMs shows increased electronic conductivity [16]. CeO₂ MNMs have been shown to decrease diesel fuel consumption by 5-8% by decreasing the activation energy required for combustion. Combustion temperatures can decrease by as much as 100°C with the addition of a CeO₂ MNM catalyst [17, 18].

1.2 Environmental release, fate and transport of MNMs

Manufactured nanomaterials can be introduced into the environment either intentionally or unintentionally. Depending on the use pattern of the product, MNMs can enter the environment through aquatic, terrestrial, and aerial routes [12]. Both industrial and domestic practices can lead to MNM environmental introduction through aquatic routes. Aquatic contamination can occur through both wastewater production and normal wear of consumer products [19, 20]. CeO₂ MNMs commonly used for polishing semiconductors pass through wastewater treatment plants [5]. Ag MNMs have been shown to be released from textile based products like socks, medical masks, and toys when washed with tap water [21]. In wastewater treatment plants, MNMs are thought to primarily partition to sewage sludge, eventually being applied to soil as a fertilizer [22], suggesting that terrestrial systems may sustain a higher likelihood for contamination than aquatic systems [19, 23]. MNMs have also been observed to be released from outdoor products including textiles and paints when exposed to weathering conditions, passing directly into the environment [24]. Additionally, MNMs may be intentionally introduced into terrestrial environments; for example, nano-zero valent Fe has been shown to remediate organic and inorganic pollutants in ground water [5].

Lastly, MNMs could be deposited to soil and water from airborne deposition. CeO₂ MNMs are added to diesel fuel to help make fuel consumption more efficient [7, 17]. Similarly to tetraethyl lead ((CH₃ CH₂)₄ Pb), CeO₂ MNMs can enter the atmosphere through diesel exhaust and be deposited on surrounding soils and surface waters [25]. Incineration of MNM-containing products such as capacitors and filters could also lead to similar airborne deposition [5].

As the presence of MNMs increases in everyday products, both intentional and unintentional environmental contamination becomes more likely. Gottschalk et al. developed a predictive model based on a probabilistic material flow analysis from the perspective of MNM-based products in sewage sludge [9, 26]. This model includes both MNMs in sewage sludge and waste water. The model predicts a consistent increase in environmental concentrations of TiO₂ MNMs, ZnO MNMs, Ag MNMs, carbon nanotubes, and fullerenes. MNM presence in sediment and sludge treated soil was predicted by the model to double every three years [9].

Ultimately, MNMs from both aquatic and terrestrial environments have the potential to interact with various components of environmental media and undergo chemical, physical, or biological transformations [27]. Naturally occurring organic matter, organisms, and mineral components have potential to interact with MNMs. In the case of CeO₂ MNMs, the sorption of soil organic matter (SOM) may alter the ratio of Ce (III)/Ce (IV) [28]. Collin et al. found that CeO₂ MNMs had decreased toxicity when coated with SOM [29]. Other chemical modifications MNMs could undergo include sulfidation, dissolution, and photoreactivity [30, 31]. Interaction with their environment could cause MNMs to aggregate, potentially affecting their toxicity [32, 33].

1.3 Mechanisms of MNM toxicity

Numerous studies have investigated the toxicity of MNMs in biota. Oxidative stress caused by the production of reactive oxygen species (ROS) is often considered to play a primary role in the mechanisms of toxicity [34-39]. Many ROS are free radicals. Free radicals are short lived, highly reactive compounds containing an unpaired electron [40]. Due to the instability created by a missing electron, free radicals either donate or abstract an electron from the first molecule with which they collide. This begins a self-perpetuating chain reaction; rarely do free radicals first collide with each other, thus pairing all electrons [41]. Common examples of oxygen based free radicals include superoxide (O^{2-}), hydroxyl radicals ($OH\cdot$), and perhydroxyl radicals ($O_2H\cdot$) [42]. Hydrogen peroxide (H_2O_2) is also a potent ROS despite containing a satisfactory number of electrons [42]. Nitric oxide ($\cdot NO$) is a well-known reactive nitrogen species (RNS). While not a free radical, peroxyntirite ($ONOO\cdot$) is also a RNS [41, 42]. Because these compounds are also intermediates of biochemical pathways, organisms have natural defenses against ROS and RNS damage [43]. Enzymes such as catalase, superoxide dismutase, and glutathione peroxidase neutralize ROS and RNS [43]. Likewise vitamins C and E help mitigate oxidative and nitrosative damage [44]. When an organism's natural defenses against ROS and RNS are overwhelmed, the organism is said to experience oxidative stress.

Different mechanisms for the creation of ROS, and consequently oxidative stress, from MNMs have been explored [45]. Defects in crystal planes and more exposed surface area on MNMs can lead to the free radical formation by creating active electronic configurations [10, 46]. This can stimulate the donation or abstraction of an electron from oxygen-based molecules. Metal oxide MNMs like ZnO, Fe_2O_3 , or CeO_2 may be subject to

Fenton chemistry, a series of reactions that produce oxygen-based free radicals through redox cycling [46-48]. Phototoxicity can occur when UV light causes an electron to split from the surface of MNMs, leaving behind an unpaired electron [30, 49]. Xiong et al. found that TiO₂ MNMs released a large number of hydroxyl radicals upon photoactivation, significantly damaging mouse macrophage cell lines at concentrations as high as 1000 µg/L [50]. ZnO MNMs and SiO₂ MNMs have also been shown to release ions with UV activation [51, 52].

Additionally, dissolution of unstable MNMs could release toxic ions [31]. Some of the toxicity caused by Ag MNMs is suspected to be due to ion release [53, 54]. Levard et al. showed that when Ag MNMs are sulfidized, consequently decreasing dissolution into Ag ions, toxicity to *Daphnia magna*, *Caenorhabditis elegans*, *Lemna minuta*, and *Fundulus heteroclitus* was significantly decreased as compared to controls [55]. CeO₂ MNMs are highly stable in suspension; dissolution into ions has generally not been shown to play a significant role in its toxicity [56]. However, a recent study showed that, 30 nm CeO₂ MNMs were bioprocessed to form an ultrafine second generation CeO₂ MNM (1-3 nm) in Dawley rat liver. These ultrafine particles have been shown to possess more antioxidant potential due to a higher occurrence of surface defects where Ce was in the +III oxidation state [57].

Lastly, MNMs can denature macromolecules such as proteins [58-60]. Many examples of MNMs causing oxidative stress in a variety of organisms can be found in the literature. Heng et al. found a dose dependent increase in ROS levels when exposing human epithelial cell lines to ZnO MNM [61]. Juvenile *Cyprinus carpio* were found to accumulate more ZnO MNMs than bulk ZnO after a 30-day exposure to 50 mg/L. The suspected mechanism of toxicity was oxidative stress as implied by gill and liver biomarker responses

[62]. SiO₂ MNM induced dose-dependent cell death and oxidative damage to human skin and lung epithelial cell lines (A431 and A549 respectively). Doses ranged from 25-200 µg/L [63]. Wu et al. observed an increase in ROS formation in nematode *Caenorhabditis elegans* with exposure to three MNMs (30 nm ZnO, TiO₂, and SiO₂) [64]. ROS formation was recorded with a laser scanning confocal microscope at 488 nm of excitation wavelength and 510 nm of emission filter. Redox status was quantified by measuring the fluorescence of CM-H₂CFDA dye when oxidized. When the relative fluorescence intensities were semi-quantified as relative fluorescent units, the damage significantly correlated with mortality, growth rates, reproduction rate and locomotion of the nematodes. Hsuet et al. suggested that oxidative stress from mercaptosuccinic acid (MSA)-capped quantum dot exposure caused decreased reproduction in *C. elegans* [65]. Park et al. suggested that a single exposure to 100 mg/kg dose of single-walled carbon nanotubes intratracheally can induce oxidative stress by activating immune responses in rats [66, 67]. Multi-walled carbon nanotubes similarly induced oxidative stress in mice, leading to mesothelioma [67, 68]. Fullerenes, spherical carbon-based MNM, have both an antioxidant and a prooxidant potential [69]. In addition to scavenging ROS, fullerenes have been shown to induce oxidative stress in human astrocytes, liver carcinomas, dermal fibroblasts, macrophages, and red blood cells [69-71].

1.4 Manufactured nanomaterials

Cerium dioxide (CeO₂), a metal-oxide compound containing one of the more plentiful rare-earth elements, is highly valued for its catalytic activity mediated through the ability of Ce to transition reversibly between Ce (III) to Ce (IV). This capability is enhanced in CeO₂ MNMs [28, 72, 73]. CeO₂ MNM crystal structures can accommodate a combination

of Ce (III) and Ce (IV), but primarily contain Ce (IV) [28]. As particle size decreases, the capability of CeO₂ MNMs to transition between redox states increases [8, 74]. The oxygen storage capacity of CeO₂ MNMs illustrates this further. CeO₂ MNMs can either reversibly abstract or donate oxygen from surface molecules with which it comes into contact [75]. The high abundance of oxygen vacancies resulting in Ce at the surface in the Ce (III) state contributes to the observed catalytic properties [28, 76]. CeO₂ MNMs are already used in fuel catalysts, oxygen sensors, energy storage devices, and more [77-81]. CeO₂ MNMs primary use by tonnage is as a semiconductor, glass or mirror polishing agent [82-84]. There is also potential for use in medical antioxidant therapies [85-87].

