# Fate, behaviour, and toxicity of engineered nanomaterials in the environmental systems

*Ndeke Musee*
*Nanotech Environ Impacts Res Group, NRE*
*nmusee@csir.co.za*

***University of Free State, South Africa, 1st – 4th April, 2012: NanoAfrica2012***

our future through science

# *Some questions: risk concerns*

- At the time of introducing nanotechnology, were there indications of society's capability to address the technology's potential risks to human health and the environment?

- Has the society learned from previous malevolent technologies failures, and inability to reach their full potential despite good intentions? **IF YES**, can this catalyse motivate a different approach to nanotechnology development trajectory?

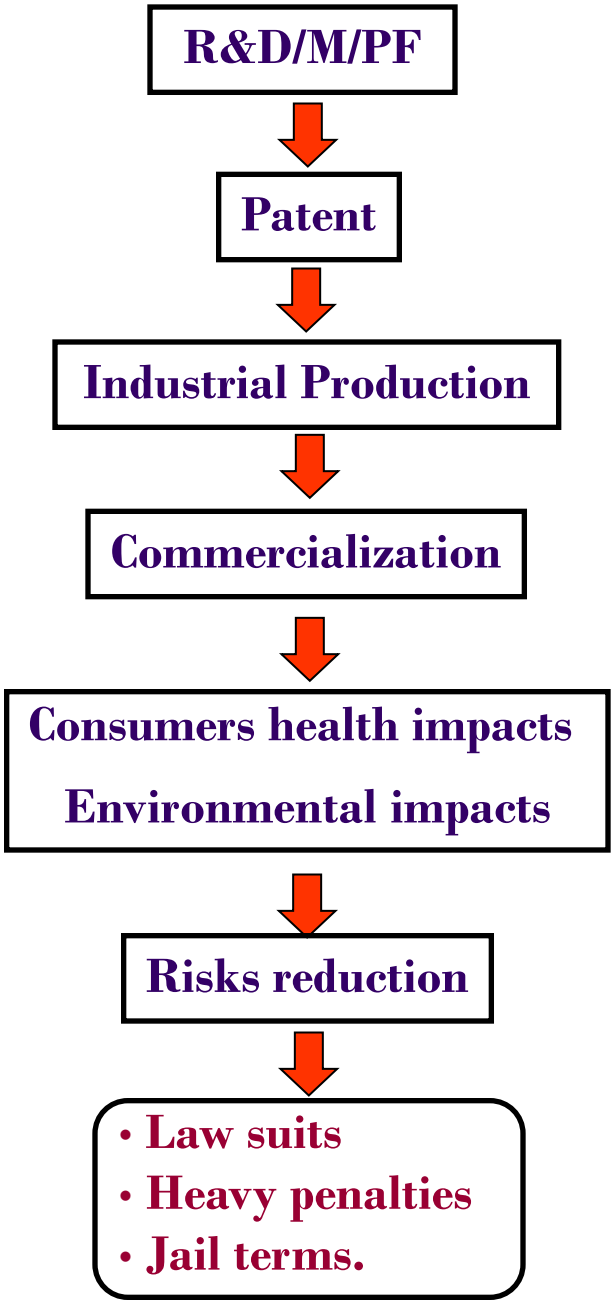
- How has risk knowledge (from previous technologies) has influenced approaches adopted to address the potential risks of nanotechnology??

# *Lessons learned*

- Asking more critical questions early on at R&D phase of a given technology related to risk management
- Development of research and governance collaborations across disciplines, departments, and international boundaries
- Development of process of establishing targeted research to generate relevant knowledge
- Engagement of diverse stakeholders (government, scientific, industry, civil society, etc)
- Interrogation of existing oversight mechanisms to establish their suitability within nanotechnology era

***However, very slow progress….***

# One-way approach




Malevolent technologies are endless:

- Dichlorodiphenyltrichloroethane (DDT)
- Asbestos
- Chlorofluorocarbons (CFS)
- Genetically modified organisms (GMOs)
- Cell research
- Space programme**
- Mining (silicosis-related ailments)
- Nuclear waste

- **Lesson: Missed early warnings became very costly to human health and the environment.**
- **Lessons learned too late!!**

*Musee et al., 2010, S. Afr. J. Sci. 67-72*

# *Environmental risks of ENMs*

- Environmental risks of ENMs to biological organisms in the environment MUST satisfy two conditions: Hazard & Exposure

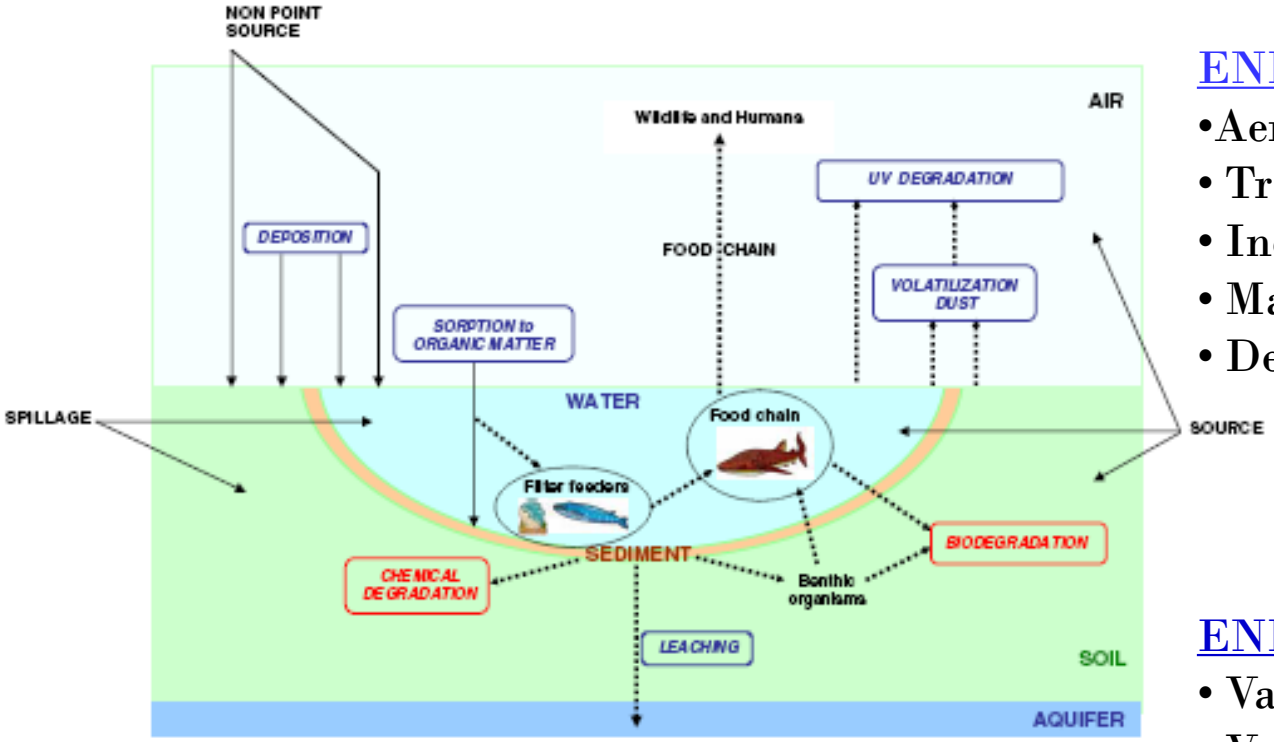
- Hazard (toxic effect): due to **nano/bio interface** –interactions of ENMs with: Biomolecules, cell membranes, the cellular interior, organisms, tissues, organs, populations, and ecosystems.

- Exposure: ability for ENMs (nanoscale toxicant) to be within the proximity of the organism or nano/bio interfaces. Depends on: **exposure media** (e.g. bacterial broth or yeast culture media), and **environmental factors** (e.g. type of water (sea, fresh or ground), pH, ionic strength, etc).

# *So, what do we know of ENMs risks*

- We know we do not know enough on ENMs risks: many unknowns
- Window of opportunity to undertake risk assessment of ENMs rapidly closing (lost golden opportunity)
- Numerous ENMs tested have shown some form of toxic effects
- Fate and behavior of ENMs controls: hazard and exposure
- Collaborative approach under tier model, best suitable
- Increasing need & demand for legislative framework: not feasible presently

# Environmental ENMs Pathways




## ENMs in Air

- Aerosol
- Transportation: Long distances
- Indoor & ambient environment
- May aggregate & attach to dust
- Deposit in water &/or soil

## ENMs in Soil

- Retention in soil matrix
- Break through on soil matrix
- Leaching into groundwater
- Possibility pathway to food chain

## ENMs in Water/Aqueous Environ

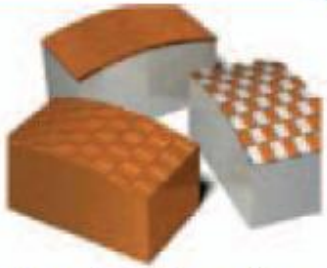
- Varied degrees of precipitation
- Varied Transport/bioavailability (stability dependent)
- Aggregation/agglomeration
- Interactions with aquatic colloids
- Possible deposition on sediments

**Farre et al., 2009, Anal Bioanal Chem**

# Exposure potential of ENMs estimation

Bulk-based NMs (one or multiphase)

*EP: Very low to low*



Structured surface, film or structured

*EP: Very low to medium*

Surface bound

*EP: Low to high*

NMs suspended in liquids

*EP: Highly likely*

NMs suspended in solids

*EP: Medium to very high*

Airborne/free ENPs

*EP: Highly likely*

*Modified from Hansen et al. 2007 (Wischers and Musee, 2010)*

***EP: Exposure potential***

# *Fate of ENMs in the Environment*

Key processes include:

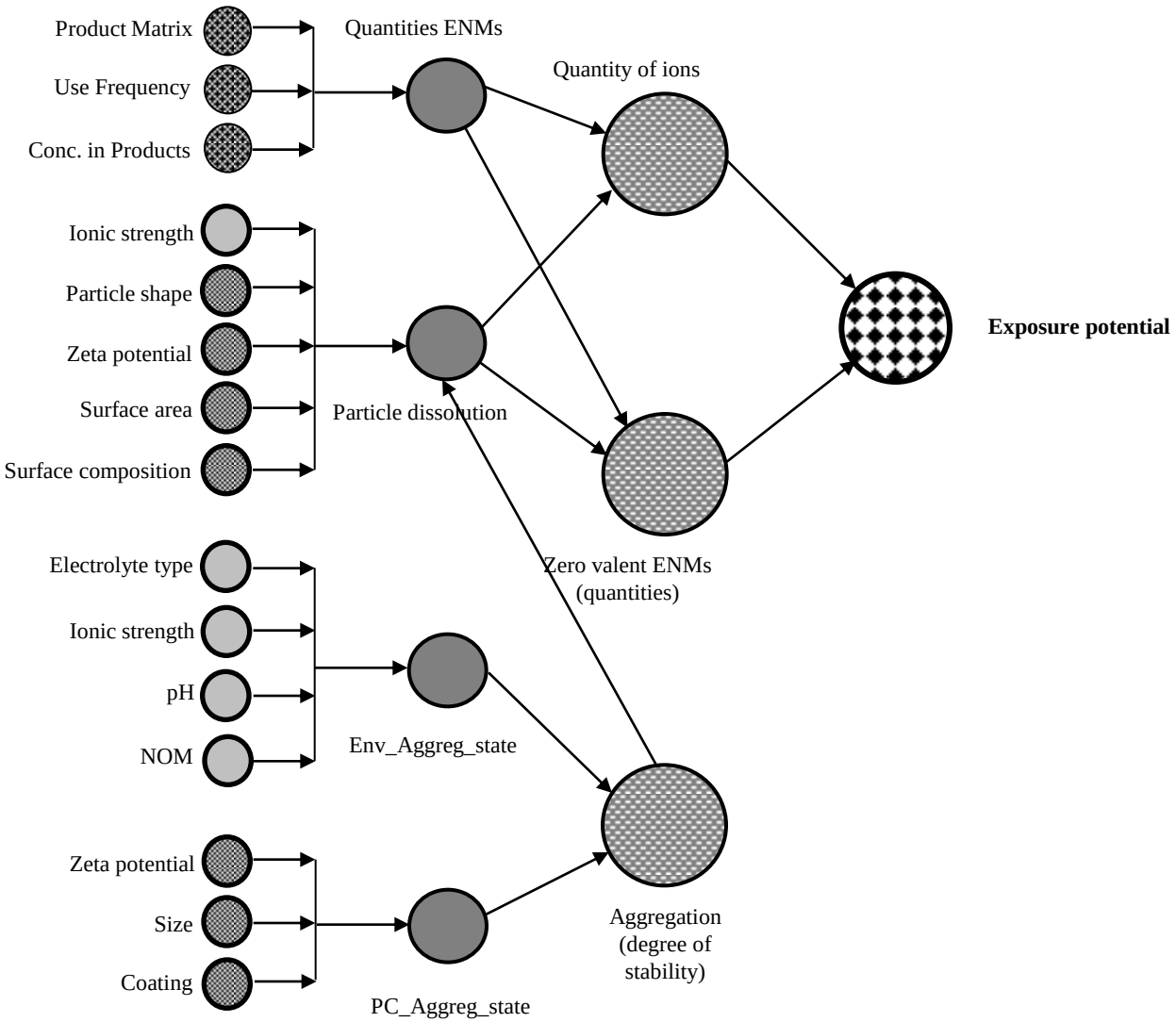
- Transformation
  - Dissolution (pH, ionic strength, NOM, etc)
  - Surface coating (type of ligands, ENM type, etc)
  - Oxidation (NPs type, light, microorganisms, etc)
  - Photodegradation (light, etc)
- Organism cleansing
  - Uptake
  - Translocation
  - Transformation
  - Degradation

# *Influencing factors to ENMs fate in aquatic systems*

- Agglomeration and /or aggregation
- Dissolution
- Chemical reactions (e.g. oxidation or reduction)
- Ligand exchange/coatings/functionalization
- Formation of new solid phases

Handy et al. 2008; Klaine et al. 2008; Navarro et al. 2008; Auffan et al., 2010; Bian et al., 2011; Liu et al., 2011.

# Fate/exposure model




**Proposed model for exposure estimation (Musee., 2012, unpublished)**

# Effect of pH, IS, NOM on Dissolution

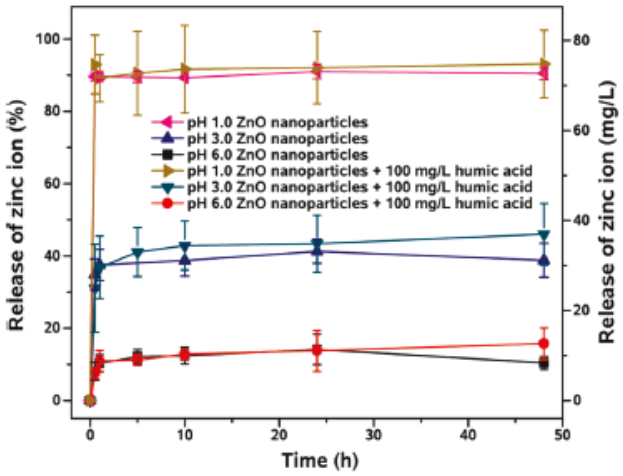



Figure 5. Time-dependent measurements of ZnO nanoparticle dissolution in the presence and absence of humic acid (100 mg/L initial mass concentration) at different pH (1.0, 3.0 and 6.0).

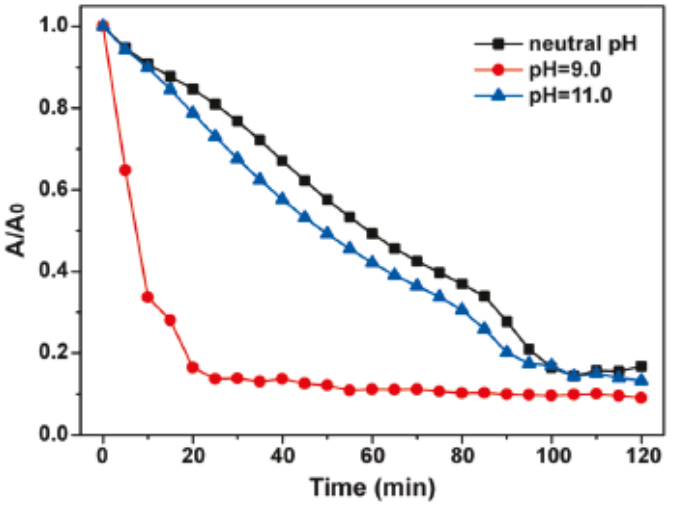
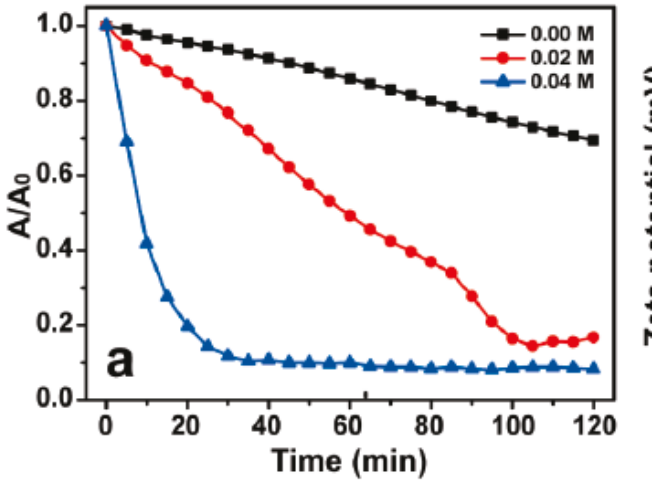



Figure 6. Sedimentation plots for ZnO nanoparticles at different pH (neutral pH, pH 9.0, and pH 11.0).




Bian et al., Langmuir, 2011,

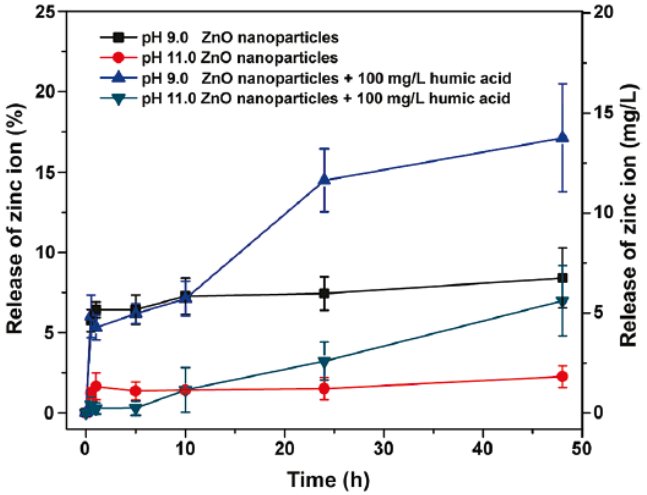
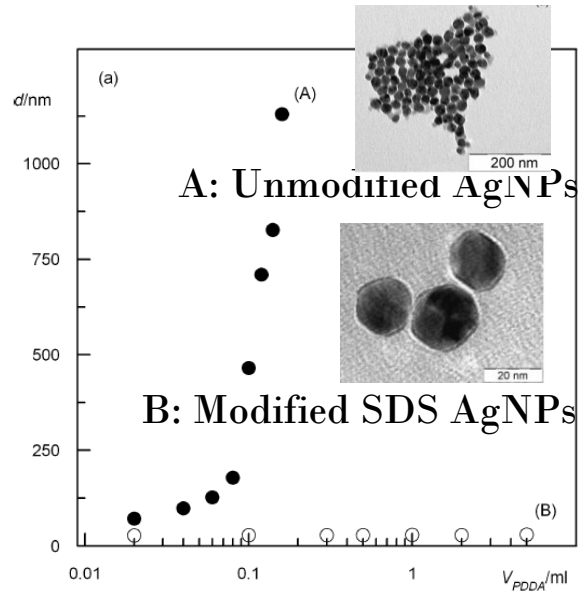



Figure 8. Time-dependent measurements of ZnO nanoparticle dissolution in the presence and absence of humic acid (100 mg/L initial mass concentration) at pH 9.0 and 11.0.