In organisms, CeO₂ MNMs has potential to behave as both a prooxidant and an antioxidant. Some research has proposed that CeO₂ MNMs behave as a biological antioxidant, making it advantageous for use in preventative medicine. Korsvik et al. found that 3-5 nm CeO₂ MNMs both mimicked and competed *in vitro* with superoxide dismutase (SOD), an enzyme that specifically neutralizes O₂⁻ radicals into O₂ and H₂O₂ [88]. Pirmohamed et al. suggest that CeO₂ MNMs also mimic catalase, another biological antioxidant enzyme that neutralizes hydrogen peroxide [72]. Similarly, other *in vitro* studies conclude that CeO₂ MNMs are not highly toxic. Singh et al. found that normal human keratinocyte cells (HaCat) were not affected negatively at concentrations as high as 0.1 mg/L [89]. Park et al. observed no toxic effects when exposing human epithelial cell lines to diesel exhausted containing CeO₂ MNM supplementation [17]. *In vivo* studies have been completed as well. Niu et al. explored the potential of using 7 nm CeO₂ MNMs to prevent cardiovascular damage, specifically left ventricular shortening, in MCP-1 rats; they found that this was feasible when using 15 nmol exposures intravenously twice a week for two weeks

[87]. Chen et al reported that 5 nm CeO₂ MNMs scavenged reactive compounds in rats with doses as high as 1.0 μM/kg, helping prevent retinal disorders [90].

Other studies have focused on potential adverse effects of CeO₂ MNM exposure. Some studies found that the redox properties of CeO₂ MNMs cause negative effects. Park et al. observed increased ROS levels, decreased glutathione levels, cell death, and an increase in natural oxidative stress defenses in cultured human lung epithelial cells [35]. Yokel et al. found that 31 nm CeO₂ MNMs induced oxidative stress in rats at intravenous doses ranging from 50 to 750 mg/kg [36]. They observed an increase in 4-hydroxy-2-nonenal in rat hippocampus 20 hours after exposure with immunochemical slot blot assays. Nalabotu et al. also observed toxic responses in rats; with intravenous injections of up to 7.0 mg/kg CeO₂ MNMs, rat liver weight was noticeably reduced [91]. Roh et al. found that 15 nm CeO₂ MNMs caused both significant mortality and decreased fecundity in *Caenorhabditis elegans* [92]. They exposed *C. elegans* to both 15 nm and 45 nm CeO₂ MNMs at 1 mg/L; the smaller particles induced more negative responses, suggesting a size dependent effect. Thill et al. found that CeO₂ MNMs speciation is modified when in contact with *Escherichia coli* [93]. They observed significant amounts of CeO₂ MNMs interacting with the bacteria's outer membrane. Van Hoecke et al. studied the acute and chronic toxicity of 14, 20, and 29 nm CeO₂ MNMs to a green algae and two crustaceans (*Pseudokirchneriella subcapitata*, *Daphnia magna*, and *Danio rerio*). No significant acute toxicity was observed for all three organisms. The LC₅₀ of the growth rate of *P. subcapitata* was affected after chronic exposure to doses between 7.6 and 28.8 mg/L, depending on particles size. The EC₅₀ for *D. magna* reproduction ranged from 20.5 to 42.7 mg/L depending on the size of CeO₂ MNMs [94]. In both cases, the smaller CeO₂ MNMs required lower doses to cause toxicity.

Observed differences in toxicity could arise from differences in properties among CeO₂ MNMs. Particle size is a strong determining factor due to differences in available surface area with smaller particles having larger surface area [48]. The dose could also cause differing observations. As the dose increases, prooxidant effects might dominate more than antioxidant. Lastly, most of the research above does not take into account any aspect of CeO₂ MNMs beyond the CeO₂ MNM core. The surface coating of CeO₂ MNM is a largely ignored factor in many of these studies. Yet because of the observed differences in the toxic potential of CeO₂ MNMs, further study is needed to understand potential hazards, or lack thereof, in the environment. We have chosen to study these effects using the model organism *Caenorhabditis elegans*.

1.5 Surface coating

When synthesizing colloidal suspensions of MNMs, a surface coating is typically included to increase colloidal stability and decrease aggregation [12, 95]. Additionally, these coatings can affect the chemical and physical properties of the MNM core [96]. Rarely are MNMs synthesized in colloidal suspension without some form of coating and functionalization to optimize desired properties. For example, fullerene particles have a well-documented inability to be dispersed in polar solvents [69, 71, 97, 98]. The hydrophilicity of fullerenes can be increased by conjugating the surface with surfactants or polymers, rendering them more usable in applications.

Understanding how surface coating affects MNM interaction with its environment is an aspect of nanotoxicology that is often overlooked. But because the surface coating is the

portion of the MNMs that first comes into contact with the external environment, it is vital to investigate its role [99]. One chemical property of interest is that of molecular charge. The charge of MNM surface—positive, negative, or neutral—can vastly change MNM behavior. Cell membranes have a net negative charge, which can repel anionic MNMs and attract cationic MNMs. Upon contact with the membrane, MNMs can induce cellular damage through absorbing to or damaging membrane [59, 100]. Goodman et al. illustrated charge dependent properties when reporting that positively-charged 2 nm Au MNMs were moderately toxic to Cos-1 (kidney) cell lines, red blood cells, and *Escherichia coli* while negatively-charged Au MNMs of the same size were significantly less toxic [101]. Chen et al. also found that cationic MNMs are more likely to induce nanoscale holes in the lipid bilayers of living cell membranes [102].

Wang et al. explored the relationship between positively-charged enzyme lysozymes from chicken egg whites and CeO₂ MNMs with surface coatings of differing charges. They found that negatively-charged CeO₂ MNMs adsorbed the most strongly to lysozyme, neutral CeO₂ MNMs the second most, and positively-charged CeO₂ MNMs the least [103]. Asati et al. found that positively-charged CeO₂ MNMs induced more toxicity than neutral or negatively-charged CeO₂ MNMs in human H9c2, HEK293, A549, and MCF-7 cell lines, which have net negatively-charged membranes [104]. Additionally, they reported that cell damage depends heavily on where CeO₂ MNMs localizes in the cell; CeO₂ MNMs are more toxic if they partition into lysosomes as opposed to residing in the cytoplasm or not passing through the membrane at all. Positively-charged CeO₂ MNMs were found to enter lysosomes while neutral and negatively-charged CeO₂ MNMs did not [104]. When exposing cancer cell lines, though, Asati et al. reported that negatively-charged CeO₂ MNMs internalized into the cell membrane more readily. He et al. further showed that the toxicity

of CeO₂ MNMs relies heavily on electrochemical properties of its surface coating. By altering exposure media to add either a positive or negative charge to CeO₂ MNM's surface, toxicity to *E. coli* was also altered. Positively-charged CeO₂ MNMs caused membrane disruption while negatively-charged CeO₂ MNMs induced no toxic effects [105]. In addition to interaction with cell membranes, CeO₂ MNMs have been shown to interact with proteins. Patil et al. found that positively-charged CeO₂ MNMs absorbed to bovine serum albumin (BSA) more so than negatively-charged CeO₂ MNMs. The researchers also exposed adenocarcinoma lung cells; negatively-charged CeO₂ MNMs absorbed more readily into the cells [106]. From these studies, one can infer that there is a relationship between CeO₂ MNM toxicity and the chemical properties of its surface coating.

1.6 *Caenorhabditis elegans*

In addition to being a model organism for developmental biology, *Caenorhabditis elegans* has been accepted as an emerging model organism in ecotoxicological testing in both aquatic and soil environments [107]. Responses to stress and basic physiological processes are relatable to human biology, lending importance to *C. elegans* as a model organism for both human and ecological studies [108]. Additionally, fully described and invariant developmental program, ease of care, short generation times, small and clear bodies, fully mapped genome, and ease of genetic manipulation all make this soil dwelling nematode an ideal organism for exploring CeO₂ toxicity in terrestrial systems [109].

Caenorhabditis elegans is a detritivorous nematode that primarily resides alongside their bacterial food source in decaying plant matter [108, 110]. *Caenorhabditis elegans* grow through

four larval stages (L1-L4) before reaching adulthood approximately three days after hatching from eggs. Molting and a stage of lethargy are indicative of the nematodes progressing to the next developmental stage. When an environment is unfavorable, nematodes at L1 and L2 developmental stages can enter into a dormant dauer stage, which is characterized with a thicker cuticle, closed mouth parts, and little to no movement [111]. Exit from this dauer stage depends on the individual nematode and is encouraged by warmer temperatures and readily available food resources [111]. Upon reaching adulthood, nematodes are self-fertilizing hermaphrodites. Approximately 0.01% of *C. elegans* are facultative males, providing small amounts of genetic variation. Most hermaphrodites are capable of producing 250-300 offspring while sexual reproduction with a male nematode may yield as many as 1,000 offspring. In the laboratory, the Bristol (N2) strain of *C. elegans* are often raised on K-agar seeded with *E. coli* OP-50 strain, a uracil auxotrophic mutant strain [110]. N2 is the reference laboratory strain of *C. elegans*, meaning there are no intentional genetic mutations [109].

The potential negative effects of MNMs on *C. elegans* have been fairly extensively studied. Using Ag NPs, Roh et al. found decreased reproductive rates [112]. Roh also suggested that oxidative stress is the cause of toxicity by observing increased levels of antioxidant enzymes. Additionally, Meyer et al. observed both increased mortality and reduced growth rates when *C. elegans* were exposed to Ag MNMs [113]. On the other hand, Kim et al. showed that Pt MNMs acts as a SOD/catalase mimetic by increasing antioxidant defenses *C. elegans* at 0.5 mM. They quantified O_2^- scavenging by measuring formazan formation in conjunction with a SOD assay kit [114]. The nematodes were then analyzed with fluorescence methods for lipofuscin formation. Wan et al. explored the toxicity of three common metal oxide MNMs: TiO_2 , ZnO , and Al_2O_3 . They found that all three MNMs negatively affected the nematodes, especially their reproductive capabilities [115]. Tsyusko et

al. explored Au MNM toxicity using toxicogenomic approach and *C. elegans* mutant strains. At 5.9 mg/L (the LC₁₀), Au MNM interference with different biochemical pathways suggested unfolded protein responses and endoplasmic reticulum stress [58]. Studies involving CeO₂ MNMs also observed toxicity to *C. elegans*. Zhang et al. found evidence to demonstrate that CeO₂ MNMs caused detrimental oxidative stress at environmentally relevant concentrations (1 nM, 127 ng/L) [116]. Oxidative stress was measured in terms of resistance to juglone exposure. Juglone induces oxidative stress in *C. elegans* [117]. With the addition of CeO₂ MNMs, the nematodes were more sensitive to juglone's effects, i.e. increased ROS formation. This was measured with lipofuscin formation using fluorescence methods. This study claims to be the first to find adverse MNM-driven effects at realistically low doses to *C. elegans*, but does not account for toxicity induced by the surface coating alone. The CeO₂ MNM tested was coated with hexamethylenetetramine (HMT), which is of unknown toxicity to *C. elegans*. Porta et al. observed no carcinogenesis in rats and mice exposed to 0.5 or 1 % HMT in drinking water for up to 104 weeks [118]. In beagle dogs, Hurni et al. observed no reproductive or teratological effects [119]. More recently, Schrimmer et al. also report the LC₅₀ of HMT to be 354.8 mM to fathead minnows [120].

1.7 Research objectives

The objective of this research was to explore the relationship between surface coating charge and CeO₂ MNM toxicity to *C. elegans*. By using CeO₂ MNMs with neutral, positively-, or negatively-charged dextran-based surface coatings, we investigated effects on nematode mortality and reproduction. Furthermore, biomarkers of oxidative and nitrosative

stress (protein carbonyls, protein-bound 3-nitrotyrosine, and protein-bound 4-hydroxy-2-nonenal formation) were measured to evaluate oxidative damage to proteins.

Chapter 2: The role of surface chemistry in the toxicity of cerium dioxide manufactured nanomaterials to *Caenorhabditis elegans*

2.1 Introduction

The American Standard Testing Methods (ASTM) defines manufactured nanomaterials (MNM) as materials with at least one dimension in the range of 1-100 nm [1]. As compared to bulk counterparts (>100 nm), MNM can display size dependent properties. A greater surface area-to-volume ratio exposes more atoms on the surface, which can increase MNM interaction with its environment [12, 45]. MNM are incorporated into products such as semiconductors, catalysts, pigments, biomedical applications, textiles, and cosmetics to name a few [2, 5-8]. Because the production and use of MNMs is consistently growing, intentional or accidental environmental release of MNMs is inevitable [5, 9]. The increased potential for exposure to MNMs in humans and other organisms has necessitated gaining an understanding their toxicity [10].

CeO₂ MNMs are valued for their catalytic properties. They are used for such applications as diesel fuel additives, chemical/mechanical polishing agents in glass and semiconductor production, in energy storage devices, and many others [72, 73, 77-79]. CeO₂ MNM also has potential in medical applications as a therapeutic antioxidants [36, 79, 85-87]. During use or disposal of these products, CeO₂ MNMs could enter the environment through wastewater treatment effluent, sewage sludge biosolids or in diesel exhaust [17, 24]. Because CeO₂ MNMs can easily accept or donate electrons, they have been shown to have both prooxidant and antioxidant properties [72, 73]. For example, CeO₂ MNM has been shown to mimic catalase and superoxide dismutase [72, 88], while other studies have found that CeO₂ MNMs can induce oxidative stress in a variety of different species such as

Caenorhabditis elegans, *Escherichia coli*, *Pseudokirchneriella subcapitata*, *Daphnia magna*, *Danio rerio*, Sprague Dawley rats, and Fisher rats [35, 36, 92-94, 121].

In recent years, *C. elegans* has emerged as a model organism for ecotoxicology for many reasons including ease of maintenance in the laboratory, short generation times, and a fully mapped genome with associated functional genomic tools [108-110]. *Caenorhabditis elegans* has been used fairly extensively as a model organism in nanotoxicology, including studies of CeO₂ MNMs [122]. For example, Roh et al. observed decreased reproduction in *C. elegans* exposed to 15 and 45 nm CeO₂ MNMs at 1 mg/L [92]. Zhang et al. reported decreased lifespan in *C. elegans* exposed to 8.5 nm CeO₂ MNMs at environmentally relevant concentrations (1, 5, 10, and 100 nM) [116]. They concluded that the toxicity was caused by oxidative stress. However, these particles were coated with hexamethyleneteramine (HMT) and there were no controls to determine if the coating alone elicited similar toxicity or if free coating molecules existed in the exposure suspensions.

Surface coatings, in the form of small ligands or polymers, are often applied to increase colloidal stability of MNMs [12, 95]. Because the coating is the first component of MNMs to come into contact with an organism, it is vital to understand how coatings affect MNM bioavailability and toxicity [99]. Charge is one of the most important properties of coating molecules. Collin et al. found that the charge of coatings had an extremely important influence on the toxicity where CeO₂ MNMs with positively-charged coatings were two orders of magnitude more toxic than CeO₂ MNMs with neutral or negative coatings [29]. They also found that Ce was reduced from the (+IV) to the (+III) oxidation state *in vivo* by *C. elegans*. The charge of the coatings influenced the degree of reduction. Positively-charged particles were reduced to a lesser extent than neutral or negatively-charged particles [29]. Asati et al. also found that CeO₂ MNM toxicity is influenced by

surface coating charge [104]. Positively-charged CeO₂ MNMs were more toxic to A549 and MCF-7 cancer cell lines than negatively-charged CeO₂ MNMs at a dose of 1.0 mM. The increased toxicity of positively-charged particles is likely explained by the fact that they are electrostatically attracted to biological membranes than negatively-charged particles [101, 102]. Wu et al. showed that positively-charged CeO₂ MNMs are less attracted to similarly charged lysozymes at pH 4.3 than negatively-charged CeO₂ MNMs [103].

The objective of this research was to explore the relationship between surface coating and CeO₂ MNM toxicity to *C. elegans*. We used identical CeO₂ MNM cores with neutral (dextran [DEX]), positively-charged (diethylaminoethyl dextran [DEAE]), or negatively-charged (carboxymethyl dextran [CM]) surface coatings. Endpoints included mortality, reproduction and oxidative and nitrosative damage of proteins. We hypothesized that positively-charged CeO₂ MNMs would be more toxic, as measured by mortality and reproduction, to *C. elegans* than neutral or negatively-charged CeO₂ MNMs. We also hypothesized that exposure to CeO₂ MNMs would induce oxidative and nitrosative stress.

2.2 Materials and methods

CeO₂ MNMs synthesis and characterization

Dextran coated CeO₂ MNMs were synthesized using a modified method developed by Perez et al. [85]. 1.0 M CeCl₃ was combined with 1.9212 μM 10 kDa dextran (Sigma Aldrich catalog number 9004-54-0, St. Louis, MO, USA) in a 1:1 volume ratio and left to incubate overnight. The CeCl₃/dextran solution was combined with 3 M NH₄OH (2:3 volume ratio) at 323 K with constant stirring for 24 hours. The resulting suspension was transferred to a Teflon vessel and held at 353 K for 24 h to further crystallize DEX-CeO₂

MNMs. To purify the suspension, the MNMs were dialyzed in 18 MΩ deionized water with a 1000 Da cut off membrane for 72 hours changing the dialysis water every 24 hours.