# Effect of surface coating

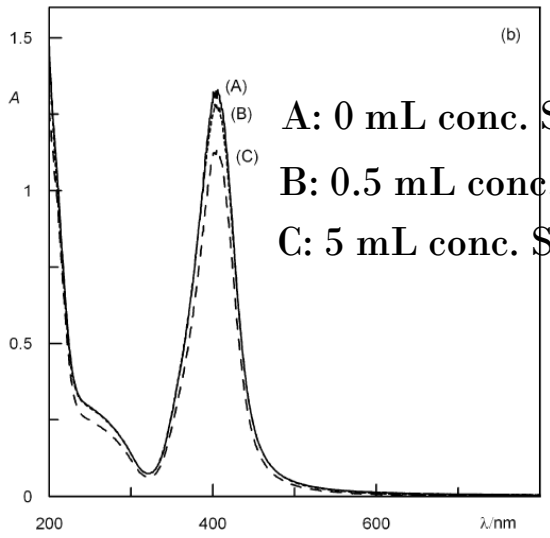
DLS size measurements




A: Unmodified AgNPs

B: Modified SDS AgNPs

UV/Vis spectra

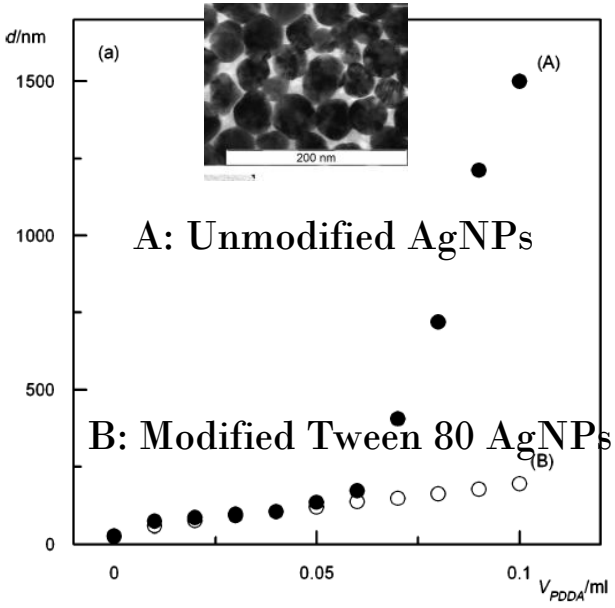



A: 0 mL conc. SDS

B: 0.5 mL conc. SDS

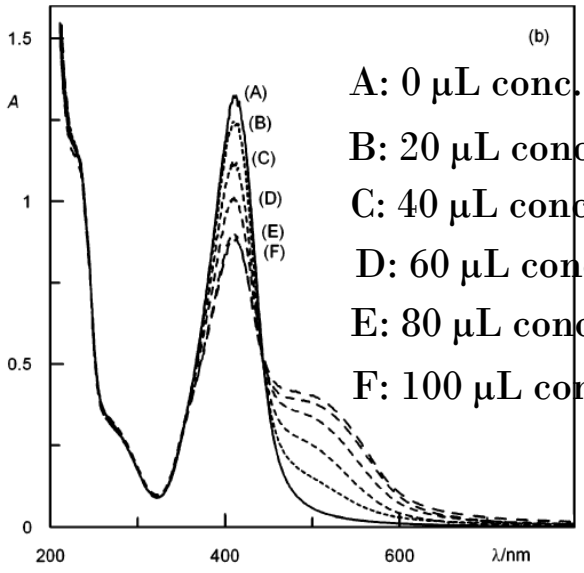
C: 5 mL conc. SDS

Steric effects due to EDL, increased zeta potential and enhanced AgNPs stability




A: Unmodified AgNPs

B: Modified Tween 80 AgNPs




A: 0 μL conc. Tween 80

B: 20 μL conc. Tween 80

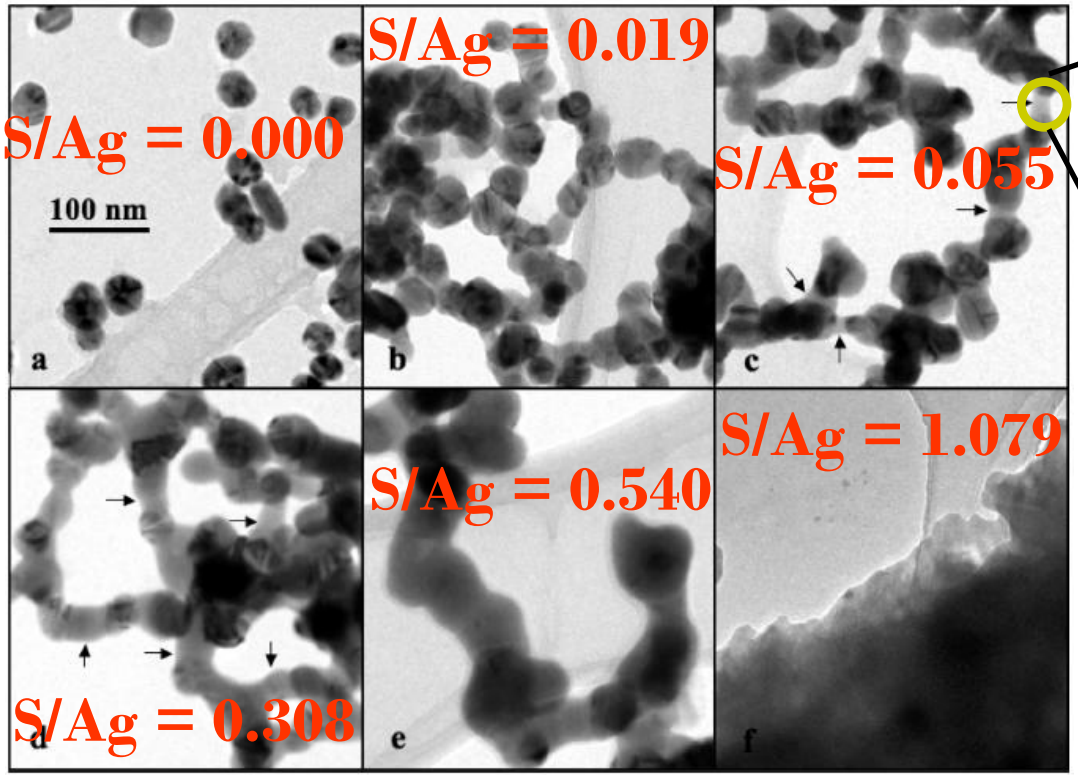
C: 40 μL conc. Tween 80

D: 60 μL conc. Tween 80

E: 80 μL conc. Tween 80

F: 100 μL conc. Tween 80

# *Effect of Sulfidation to AgNPs Dissolution*




TEM images of initial and sulfidized Ag-NPs

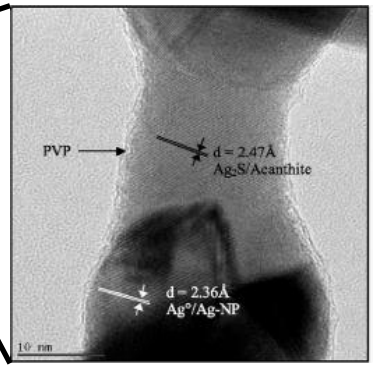
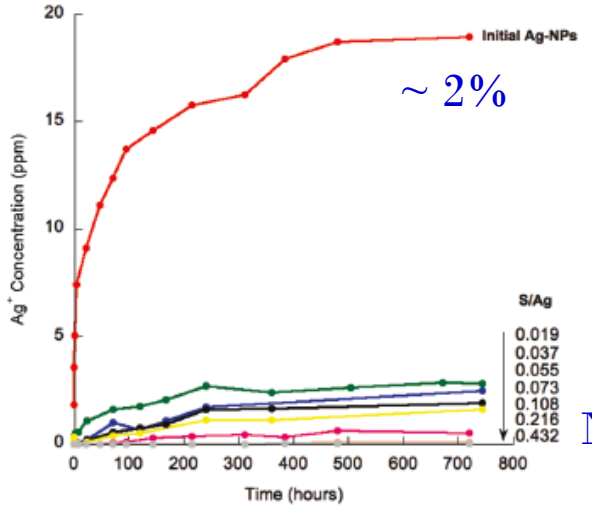



Image of nanobridge ($Ag_2S$)

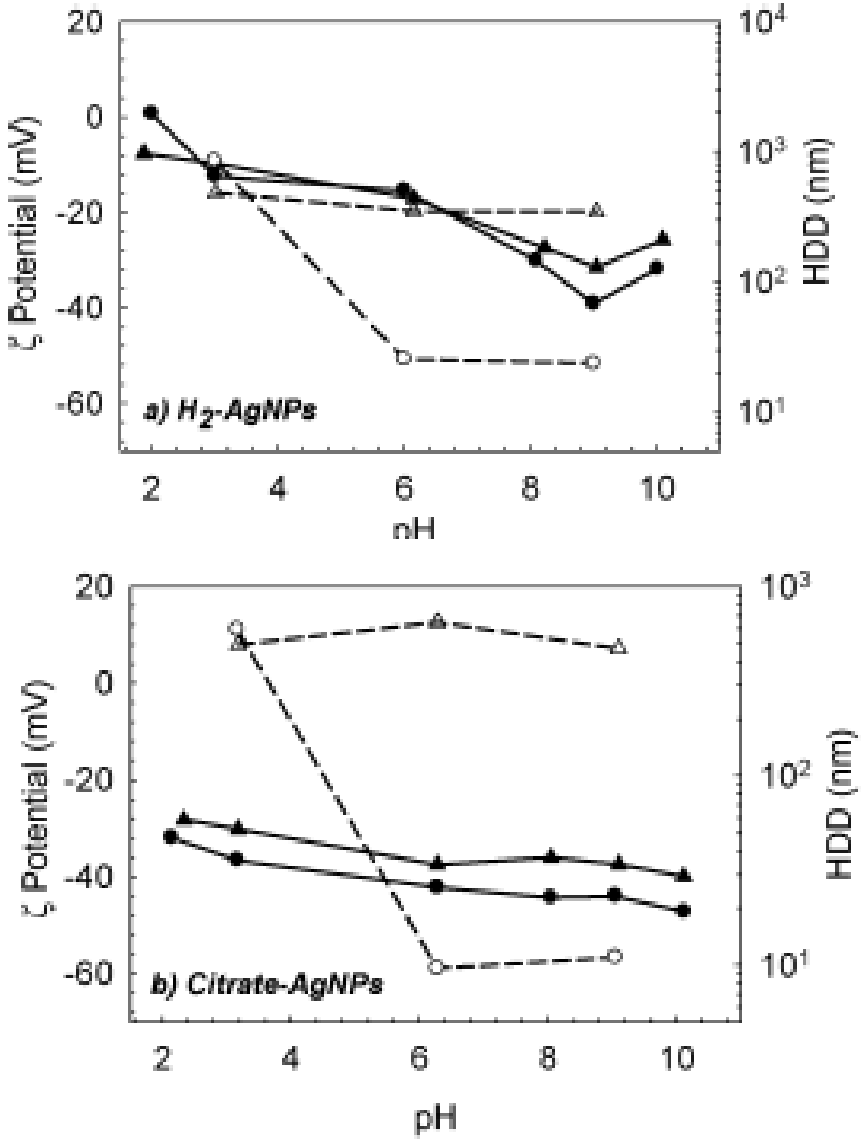



Negligible

***Levard et al., 2011, Environ. Sci. Technol***

Figure 6. Dissolution rate measurements of Ag-NPs before and after reaction with increasing concentrations of aqueous $Na_2S$. (Initial Ag-NPs concentration for dissolution rate measurements was 1000 ppm in 0.01 M $NaNO_3$, pH = 7).

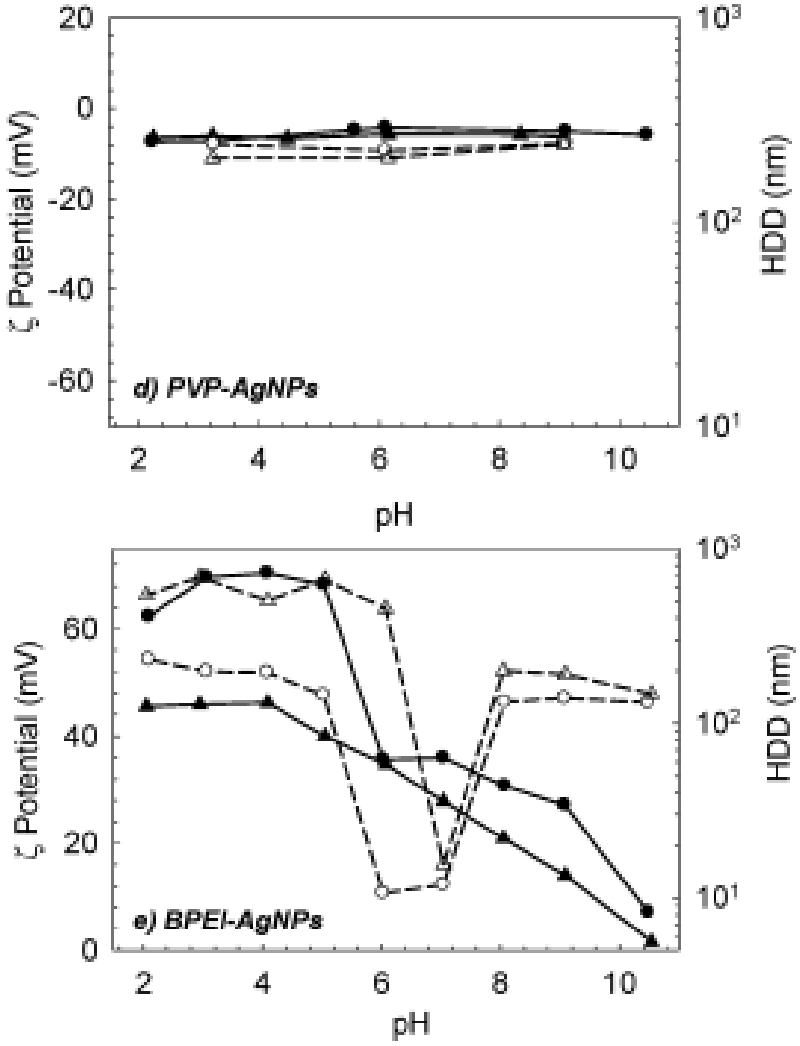
# *Effect of pH, IS, electrolyte to zeta potential & aggregation*




**Uncoated AgNPs (H2-AgNPs) and electrostatically stabilized (citrate and NaBH4-AgNPs) aggregate at higher ionic strengths (monovalent) and/or acidic pH (3.0) conditions, or at any conc. of divalent electrolyte (e.g. $Ca^{2+}$)**

*Badawy et al., Environ. Sci. Technol.* 2010

# *Effect of pH, IS, electrolyte to zeta potential & aggregation*




**PVP coated AgNPs (sterically stabilized AgNPs) WERE NOT AFFECTED BY ionic strength, pH and electrolyte type, hence no aggregation observed.**

**Surface charge and aggregation of the BPEI coated AgNPs varied according to the solution pH**

*Badawy et al., Environ. Sci. Technol.* **2010,** *44,* 1260–1266

# *Key findings: summary*

- Capping agents dramatically influences surface behavior and aggregation of AgNPs.
- Type of stabilizing mechanism profoundly effects aggregation potential of AgNPs.
- Thus, fate and transport of AgNPs are closely associated with the chemistry of the capping agent (similar effect on AuNPs – Stankus et al., 2010) both in natural and engineered environments
- Acidic and/or with high ionic strength (e.g. with divalent cations) environments promotes NPs aggregation and settling may occur.
- Elevated levels of $Cl^-$ may increase the stability of uncoated AgNPs in the presence of silver ions and at low ionic strength conditions.

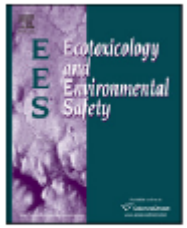
# Toxicity of ENMs

Ecotoxicology and Environmental Safety 74 (2011) 416–423

Contents lists available at ScienceDirect

Ecotoxicology and Environmental Safety

journal homepage: www.elsevier.com/locate/ecoenv



## Assessment of the effect of nanomaterials on sediment-dwelling invertebrate *Chironomus tentans* larvae

P.J. Oberholster [a,b,1], N. Musee [a,*,1], A.-M. Botha [c], P.K. Chelule [d], W.W. Focke [e], P.J. Ashton [a]

[a] CSIR Natural Resources and the Environment, P.O. Box 395, Pretoria 0001, South Africa
[b] Department of Paraclinical Sciences, Faculty of Veterinary Science, University of Pretoria, P/Bag X04, Onderstepoort 0110, South Africa
[c] Department of Genetics, University of Stellenbosch, Private Bag X1, Matieland 7601, South Africa
[d] Department of Public Health, University of Limpopo, MEDUNSA Campus, MEDUNSA 0204, South Africa
[e] Built Environment and Information Technology, University of Pretoria, Hillcrest, Pretoria 0002, South Africa

ARTICLE INFO

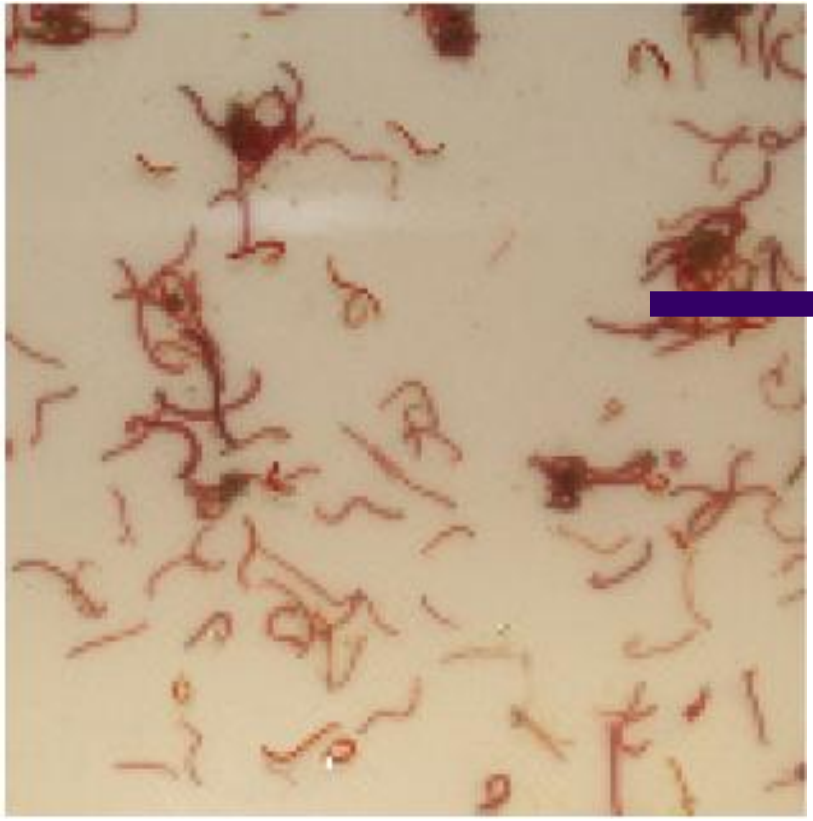
*Article history:*
Received 8 January 2010
Received in revised form
9 November 2010
Accepted 21 December 2010
Available online 7 January 2011

*Keywords:*
Nanomaterials
*Chironomus tentans*
Bioassays
Ecotoxicology
DNA damage

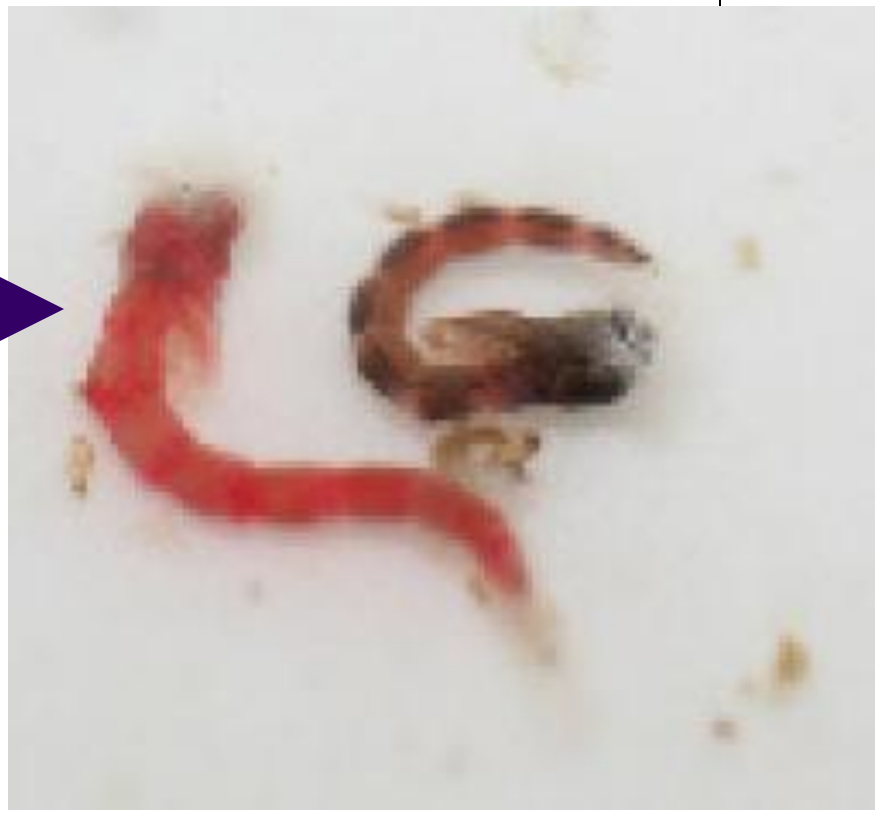
ABSTRACT

Studies were conducted to determine the effects of a panel of seven nanomaterials (NMs), namely: α-alumina, γ-alumina, precipitated silica; silica fume, calcined silica fume, colloidal antimony pentoxide ($Sb_2O_5$), and superfine amorphous ferric oxide ($Fe_2O_3$), on sediment dwelling invertebrates *Chironomus tentans* under controlled laboratory conditions. Percentage survival, enzyme activities, growth development, and DNA fragmentation parameters were studied as acute, biochemical, and physiological toxicities of NMs, respectively. Quantitation of catalase and peroxidase enzyme activity demonstrated that toxicant stress of the NMs increased enzyme activity in a concentration dependent fashion across all treatments. The percentage growth length of the test specimens exposed to different NMs was significantly reduced compared to the negative control while only five concentrations were not in the toxic range, namely; $Fe_2O_3$ (5 μg/kg); silica fume (5 μg/kg, 50 μg/kg); $Sb_2O_5$ (5 μg/kg) and calcined silica fume (5 μg/kg). Genotoxic stress assessed by use of DNA laddering showed complementary findings to the other ecotoxicological endpoints tested in this study—the percentage survival and growth length inhibition.

# *Sediment toxicity of Chronomus tentans*



0 days exposure



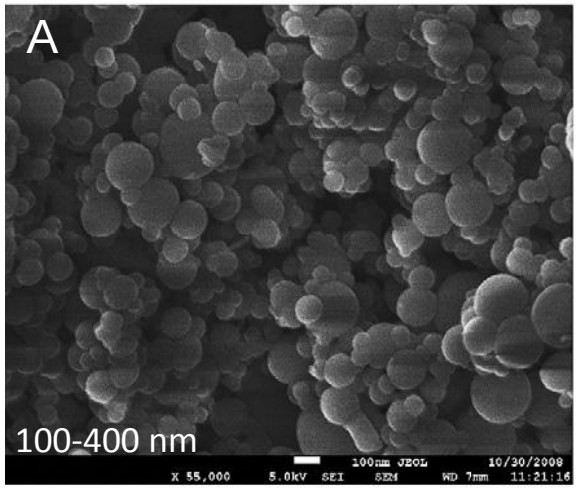
10 days exposure

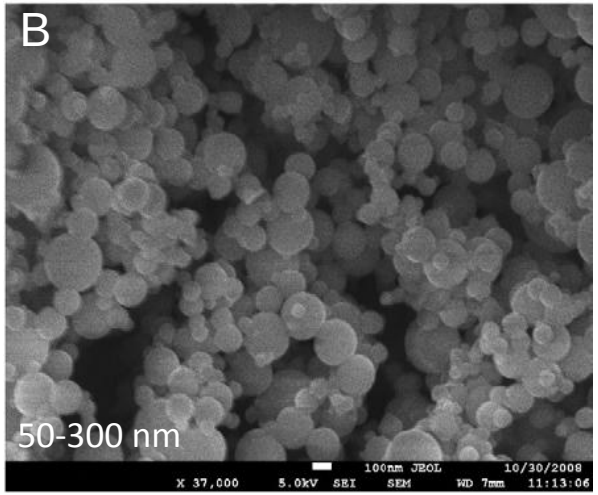
**Table 2:** Physicochemical properties and ranking of the essay findings [13].