Removal of NH_4^+ from solution was verified by phenol hypochlorite assay [123]. Synthesis of CM- and DEAE-CeO₂ MNMs was accomplished by combining 10 mL DEX-CeO₂ MNM solution with 1.2 g of C₂H₂ClNaO₂ or C₆H₁₅Cl₂N, respectively. These solutions were combined with 2 N NaOH (1:1 volume ratio) and stirred overnight at room temperature. CM-CeO₂ MNMs and DEAE-CeO₂ MNMs were dialyzed using the same method as the DEX-CeO₂ MNMs.

CeO₂ MNMs were characterized by transmission electron microscopy (TEM), dynamic light scattering (DLS), and phase analysis light scattering (PALS). Further characterization of the functionalization of the coatings was performed using Fourier transform infrared spectroscopy (FTIR). The FTIR results are reported by Collin et al. [29]. TEM was performed using a JOEL 2010 F microscope (Tokyo, Japan). To prepare grids for TEM analysis, a drop of CeO₂ MNM suspension was placed on glassine paper and spread into a thin layer. A lacey carbon copper coated Cu grid (400 mesh, Ted Pella, Inc., Redding, CA) was placed on the thinnest part of the solution and allowed to dry overnight before imaging. Both DLS, to determine hydrodynamic diameter, and PALS, to determine ζ potential, were completed using a Malvern zetasizer (NanoZS 90, Malvern, United Kingdom). ζ potential and hydrodynamic diameter were determined in *C. elegans* exposure media (moderately hard reconstituted water, MHRW: 96 mg NaHCO₃, 60 mg CaSO₄, 60 mg MgSO₄, 4.0 mg KCL per 1000 L DI H₂O [124]) at pH 7.4. The Hückel approximation was used to calculate ζ potential from electrophoretic mobility of the particles.

Ce concentrations in the CeO₂ MNM suspensions were analyzed with inductively couple plasma mass spectrometry (ICP-MS) (Agilent 7500cx, Santa Clara, CA). 50 μL of

CeO₂ MNM suspensions were dissolved in 6 mL trace metal grade HNO₃ and 3 mL H₂O₂ in Teflon vessels using a MARS Xpress microwave digestion system (CEM, Matthews, NC) following US EPA methods 3015 [125].

Mortality

Caenorhabditis elegans (Wild type, N2 Bristol Strain) were obtained from the *Caenorhabditis* Genetics Center (Minneapolis, MN). Nematode stocks and age synchronization were performed with previously established methods [1, 126].

Age synchronized *C. elegans* were exposed at either L3 or L2 larval stages for 24 or 48 hours, respectively, in MHRW. For each experiment, 9-11 *C. elegans* were exposed in 1 mL of CeO₂ MNM suspension for 48 or 24 h in a polycarbonate twenty-four well plate with three replicates per dose. Nematodes exposed from the L3 stage were kept in CeO₂ MNM suspensions for 24 hours either with or without 10 µL/mL *E. coli* (OP-50 strain). The inclusion of food can detract from stress the nematodes may encounter with CeO₂ MNM exposure. To establish safe doses for sublethal reproductive studies, nematodes were exposed from L2 stage in CeO₂ MNM suspensions for 48 hours and fed 10 µL/mL OP-50. The food was included to prevent *C. elegans* from entering into dauer stages. CeO₂ MNM suspensions were changed and the worms given an additional 10 µL/mL OP-50 every 24 hours. At the end of the exposure periods, *C. elegans* were determined dead if unresponsive to a gentle prodding [127]. Dose-response curves were generated from the collected data.

Reproduction

To observe CeO₂ MNM effects on nematode reproduction, L1 nematodes were exposed to 3 mL CeO₂ MNMs in MHRW in 6 cm polystyrene petri dishes with 10 µL *E. coli*

OP-50/mL exposure suspensions. The nematodes were allowed to hatch on K agar petri dishes seeded with OP-50 and were approximately 12 hours old when placed in CeO₂ MNM suspensions. Exposure suspensions were changed at 24 hours and an additional 10 µL/mL *E. coli* food was provided. Upon completion of the exposure period, one nematode was placed on a 6 cm K-agar filled polystyrene petri dish seeded with an *E. coli* lawn. The nematode was allowed to lay eggs for 48 hours and then moved to a new petri dish with K-agar. This was repeated for a total of three petri dishes. After moving the adult nematode, the newly hatched nematodes were stained with 0.5 mg/L rose Bengal stain (Acros Organics, New Jersey, USA) in DI water, heat killed for one hour at 50°C, and scored. Nematodes were counted as viable offspring if they were fully emerged from the egg cuticle. Each CeO₂ MNM dose included five to six replicates. Dose-response curves were generated from the collected data.

Oxidative and nitrosative damage of proteins

L1 *C. elegans* were exposed to 6 mL CeO₂ MNMs with 10 µL/mL OP-50 in 15 mL polypropylene conical centrifuge tubes (Corning Life Sciences, Tewksbury, MA) for 48 hours. We exposed the nematodes to 500 mg/L DEX-CeO₂ MNMs, 750 mg/L CM-CeO₂ MNMs, and 3.25 mg/L DEAE-CeO₂ MNMs, which corresponded to the EC₃₀ values for reproduction for each particle type. CeO₂ MNM suspensions were changed and 20 µL/mL *E. coli* added after 24 hours. For an additional 24 hours, nematodes were allowed to grow on a 10 cm K agar filled vented polystyrene petri dish seeded with an *E. coli* lawn. Nematodes were then washed off the petri dish with K-Media (2.36 mg KCl and 3 mg NaCl/1000 mL DI H₂O). The nematodes were washed twice more with K-media to remove *E. coli* and suspended in 0.5 mL sucrose isolation buffer (0.32 M sucrose, 2 mM EDTA, 2 mM EGTA,

20 mM HEPES) with a protease inhibitor cocktail (104 mM AEBSF, 80 μ M aprotinin, 4 mM bestatin, 1.4 mM E-64, 2 mM leupeptin, 1.5 mM pepstatin A). The nematode pellet was sonicated in an ice bath with a Misonix Ultrasonic Liquid Processor (Misonix, Inc., New York, USA) using the microtip for 20 seconds at 30% amplitude, with a 10 second pause after the first 10 seconds to avoid excessive heating. Protein concentration was determined using a BCA Protein Assay Reagent kit (Pierce Protein Biology Products, Rockford, IL). Extracted proteins were stored at -80°C before analysis.

The nematode protein samples were first derivatized to determine levels of protein carbonyls (PC) [128]. This step conjugates a 2,4-nitrophenol group to the protein carbonyl to form the hydrazine, which is then recognized subsequently by an antibody. Protein solutions (5 μ L) were combined with 5 μ L of 12% sodium dodecyl sulfate (SDS) and vortexed. 10 μ L of 2,4-dinitrophenylhydrazine (DNPH) solution were added and the solution allowed to incubate at room temperature for 20 min. Neutralization solution (7.5 μ L)(EMD Millipore, Billerica, MA) was added, and the solution was vortexed. Lastly, samples were diluted with 72.5 μ L phosphate buffered saline (PBS) to a final concentration of 250 ng protein /mL.

Proteins set aside for 3-nitrotyrosine (3-NT) and 4-hydroxy-2-nonenal (HNE) slot blots were not derivatized since primary antibodies can bind directly to protein resident 3-NT or protein-bound HNE. Samples were prepared as follows: 5 μ L of protein solution, 5 μ L of 12% SDS, and 10 μ L of Lamelli buffer (0.125 M Trizma (pH 6.8), 4% SDS, and 20% glycerol) were vortexed and allowed to rest at room temperature for 20 minutes. The solution was then diluted with 80 μ L PBS to a final volume of 250 ng/mL.

Slot blot analysis was then performed with a Bio-Dot SF apparatus (Bio-Rad Laboratories, Eugene, OR). The apparatus contained three filter papers and one nitrocellulose membrane (0.2 μ L, Bio-Rad) that were previously soaked in PBS. 250 μ L PBS

were washed through the membrane. Then 250 μ L of sample in three replicates each were placed in the slots and allowed to incubate for five minutes. After washing the samples through the membrane, a final wash of 250 μ L PBS was performed to elute unbound protein. The nitrocellulose membrane was placed in blocking solution (3% w/v bovine serum albumin in 20 mL washblot (0.2% (w/v) Tween 20 and 0.01% (w/v) sodium azide dissolved in PBS stored at room temperature) was rocked gently overnight at 5°C.

The following day, the membranes were developed with the following primary antibodies: Rb x dinitrophenol (DNP) for protein carbonyls (EMD Millipore, Billerica, MA), anti-nitrotyrosine for 3-NT (Sigma Aldrich, St. Louis, MO), or anti-4-hydroxy-2-nonenol polyclonal antibody for HNE (Alpha Diagnostics International, San Antonio, TX). 2.5 μ L primary antibodies were added directly to the 20 mL blocking solution and rocked gently for two hours. Following three washes with washblot to remove excess antibody, 2.5 μ L of anti-rabbit IgG alkaline phosphatase produced in goat was added to 20 mL washblot. This solution was rocked gently over the membrane for one hour. Upon completion, the membrane was washed thrice with washblot. Lastly, the membrane was developed for colorimetric analysis with 30 mL alkaline phosphatase, 99 μ L 5-bromo-4-chloro-3-indolyl phosphate (BCIP), and 198 μ L nitro blue tetrazolium (NBT). The membrane was allowed to dry overnight. Membranes were scanned into a TIFF data file form using a ChemiDoc MP System with ImageLab software (Bio-Rad).

Statistical analyses

For the mortality data, we calculated the percent mortality and normalized the data to controls. Two-tailed Bonferonni corrected student's T-tests compared each treatment and dose to controls. Lastly, significance was evaluated at $\alpha=0.05$ and $\alpha=0.01$ levels.

Reproduction was quantified by counting the total offspring per nematode. The data were then analyzed using the same statistical methods as mortality. Normalized data from the immunochemical slot blots were analyzed with analysis of variance (ANOVA), followed by Dunnett's post hoc comparisons between treatments and control when ANOVA was significant at $\alpha=0.05$. For all statistical tests the normality and homoscedasticity assumptions were tested using Shapiro-Wilk's and Bartlett's tests respectively. For the slot-blot analyses, the technical replicates (individual blots) were averaged for each biological replicate and therefore the n corresponded to the number of biological replicates, which were independent exposures.

2.3 Results

CeO₂ MNM characterization

TEM analysis showed the diameter of the DEX-CeO₂ MNMs to be 3.99 nm \pm 0.71 (mean \pm standard deviation), CM-CeO₂ MNM 3.36 nm \pm 0.80, and DEAE-CeO₂ MNM 3.88 nm \pm 0.90 (**Fig 2.1**). The Z-average (intensity weighted) hydrodynamic diameters, as measured by DLS analysis were 15.69, 8.72 and 13.54 nm for DEX-CeO₂ MNM, CM-CeO₂ MNM and DEAE-CeO₂ MNM. The mean ζ potentials were 2.27 mV, -22.2 mV, and +27.0 mV for DEX-CeO₂ MNM, CM-CeO₂ MNM and DEAE-CeO₂ MNM respectively.

C. elegans mortality

When exposing L3 *C. elegans* to CeO₂ MNM without food, no surface coating treatment induced greater than 50% mortality. The control mortality rate was 3.2 \pm 4.7 %.

The highest mortality rate observed for CM-CeO₂ MNM was 16.4 ± 8.1 % at a concentration of 1000 mg Ce/L. A concentration that induced comparable mortality in

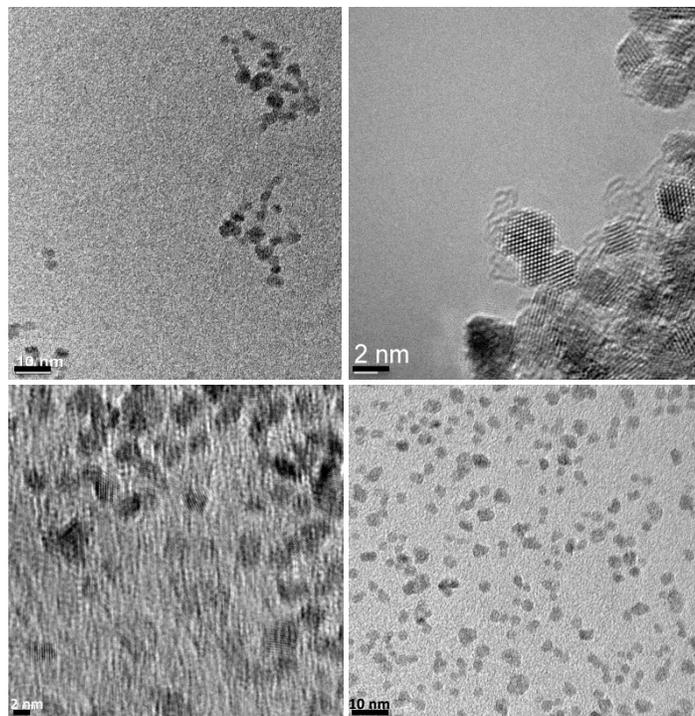


Figure 2.1. Transmission electron microscopy images of synthesized CeO₂ MNMs. Clockwise from top left: dextran (DEX), dextran (DEX) [higher resolution], diethylaminoethyl-dextran (DEAE), carboxymethyl-dextran (CM) coated CeO₂ manufactured nanomaterials.

DEAE-CeO₂ MNM ($16.3 \pm 6.1\%$) was 100 mg/L, which was a full order of magnitude lower. The mortality decreased steadily as the dose increased to 5000 mg/L DEX-CeO₂ MNMs. Mortality in DEX-CeO₂ MNMs exposures were significantly different from control ($p < 0.05$) at 10, 100, and 2500 mg/L. Mortality in response to CM-CeO₂ MNMs exposure was significantly greater than control at 100 and 1000 mg/L ($p < 0.05$). All but one concentration of DEAE-CeO₂ MNMs showed a significantly greater mortality than control ($p < 0.05$). (**Fig 2.2**)

In L3 exposures with feeding, CM-CeO₂ MNM did not induce any significant mortality below 5000 mg/L, where it was $14 \pm 7\%$. Similar mortality was observed for DEAE-CeO₂ MNMs and DEX-CeO₂ MNMs at 10-fold lower concentration of 500 mg/L with mortality of $16 \pm 10\%$ and $10 \pm 1\%$, respectively. As concentration increased, DEAE-CeO₂ MNMs elicited greater mortality than DEX-CeO₂ MNMs. Ultimately, DEAE-CeO₂ MNMs induced $80 \pm 10\%$ mortality at 5000 mg/L compared to DEX-CeO₂ MNM's $25 \pm 6\%$ and $14.1 \pm 7.1\%$ for CM-CeO₂ MNM's at the same concentration. At all tested concentrations of DEX-CeO₂ MNMs and DEAE-CeO₂ MNMs and the highest CM-CeO₂ MNM concentration mortality was significantly greater than in control ($0 \pm 0\%$) ($p < 0.05$). Additionally, mortality in all DEX-CeO₂ MNM concentrations and the highest concentration for CM-CeO₂ MNM and DEAE-CeO₂ MNM were significantly greater than control ($p < 0.01$) (**Fig 2.3**).

When the L2 nematodes were exposed for 48 hours with food, CeO₂ MNM induced higher mortality than in the L3 exposures. CM-CeO₂ MNM cause $10 \pm 6\%$ mortality at 750 mg/L. DEX-CeO₂ MNM induced a similar mortality ($8 \pm 7\%$) at 300 mg/L. DEAE-CeO₂ MNM, however, vastly increased in toxicity. At 50 mg/L, $45 \pm 19\%$ mortality was induced. All DEAE-CeO₂ MNM concentrations were significantly greater than control ($p < 0.01$).

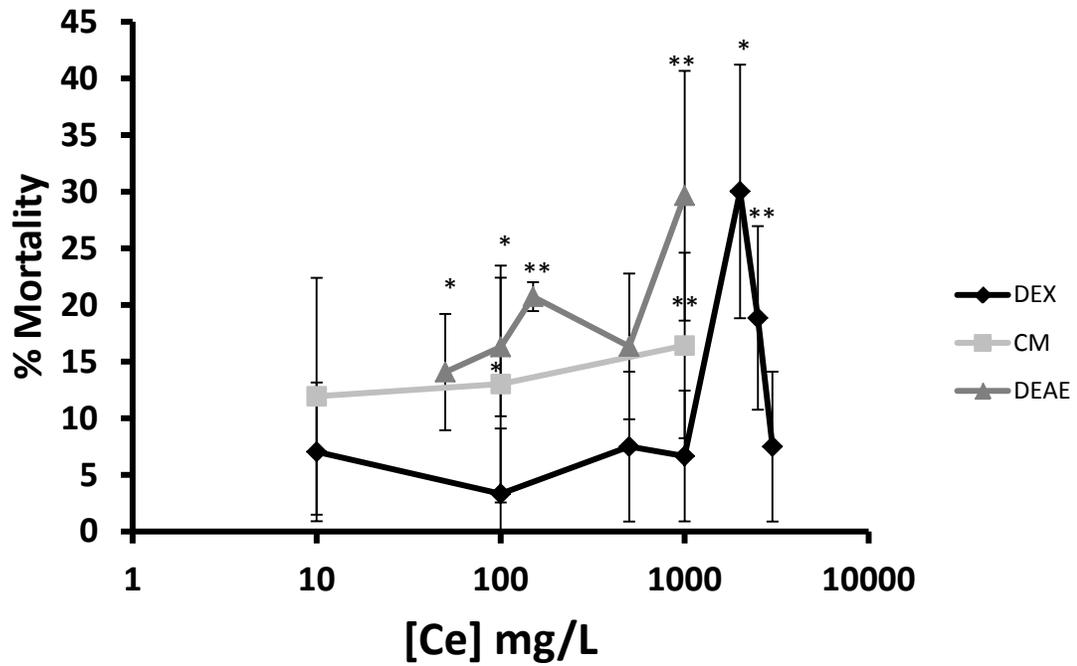


Figure 2.2. Mortality in L3 *Caenorhabditis elegans* exposed to dextran (DEX), carboxymethyl-dextran (CM), or diethylaminoethyl-dextran (DEAE) coated CeO₂ manufactured nanomaterials without feeding. Asterisks indicate that mortality is significantly greater than controls (* $p < 0.05$, ** $p < 0.01$, error bars indicate standard deviation).