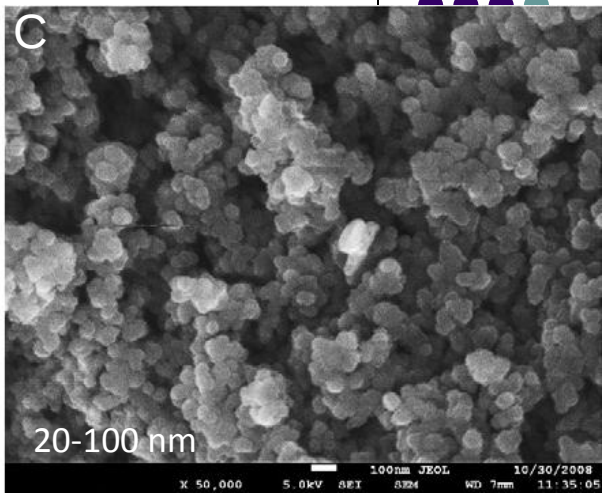
| Test | Property/units | $Fe_2O_3$ | Silica fume ($SiO_2$) | Calcined silica fume ($SiO_2$) | Precipitated silica ($SiO_2$) | $Sb_2O_5$ | α-alumina | γ-alumina |
|---|---|---|---|---|---|---|---|---|
| Zeta potential | mV | −18.3 | −21.1 | −14.6 | −1.76 | −23.4 | 19.7 | −18.7 |
| BET | Surface area ($m^2/g$) | 235 | 24 | 17 | 157 | 3 | 13 | 72 |
| | Density ($g/cm^3$) | 5.2 | 2.10 | 2.1–2.4 | 2.0 | 4.07 | 3.6 | 3.97 |
| Surface/volume ratio | $m^2/mm^3$ | 1274 | 50 | 41 | 314 | 12 | 47 | 286 |
| XRD | Morphology | Crystalline | Amorphous | Amorphous | Amorphous | Crystalline | Amorphous | Crystalline |
| SEM | Particle shape | Spherical | Spherical | Spherical | Spherical | Mixture (spheres, irregular) | Spherical | Spherical |
| Zetasizer | Size (nm) | 50–150 | 100–400 | 50–300 | 20–100 | 5000–15,000 | 20–50 | 80–400 |
| Solubility | Degree | Insoluble | Insoluble | Insoluble | Insoluble | Insoluble | Insoluble | Slightly soluble |
| Degree of dispersion | No units | Mono | Poly | Poly | Mono | Poly | Mono | Poly |
| Ranking of the toxic effects | Growth inhibition | 4 | 7 | 6 | 3 | 5 | 2 | 1 |
| | DNA damage | 4 | ND | ND | 3 | 5 | 2 | 1 |
| | Survival levels | 5 | 7 | 6 | 3 | 4 | 2 | 1 |
| | Enzymatic activities | 4 | 7 | 6 | 3 | 5 | 1 | 2 |

ND: not detectable.

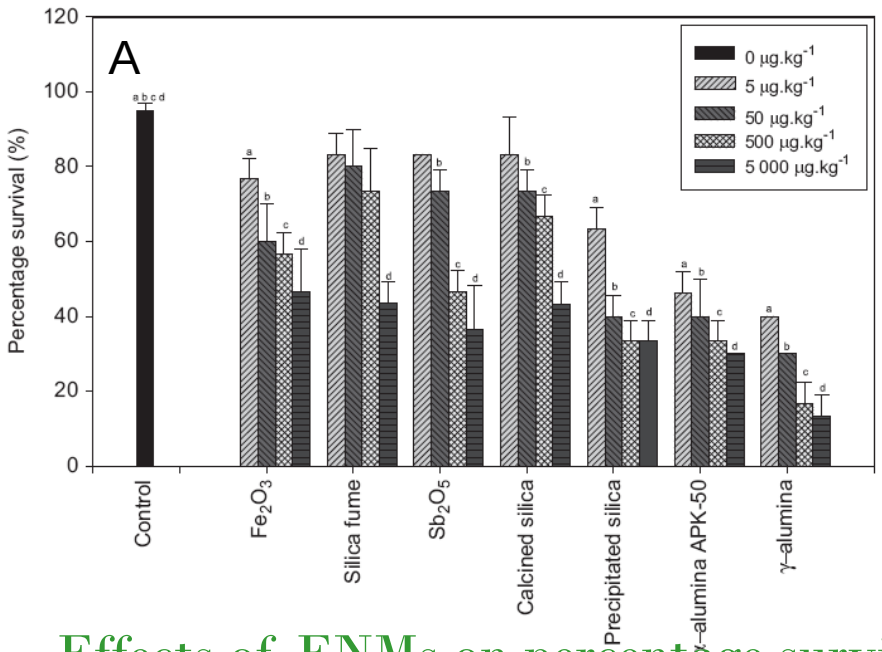
PC: Physicochemical properties

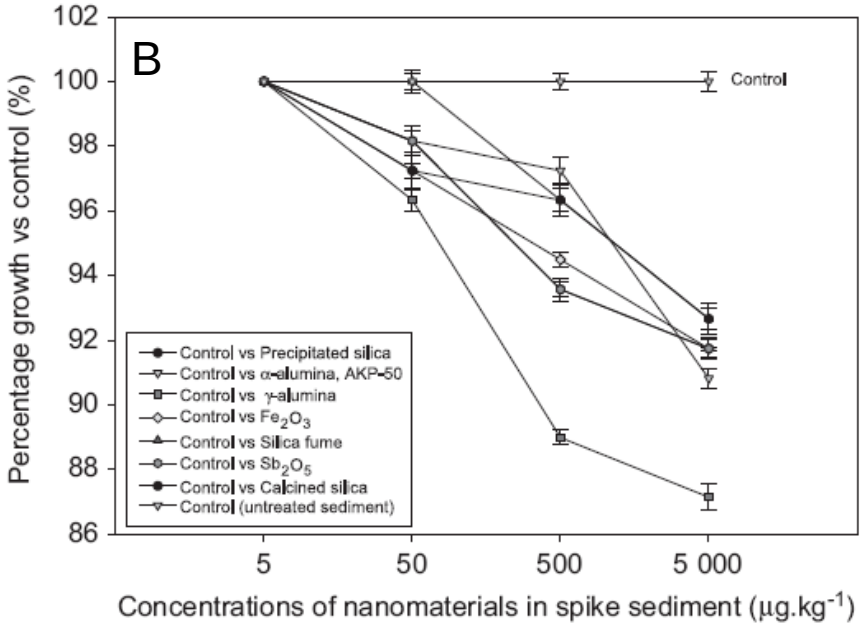


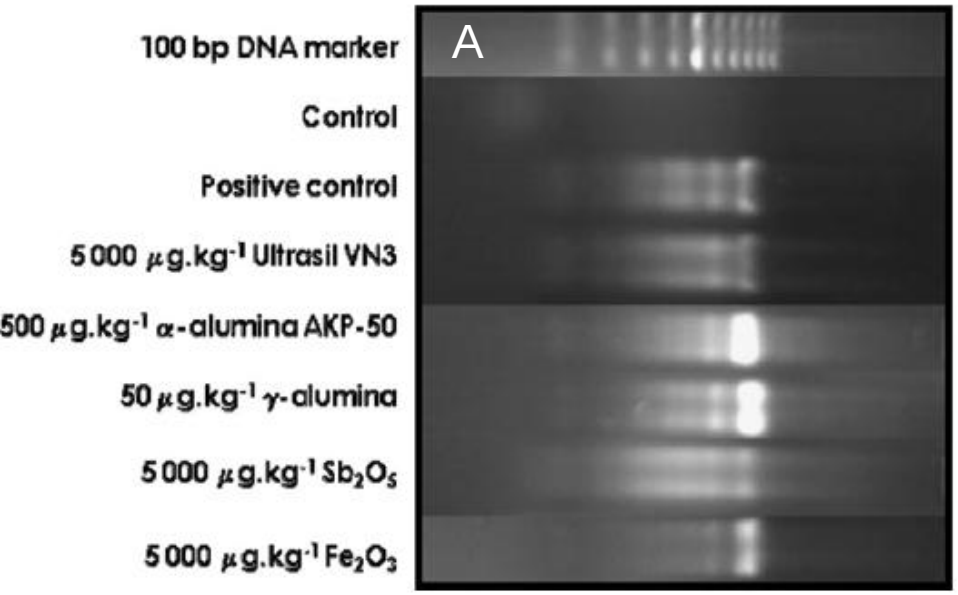



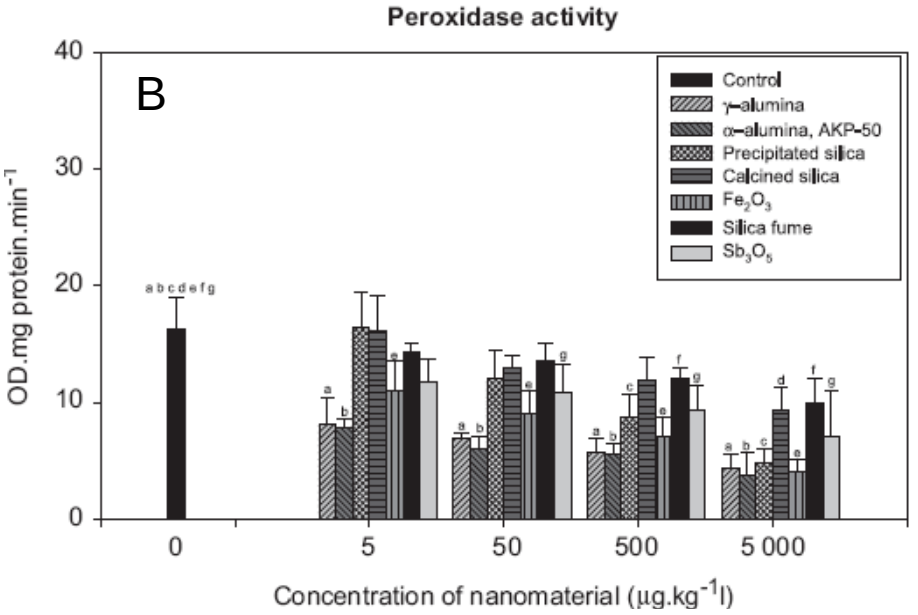

SEM images of: A: Silica fume, B: Calcined silica fume, and C: precipitated silica fume (Musee & Colleagues, Ecotocol Environ Saf, 2011)