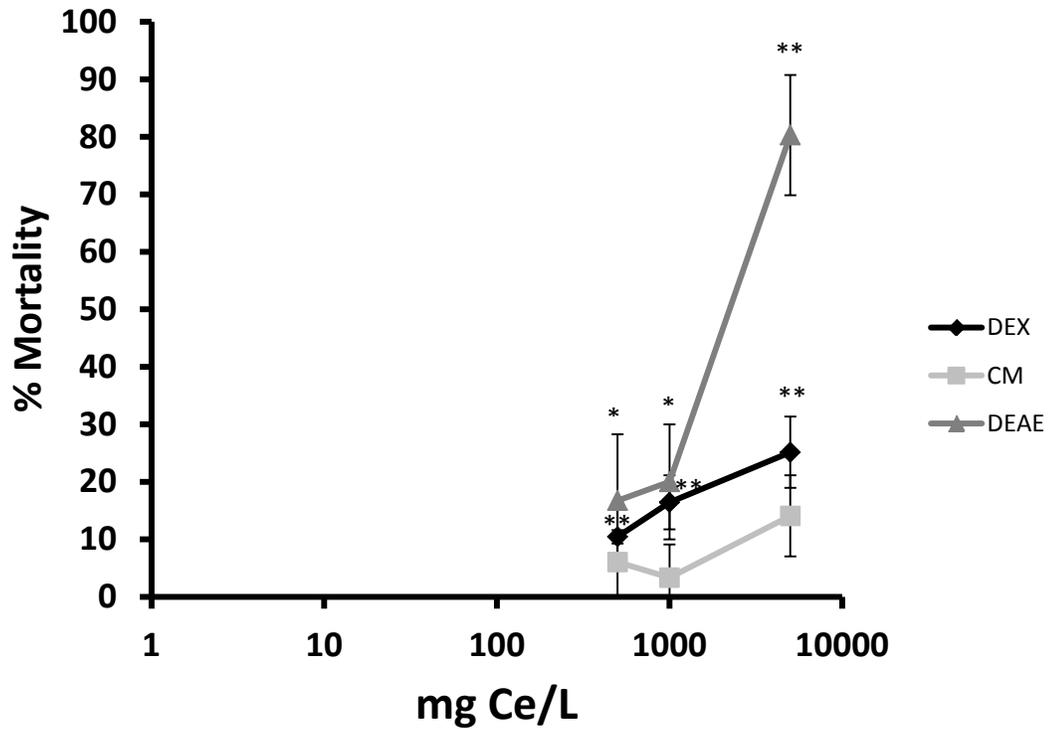


Figure 2.3. 24 Hour mortality in L3 *Caenorhabditis elegans* exposed to dextran (DEX), carboxymethyl-dextran (CM), or diethylaminoethyl-dextran (DEAE) coated CeO₂ manufactured nanomaterials with feeding. Asterisks indicate that mortality is significantly greater than controls (* $p < 0.05$, ** $p < 0.01$, error bars from standard deviation).

Mortality at 750 mg/L CM-CeO₂ MNM = also significantly greater than control = mortality (9.8 ± 6.3%) ($p < 0.01$). Lastly DEX-CeO₂ MNM 10, 100, 1000, 2500, and 5000 mg/L doses were significantly different from controls (1.2 ± 3.2%) ($p < 0.05$) (**Fig 2.4**).

Reproduction

The concentrations used for studying sublethal effects of CeO₂ MNM exposure were derived from the 48 hour mortality experiments in L2 larvae with feeding. We found that DEAE-CeO₂ MNMs caused decreases in reproduction at the lowest concentrations. The control treatment nematodes produced 168 ± 32 offspring, while nematodes exposed to 600, 700 and 1000 mg/L DEX-CeO₂ MNMs produced 82 ± 33, 82 ± 26, and 90 ± 64 offspring, respectively. Reproduction at all three concentrations were significantly lower than controls ($p < 0.05$). While reproduction was significantly lower than control only at higher concentrations ($p < 0.05$), a concentration response relationship is still evident (**Fig 2.5**). DEAE-CeO₂ MNMs and CM-CeO₂ MNMs were only significantly lower than controls at 3.0 mg/L (DEAE-CeO₂ MNMs) and 1000 mg/L (CM-CeO₂ MNMs) ($p < 0.05$) (87.09 ± 49.46 and 86.67 ± 77.13, respectively) (**Fig 2.5**). As with the 48 hour mortality exposures, positively-charged DEAE-CeO₂ MNMs required much lower concentrations than the other treatments to take effect.

Immunochemical slot blots

The concentrations used for slot blots were the estimated EC₃₀ values for reproduction studies: 500 mg/L DEX-CeO₂ MNMs, 750 mg/L CM-CeO₂ MNMs, and 3.25 mg/L DEAE-CeO₂ MNMs. Protein carbonyl (PC) and 3-nitrotyrosine (3-NT) levels were not significantly greater than controls for all three treatments; however, mean PC levels were

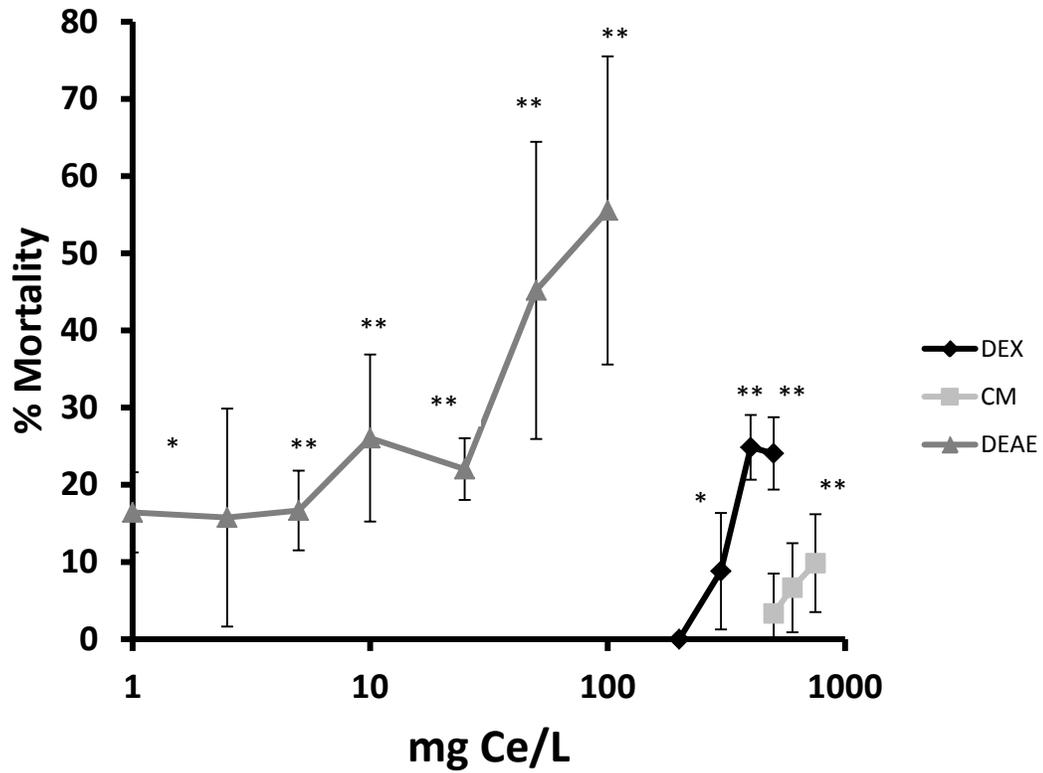


Figure 2.4. Mortality in juvenile *C. elegans* (L2) after 48 hr exposure to dextran (DEX), carboxymethyl-dextran (CM), or diethylaminoethyl-dextran (DEAE) coated CeO₂ manufactured nanomaterials with feeding. Asterisks indicate that mortality is significantly greater than controls (* $p < 0.05$, ** $p < 0.01$, error bars from standard deviation).