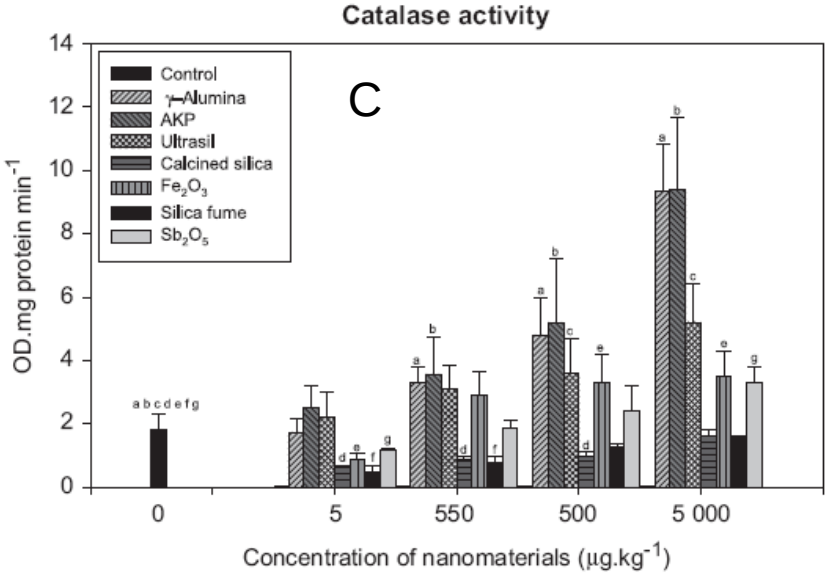



Effects of ENMs on percentage survival (A) and growth inhibition percentage (B) of *C. tentans* (Musee & Colleagues, Ecotocol Environ Saf, 2011)




Results of DNA laddering (A) , peroxidate activity (B), and catalase activity (C) (Musee et al., Ecotox Environ Saf, 2011)

Chemosphere 81 (2010) 1196–1203

Contents lists available at ScienceDirect

Chemosphere

journal homepage: www.elsevier.com/locate/chemosphere

# The effects of engineered nanoparticles on survival, reproduction, and behaviour of freshwater snail, *Physa acuta* (Draparnaud, 1805)

N. Musee [a,*], P.J. Oberholster [b], L. Sikhwivhilu [c], A.-M. Botha [d]

[a] CSIR Natural Resources and the Environment, P.O. Box 395, Pretoria 0001, South Africa
[b] CSIR Natural Resources and the Environment, P.O. Box 320, Stellenbosch 7599, South Africa
[c] DST/CSIR Nanotechnology Innovation Centre, NCNSM, P.O. Box 395, Pretoria 0001, South Africa
[d] Department of Genetics, University of Stellenbosch, Private Bag X1, Matieland, Stellenbosch 7601, South Africa

ARTICLE INFO

*Article history:*
Received 9 April 2010
Received in revised form 26 August 2010
Accepted 14 September 2010
Available online 12 October 2010

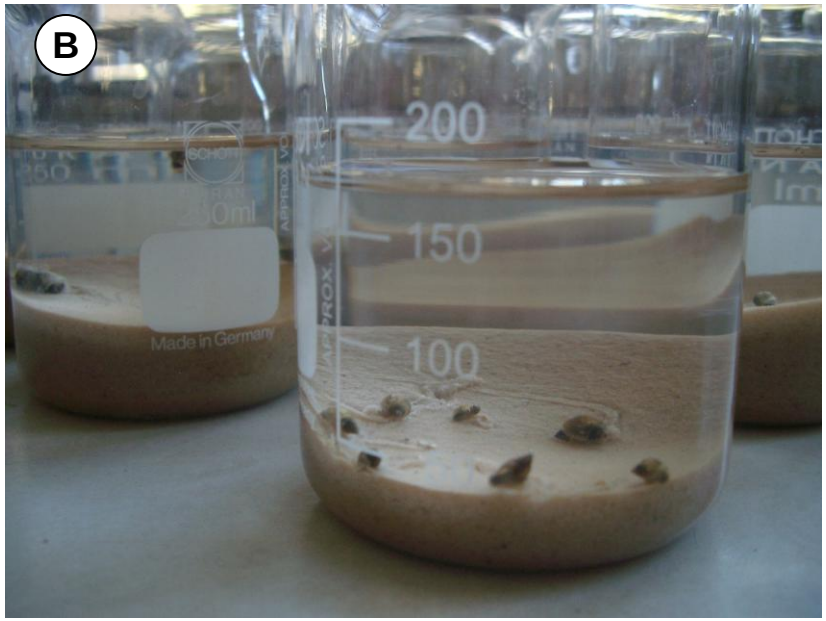
*Keywords:*
Sediments
*Physa acuta*
Antioxidant enzymes
Embryonic growth
Hatchability
Snails

ABSTRACT

Increasing uses of engineered nanoparticles (ENPs) in commercial products and industrial applications has eventually resulted to their releases into atmospheric, terrestrial, and aquatic environments. However, knowledge gaps in ENPs toxicity, fate, and behaviour currently limit our ability to quantify risk assessment of materials with nanoscale dimensions, and therefore, the extent of the resultant environmental impacts remains unknown. In the present study, we evaluated the effects of γ-alumina, α-alumina, modified $TiO_2$ (M-$TiO_2$), and commercial $TiO_2$ (C-$TiO_2$) ENPs on the survival, behaviour, and early life stages of the freshwater snail *Physa acuta* (Draparnaud). The toxicity evaluation was carried out after spiking commercial sand with ENPs concentrations of 0.005, 0.05, or 0.5 g $kg^{-1}$. Our findings suggest that increases of γ-alumina and α-alumina concentrations at sub-lethal level concentrations caused significant reduction in the embryo growth rate and embryo hatchability. In addition, these ENPs induced observable developmental deformities of the embryos. In addition, toxicity evaluations using acute 96-h and chronic 28-d tests showed exposure duration may be a significant factor in ENPs-induced toxicity. Therefore, long-term exposure of aquatic organisms to ENPs – potentially can alter certain ecological populations at different trophic levels – and may compromise the entire aquatic ecological functionality. The percentage hatchlings in test chambers containing 0.5 g $kg^{-1}$ γ-alumina and α-alumina concentration was 50% less to those observed in the controls. Our results suggest the embryonic growth and hatchability tests are useful endpoints in chronic sediment toxicity tests for determining the toxic thresholds of ENPs in sediment environment. Although no snail mortalities were observed during the static 96-h test containing sediment spiked with different concentrations of M-$TiO_2$, C-$TiO_2$, γ-alumina and α-alumina – the antioxidant enzymatic assay results indicated a significant change in antioxidant levels which altered peroxidation at 0.05 or 0.5 g $kg^{-1}$concentrations for both γ-alumina and α-alumina.

# *Exposure of ENMs to Physa acuta*


***Water Column Compartment***




**Water/sediment column compartment**

# Results

**Table 1**
Measured physicochemical properties of the ENPs.

| Test | Property/units | C-$TiO_2$ | M-$TiO_2$ | α-Alumina | γ-Alumina |
|---|---|---|---|---|---|
| Zeta potential | mV | – | – | 19.7 | −18.7 |
| BET | Surface area ($m^2\ g^{-1}$) | 50.3 | 301.7 | 13 | 72 |
| XRD | Morphology | Crystalline | Crystalline | Amorphous | Crystalline |
| SEM | Particle shape | Spherical | Tubular | Spherical | Spherical |
| Particle size | Size (nm) | 40–60 nm | 7–11 nm | 20–50 | 80–400 |
| Solubility | Degree | Insoluble | Insoluble | Insoluble | Slightly soluble |
| Degree of dispersion | No units | Mono | Mono | Mono | Poly |

*Notes*: BET: Braunner, Emmett, and Teller; XRD: X-ray diffraction; SEM; scanning electron microscope.

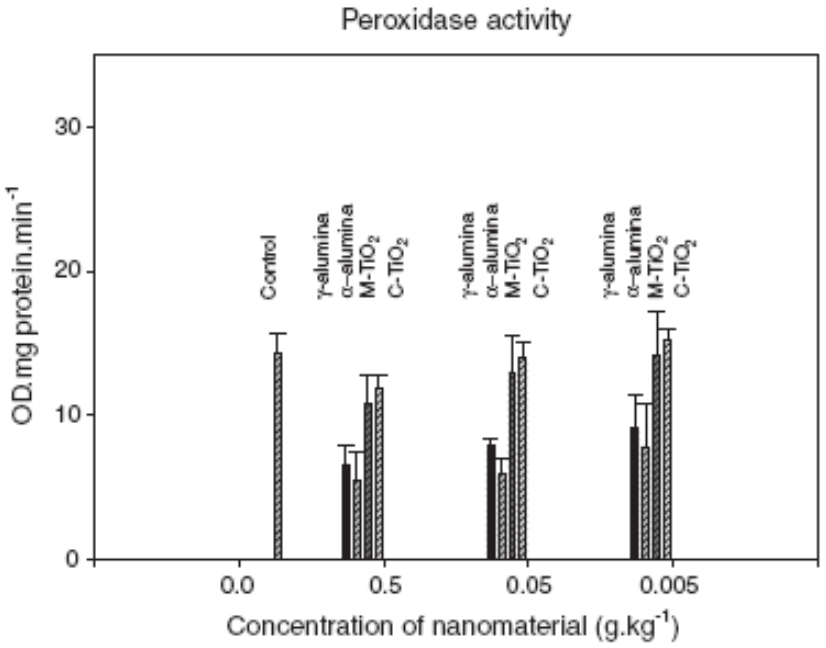
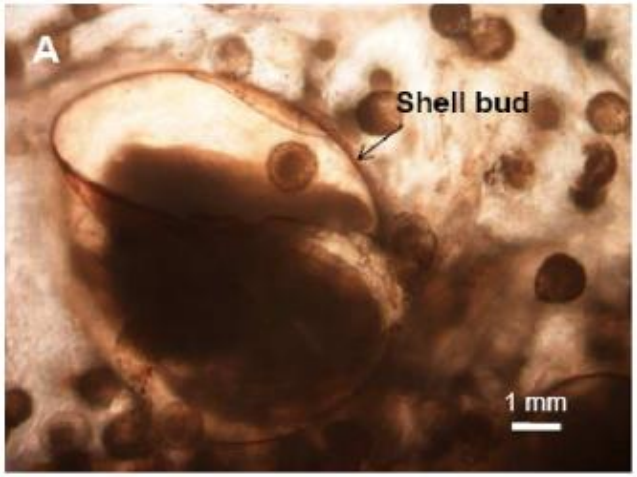