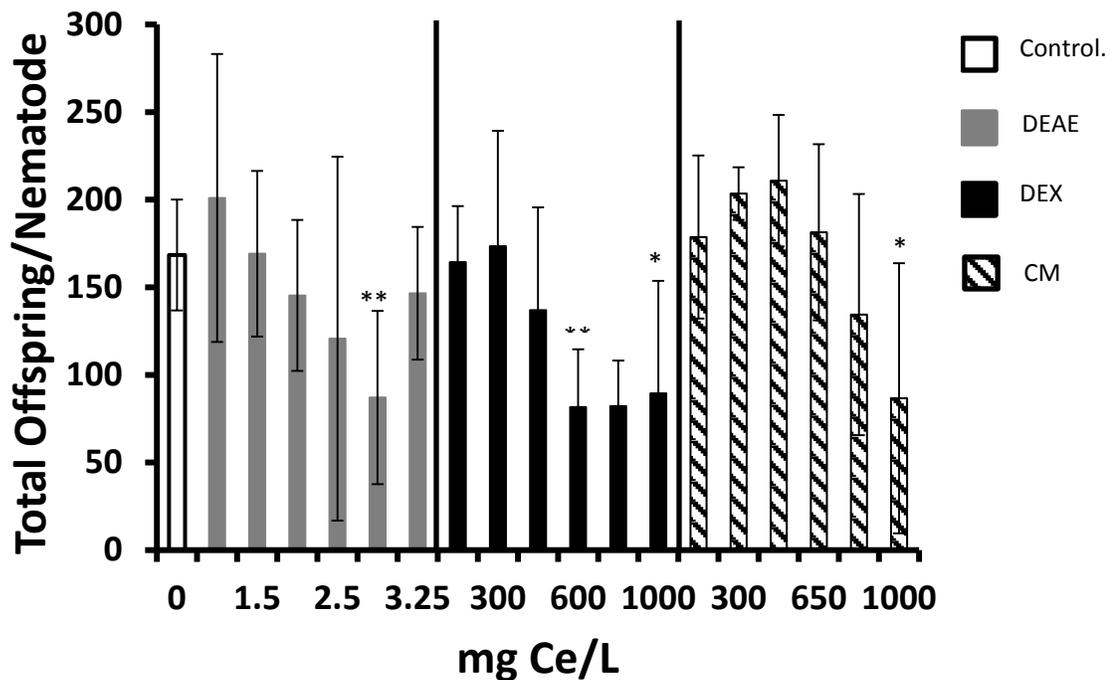


Figure 2.5. *Caenorhabditis elegans* reproduction based on total offspring per nematode exposed to dextran (DEX), carboxymethyl-dextran (CM), or diethylaminoethyl-dextran (DEAE) coated CeO₂ manufactured nanomaterials. Asterisks indicate that reproduction is significantly different from controls (*p<0.05, **p<0.01, error bars from standard deviation).

consistently higher than controls for all CeO₂ MNM treatments, although not significantly different ($F=1.68$, $p>0.2247$). DEX-CeO₂ MNMs and CM-CeO₂ MNMs had no significant effect on 4-hydroxy-2-nonenol (HNE) levels ($F=3.46$, $p>0.0512$). There was a significant decrease in HNE levels for the DEAE-CeO₂ MNMs treatment as compared to controls as determined by Dunnett's test ($p<0.05$). (**Fig 2.6**)

2.4 Discussion

As outlined below, these results indicate that the surface coating of CeO₂ MNMs has a profound impact on their toxicity. Importantly, exposure to the surface coating materials used in this study alone does not explain the observed toxicity, as we demonstrated in a previous study [29]. But when present on the surface of CeO₂ MNMs, these compounds have a profound influence on CeO₂ MNMs's toxicity to *C. elegans*.

Increases in mortality occurred for DEX-, CM-, and DEAE-CeO₂ MNMs; however, this tended to occur at far lower concentrations for DEAE-CeO₂ MNMs than for DEX- or CM-CeO₂ MNMs, particularly in the experiments where L2 and L3 nematodes were exposed with feeding for 48 hr and 24 hr, respectively. L3 nematodes exposed without food generally experienced greater mortality for all particle types than those with food. This could be related to greater physiological vigor in the fed nematodes helping them resist CeO₂ MNM toxicity or it could relate to changes in the surface chemistry or bioavailability of the particles. If bound to the microbial cells, the bioavailability of the particles may have decreased versus water only exposures. Nematode absorption could have occurred either through the cuticle or by absorption from the gut [29]. The L2 nematodes experienced greater mortality than L3 nematodes. Both nematode's developmental stage and length of

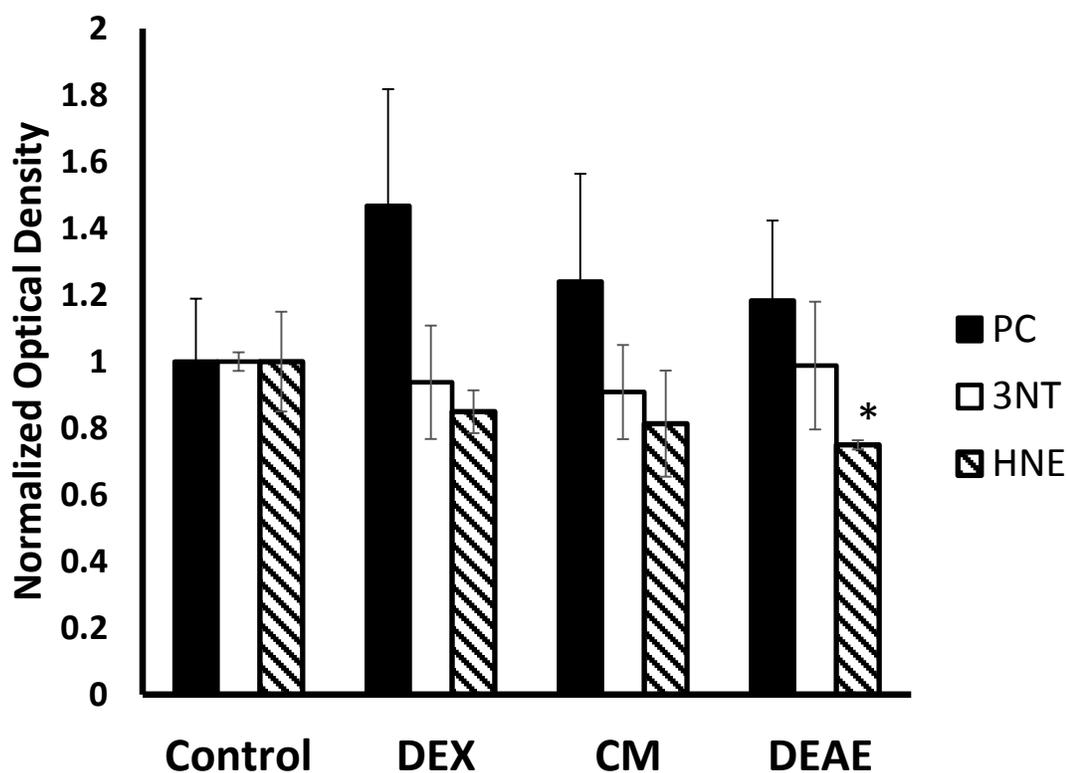


Figure 2.6. Immunochemical slot blots with *Caenorhabditis elegans* proteins probing for oxidative/nitrosative stress markers protein carbonyls (PC), 3-nitrotyrosine (3-NT), and 4-hydroxy-2-nonenol (HNE) after exposure to dextran (DEX), carboxymethyl-dextran (CM), or diethylaminoethyl-dextran (DEAE) coated CeO₂ manufactured nanomaterials. Asterisks indicate that reproduction is significantly different from controls ($*p < 0.05$, error bars indicate standard deviations).

exposure could influence the increase in mortality rates in L2 nematodes, since they were exposed for 48 hours as opposed to 24 hours for the L3 nematodes.

All three CeO₂ MNM treatments affected *C. elegans* fecundity, but as with mortality DEAE-CeO₂ MNMs caused effects at more than 100 fold lower concentrations than the CM- or DEX-CeO₂ MNMs. However, the lowest observed effect concentration for the DEAE-CeO₂ MNMs was 3 mg/L, which is far greater than the concentrations (1 nM or 172 ng Ce/L) at which Zhang et al. observed decreased in lifespan of *C. elegans* [116]. Zhang did not control for toxicity of the molecule used to coat their particles, which was HMT. It is possible that either this coating molecule in the dissolved state is toxic or that the HMT coating greatly increases the toxicity of the CeO₂ MNMs. The exposure duration in their experiment was also longer and they looked at nematode lifespan, which is a different endpoint. Zhang exposed nematodes until death (up to 25 days), where as we exposed the nematodes for a set time period (2 days maximum). The HMT coated particles in this experiment were also positively-charged which may have contributed to their great toxicity as evidenced by our data.

Immunochemical slot blots were performed on proteins extracted from nematodes exposed to concentrations of CeO₂ MNMs that provided the same sublethal response rather than the same concentration (the EC₃₀ for reproduction). DEAE-CeO₂ MNMs appeared to decrease the HNE concentrations *C. elegans*, suggesting that lipid peroxidation diminished. Additionally, the data suggested a trend that all three treatments produce greater concentrations of protein carbonyls as compared to controls; however, these were not significantly different from control at $\alpha = 0.05$. With more replicates, it is possible a significant difference could be realized. Given the difficulties in obtaining sufficient quantities of protein for this assay, we were limited to only 4 independent biological

replicates. Given previous results that show increases in protein carbonyls in rats exposed to CeO₂ MNMs [121], further investigation into oxidative stress as a possible contributor to the mode of action is warranted.