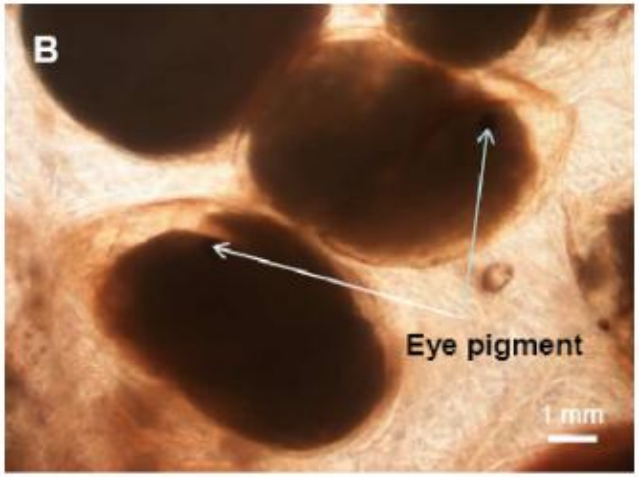

**Table 2**
Egg production and hatching success for *Physa acuta* during 28-d period.

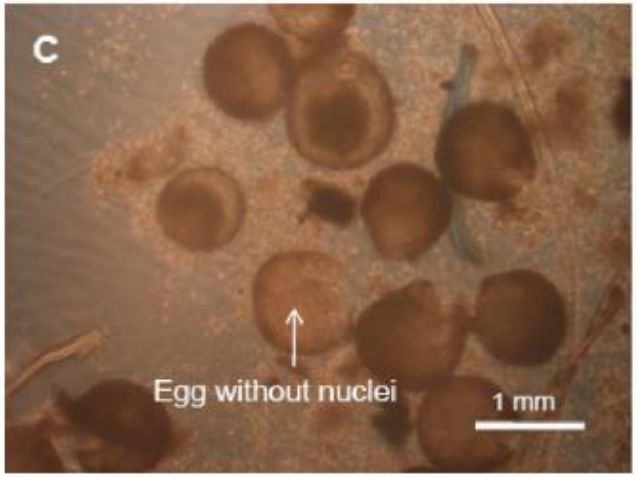
| Concentration ($g\ kg^{-1}$) | Number of egg masses from week 1 to 4 | Number of eggs week 1 to 4 | Mean (±SD) eggs per egg mass | Total (±SD) hatchlings in 4 weeks | Mean% per week |
|---|---|---|---|---|---|
| *M-$TiO_2$* | | | | | |
| 0 (control) | 11 | 201 | 18 (±2) | 156 (±4) | 19 |
| 0.005 | 10 | 200 | 20 (±3) | 161 (±3) | 20 |
| 0.05 | 11 | 198 | 18 (±1) | 163 (±6) | 20 |
| 0.5 | 11 | 194 | 17 (±2) | 167 (±4) | 21 |
| *C-$TiO_2$* | | | | | |
| 0 (control) | 10 | 200 | 20 (±2) | 147 (±4) | 18 |
| 0.005 | 11 | 205 | 18 (±1) | 162 (±4) | 19 |
| 0.05 | 11 | 202 | 18 (±3) | 157 (±5) | 19 |
| 0.5 | 10 | 199 | 19 (±2) | 164 (±6) | 20 |
| *α-Alumina* | | | | | |
| 0 (control) | 10 | 197 | 19 (±3) | 161 (±4) | 20 |
| 0.005 | 10 | 140 | 14 (±3) | 112 (±5) | 20 |
| 0.05 | 6 | 71 | 11 (±2) | 40 (±3) | 14 |
| 0.5 | 3 | 25* | 8 (±1)* | 8 (±1)* | 8* |
| *γ-Alumina* | | | | | |
| 0 (control) | 11 | 198 | 18 (±2) | 161 (±5) | 20 |
| 0.005 | 9 | 131 | 14 (±3) | 92 (±6) | 17 |
| 0.05 | 5 | 49 | 9 (±2) | 18 (±1)* | 9* |
| 0.5 | 3 | 22* | 7 (±1)* | 7 (±1)* | 7* |

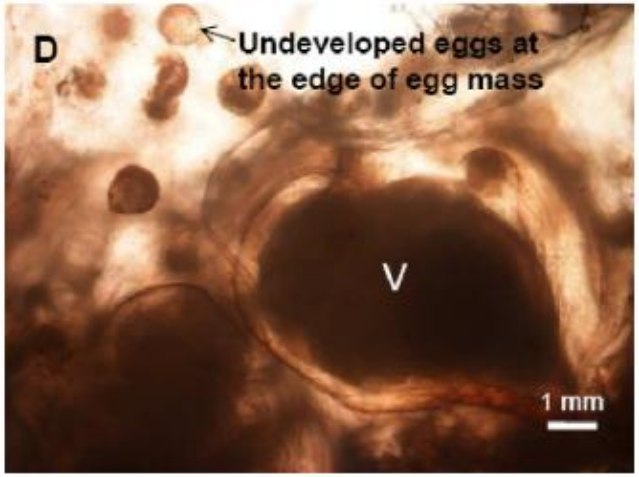
* Significant difference compared with control ($P < 0.05$).

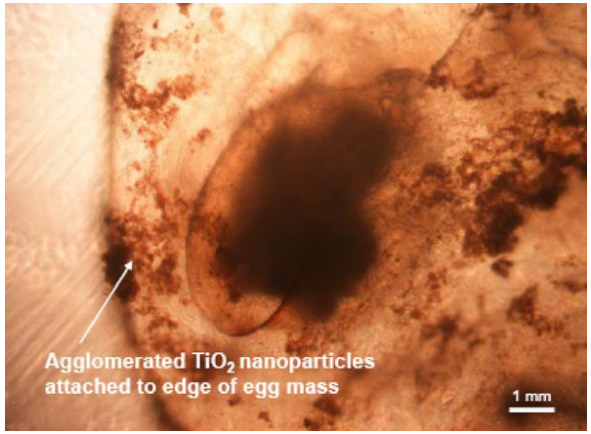
(Musee et al., Chemosphere, 2010)




A: Delayed hatching & anomalies of embryogenesis.

B: Normal eggs (control – hatches in 10 days)

C: No nuclei & no development after 4 weeks

D: Exacerbated delays in hatching process

Musee et al., Chemosphere, 2010

# *Fate of $SiO_2$ NPs in wastewater*

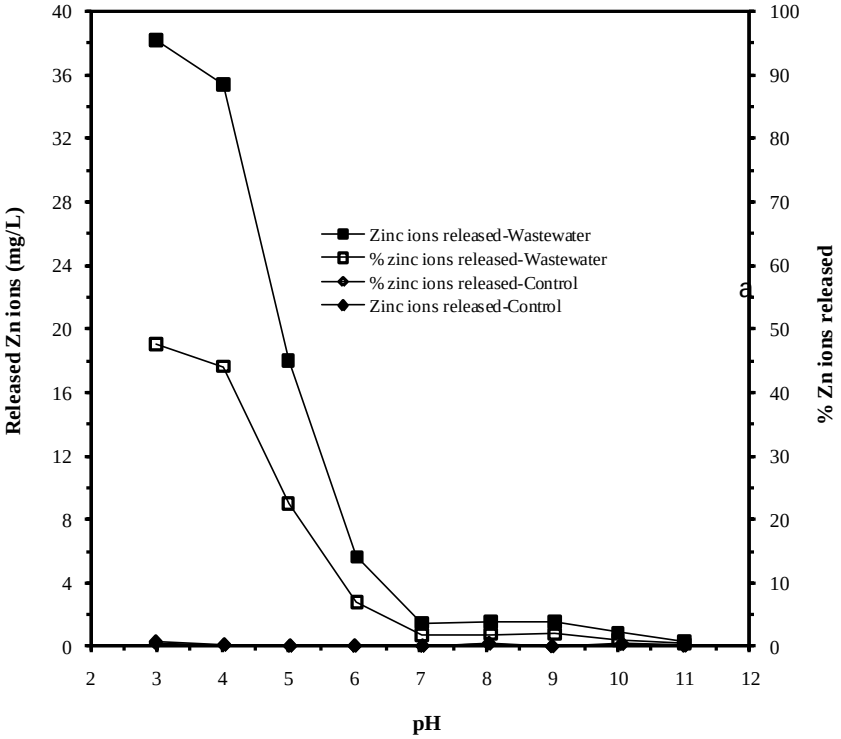
**TABLE 2. Summary of Supplementary Tests of $SiO_2$NP Colloidal Stability in Electrolyte Solutions**

| nanoparticle type | electrolyte solution | observations |
|---|---|---|
| unfunctionalized (uncoated) $SiO_2$NP | 0.01 M $La(NO_3)_3$ | rapid and significant flocculation within 8 min; complete flocculation after 30 min |
| | 0.10 M $La(NO_3)_3$ | slow flocculation over the first 30 min but incomplete |
| functionalized (Tween-coated) $SiO_2$NP | 0.01 M NaCl | no effect after 72 h |
| | 0.01 M $La(NO_3)_3$ | no effect in first 5 min; slow flocculation over the next hour; complete flocculation after 2 h |
| | 0.10 M $La(NO_3)_3$ | no effect in first 5 min; slow flocculation over the next hour; complete flocculation after 2 h |

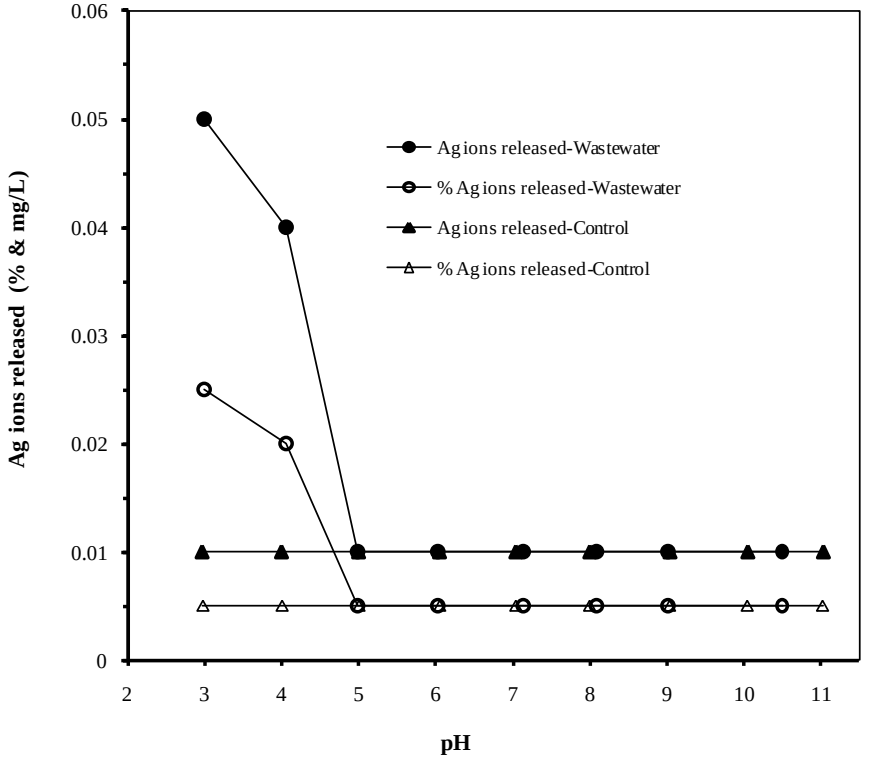
Key findings:

- Surface-functionalized $SiO_2$NPs likely to be removed via sedimentation to sewage sludge
- Uncoated $SiO_2$NPs will continue through the effluent stream (likely to go to secondary treatment stages)

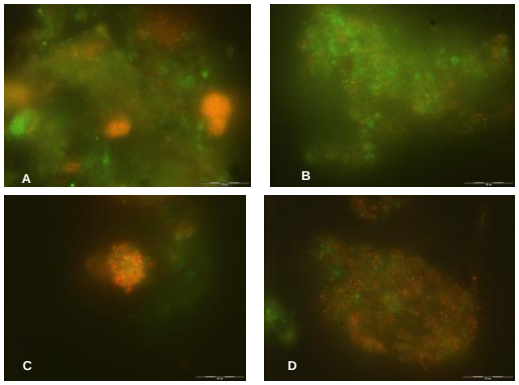
**Jarvie et al., Environ. Sci. Technol. 2009**