There are several explanations for the increased toxicity of positively-charged CeO₂ MNMs, but perhaps the most likely is that the particle uptake is greater for positively-charged particles. Collin et al. found that the coating of CeO₂ MNMs greatly influences bioaccumulation in *C. elegans* [29]. Positively-charged MNMs bioaccumulated in the nematode's tissue to a far greater extent than negative or neutral MNMs. Similarly, Asati et al. explored charged CeO₂ MNM internalization within normal and cancerous human cell lines. Positively-charged CeO₂ MNMs were generally taken up into the cells more so than negative or neutral CeO₂ MNMs [104]. Other explanations involve differences in the subcellular distribution of the particles. Our results add to this trend: positively-charged DEAE-CeO₂ MNM induced more toxicity to *C. elegans* in both the lethal and sublethal endpoints, sometimes with doses differing by one or more orders magnitude for the same effect; however, we found no differences in biomarkers for oxidative or nitrosative stress at the EC₃₀ for each particle type. There was a distinct trend towards increased protein carbonyl content from all three treatments as well as an exception of a significant decrease in HNE only caused by the positively-charged DEAE CeO₂ MNMs.

Similar surface chemistry dependent effects have been seen on other MNMs as well [96]. Goodman et al. showed that 2 nm Au MNM coated with anionic side chains required an exposure concentration two to three times more concentrated than the same MNM with a cationic coating to see the similar responses from *E. coli* [101]. El Badawy et al. observed that toxicity of Ag MNMs with hydrodynamic diameters ranging between 10 and 18 nm depended on the charge of their coatings to impart toxicity to a Gram-positive *Bacillus*

species, measured with mortality and respiration [129]. Positively-charged Ag MNMs were the most toxic, negatively-charged Ag MNM the least toxic, and neutral Ag MNM were in between. Hoshino et al. synthesized ZnO coated CdSe 3.5 nm quantum dots. When they functionalized either a positively- or a negatively-charged group to the ZnO coating, they observed that positively-charged MNM were more toxic than negatively-charged. Interestingly, they noted that uncoated MNMs were not toxic to WTK-1 cells at concentrations as high as 400 mg/L [130].

In conclusion, we observed that the toxicity of CeO₂ MNM is highly dependent on the molecular charge of the surface coating. While all three treatments increased *C. elegans* mortality rates and lowered their reproduction rates, positively-charged DEAE-CeO₂ MNM affected the nematodes at much lower doses than negatively-charged CM-CeO₂ MNM or neutral DEX-CeO₂ MNM. While not statistically significant as compared to controls, there was a noticeable trend towards increased protein carbonyl content with all three CeO₂ MNM treatments. In future studies, we plan to further explore the role of oxidative stress in the mechanism of toxicity given that these results provided some indication that protein carbonyls may be elevated. Optimization of *C. elegans* exposures to provide greater replication for the slot-blot measurements will be necessary.

Chapter 3: Conclusions

The aims of this research were to better understand the role of CeO₂ MNM coating charge on toxicity to model soil organism *Caenorhabditis elegans*. By observing mortality, reproduction, and formation of biochemical oxidative stress indicators, we were able to add to the understanding of the properties of CeO₂ MNMs that contribute to toxicity. We hypothesized that positively-charged CeO₂ MNMs would more toxic to *C. elegans* and that CeO₂ MNM exposure will induce oxidative stress. To test these hypotheses, we first synthesized CeO₂ MNMs with either positively-, negatively-charged, or neutral dextran-based coatings. Toxicity was tested with both lethal and sublethal endpoints with exposure to a wide range of concentrations. We probed for oxidative stress indicators with a well-established oxidative stress assay. Overall we confirmed that coating charge plays a very important role in determining the toxicity of these materials. Furthermore, we also developed a set of model nanomaterials that have identical cores with polymer coatings that differ only in the nature of the functional groups present and the molecular charge. These materials were used in other concurrent studies [29] and will be a resource for future investigations on the role of coating charge on CeO₂ MNM toxicity.

When MNM are manufactured, a surface coating is frequently employed to increase stability and decrease aggregation. Many of the studies previously published did not include surface coating as an experimental variable. But because the surface coating is the first part of MNMs to come into contact with biological membranes, it is vital to explore this aspect of MNM use and their toxicity [99]. Specifically of interest are coatings with different molecular charges. Previous research supports that MNMs with positively-charged coatings are more readily attracted to most biological membranes as compared to neutral or

negatively-charged MNMs [101, 102]. Furthermore, Wang et. al demonstrated that positively-charged CeO₂ MNM were repelled from positively-charged lysozymes [103]. Asati et. al also demonstrated that CeO₂ MNM surface charge is an important factor. By studying neutral, positively-, or negatively-charged CeO₂ MNM, they found that positively-charged and neutral CeO₂ MNMs internalized into the normal human cell lines studied. Negatively-charged CeO₂ MNMs did not interact with normal cells as much, but did internalize more into cancerous cells. Once inside, CeO₂ MNMs still relied on surface charge to impart toxic effects [104]. Our research lends strength to existing literature by showing that surface coating effects is a vital aspect of MNM synthesis to consider. On their own DEX, DEAE, and CM are not toxic to *C. elegans* [29]. But when bound to the CeO₂ MNM surface, they do influence the MNM's toxicity: positive DEAE-CeO₂ MNMs generated toxic effects at dramatically lower doses than both DEX-CeO₂ MNMs and CM-CeO₂ MNMs.

The differences between CeO₂ MNM's behavior observed in this research and previously published studies in *C. elegans* could be due to different sizes of MNM tested, exposure methods, or surface chemistry of the particles themselves. Arnold et al. published that CeO₂ MNMs were more toxic than bulk CeO₂ (>100 nm) [32]. Roh et al. studied the toxicity of 15 nm and 45 nm CeO₂ MNMs to *C. elegans*; the smaller particles were more toxic than the larger ones [92]. To provide context, our CeO₂ MNMs averaged 4 nm in diameter. DEAE-CeO₂ MNMs did induce similar toxic responses to previously published studies, but DEX- and CM-CeO₂ MNMs required far greater concentrations than previously studied particles. This suggests that the DEX and CM coatings greatly reduce the toxicity of CeO₂ MNMs; however, they did not appear to have antioxidant properties as measured HNE, 3-NT or PC at the concentrations tested. While we used established aquatic exposures [126], other researchers may have utilized other methods. Zhang et al. embedded CeO₂ MNMs

into solid nematode growth medium [116]. In comparison with liquid exposure, this could either limit the bioavailability of CeO₂ MNMs or even lead to agar-mediated surface modifications. Interestingly, both our research and Zhang's work show decreased fecundity in *C. elegans*; Zhang reported dramatically lower doses to see a significant effect. Bearing these differences in mind, our research adds to the general consensus that CeO₂ MNMs can impart toxicity and that the surface coating, particularly a positively-charged coating, is an incredibly important factor to consider.

The existing literature suggests that CeO₂ MNMs has potential to be both a prooxidant and an antioxidant [36, 87, 90, 116, 131]. At low doses, CeO₂ MNMs can act as an antioxidant [121, 132]. It can mimic catalase and superoxide dismutase [72, 88]. But at higher doses, CeO₂ MNMs instead could be a prooxidant [116]. In our study, exposure to positively-charged DEAE-CeO₂ MNMs decreased 4-HNE formation at 3.25 mg/L. However, a significant decrease in reproduction was observed at this concentration, so there was a net adverse effect on the nematodes. Furthermore there were also large, but not statistically significant increases in protein carbonyl levels. Regardless, if CeO₂ MNMs do not induce oxidative stress, they must impart toxicity through a different mechanism. We know from previous research that DEX, DEAE, and CM coatings by themselves are not toxic [29]. Several mechanisms have been described by which MNMs may cause toxicity independent of ROS. For example, Tsyusko et al. published evidence that Au MNMs causes endoplasmic reticulum stress and protein misfolding [58]. Another possibility is that our CeO₂ MNMs did not internalize into cells in exactly the same fashion as in previous research. Asati et al. report that the surface chemistry of CeO₂ MNMs dictate not only how much is internalized into the cell, but the final location as well. If CeO₂ MNMs are localized

in an acidic microenvironment, such as inside a lysosome, they are more likely to behave as a prooxidant [104].

In future research, we plan to probe further into *C. elegans* biochemical responses to CeO₂ MNM exposure. By identifying which proteins are modified either in expression or oxidative damage, we can outline CeO₂ MNM's mode of action more accurately and better understand where the MNMs localize within inside the nematode's cells. Additionally, we will explore other MNM surface modifications such as lower or higher molecular weight coatings. By using longer or shorter dextran molecules when synthesizing CeO₂ MNMs, observing physical changes in coating molecular weight and conformation rather than charge could lead to a deeper understanding of the role of surface coatings in CeO₂ MNM toxicity.

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