Release kinetics of $Zn^{2+}$ from ZnO NPs as a function of pH in wastewater



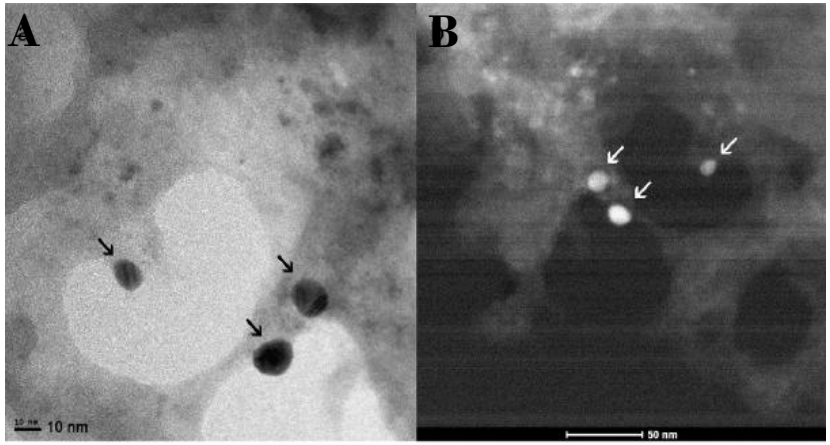

Release kinetics of $Ag^{+}$ from AgNPs in wastewater as a function of pH



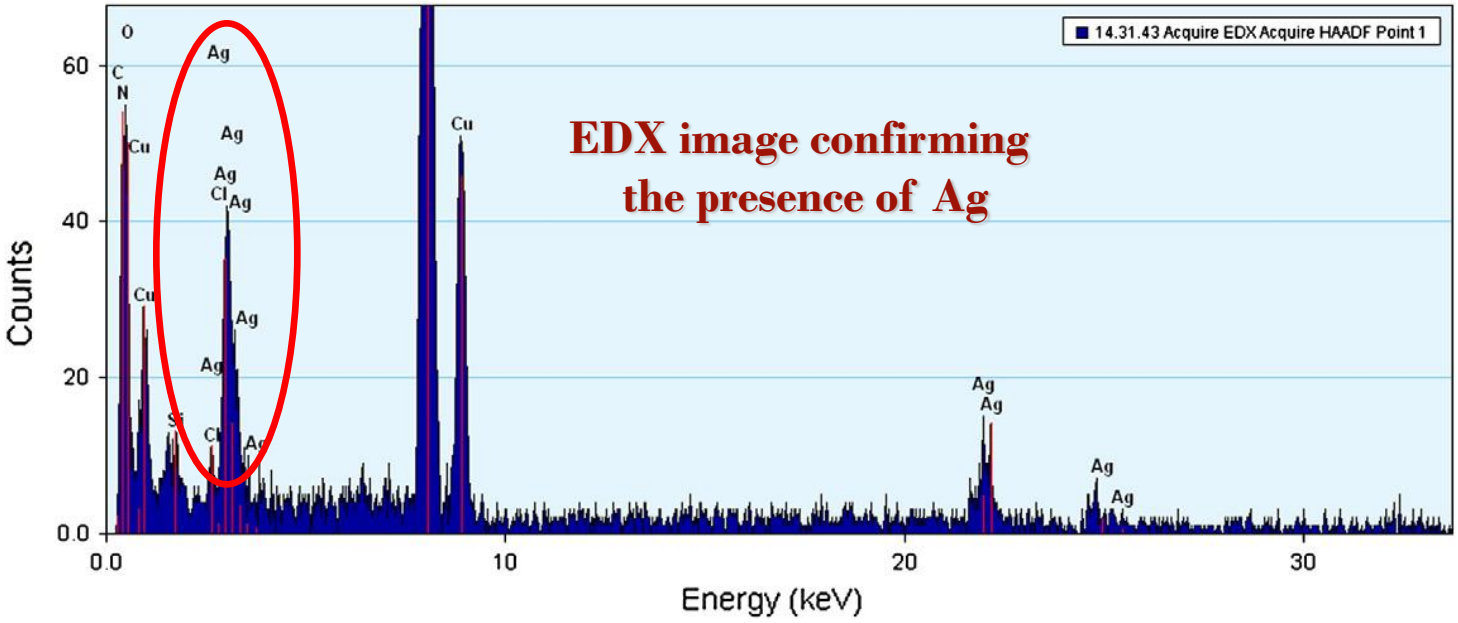

Dead/live baclight tests show enhanced dead Bacteria after exposure to NPs

***Musee et al., 2012 (unpublished data)***

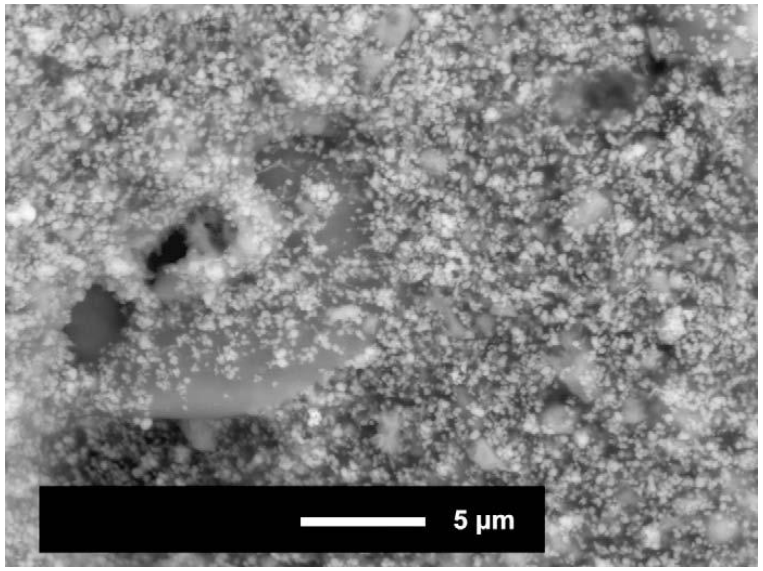
# *Fate of ENMs in actual environmental systems*



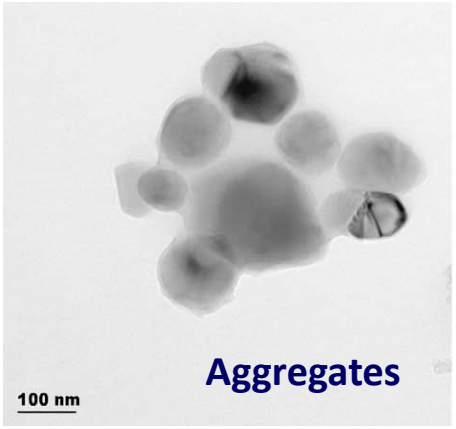

**Average Ag-NP size in the effluent ~ 10 nm measured with TEM and STEM (St dev=3.2 nm, range 5–18 nm; n=26). The particles were spherical or irregular. TEM (a) and high angle annular dark field (HAADF) images; (b) of the nanoparticles (black and white arrows) in the washing machine effluent.**

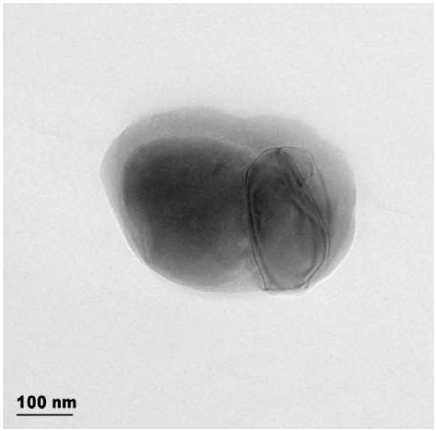



*Farkas. et al. Environ. Int. (2011).*

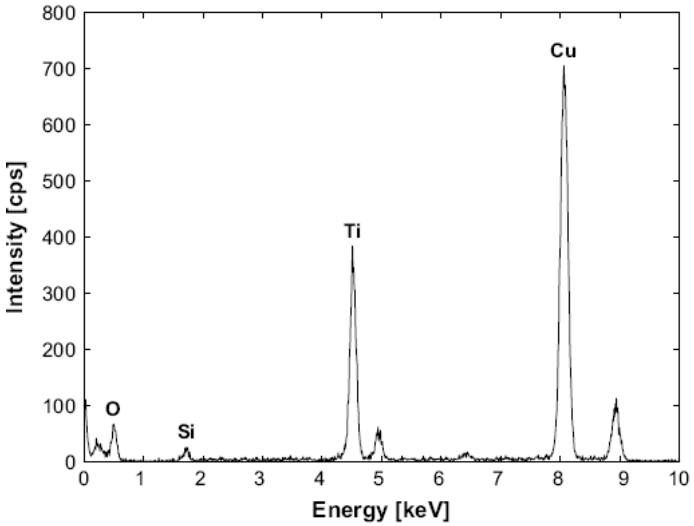



SEM-BSE image of the aged façade (white spots represent $nTiO_2$ particles).




TEM bright field image of $TiO_2$ particles from the runoff of the new facade

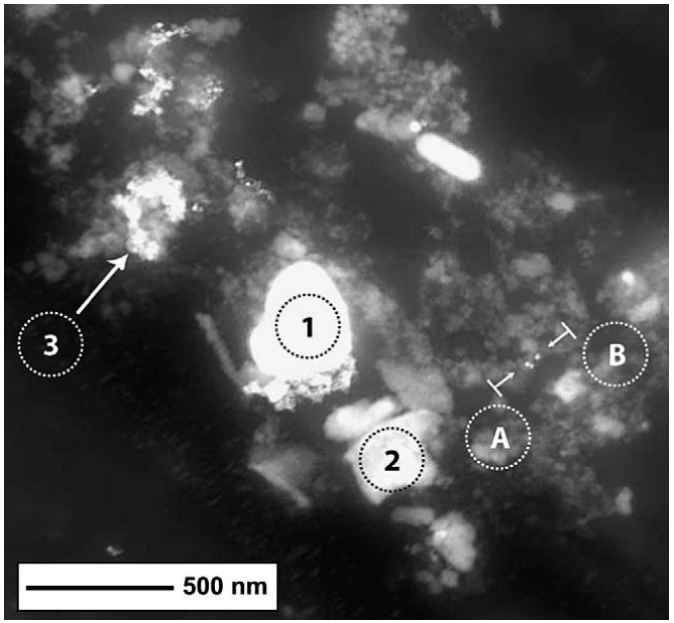



Synthetic $nTiO_2$ within a size range of a few tens to a few hundreds of nm in diameter were successfully detected and identified in the environment using a combination of analytical electron microscopy (TEM-EDX) and bulk chemical (ICP-MS) methods.

Kaegi et al. Environ. Poll. 156 (2008) 233–239

TEM-EDX of $TiO_2$ particles detected in the runoff of the aged facade.


Model house with panels with the Ag-NP paint




TEM image (HAADF-STEM) of the Ag-NP

- **Findings provide first direct evidence for the release of Ag-NP from a typical outdoor application to the aquatic environment.**
- **About 30% of the Ag-NP initially contained in the paint were lost within one year of exposure**
- **Ag-NP were attached to an organic binder from the paint and released mostly as composite colloids.**
- **Microscopic findings clearly showed the difficulties encountered in detecting, or monitoring ENMs in the environment**

***Kaegi et al. Environ. Poll. 158 (2010) 2900 – 2905***

# Nanowastes classification

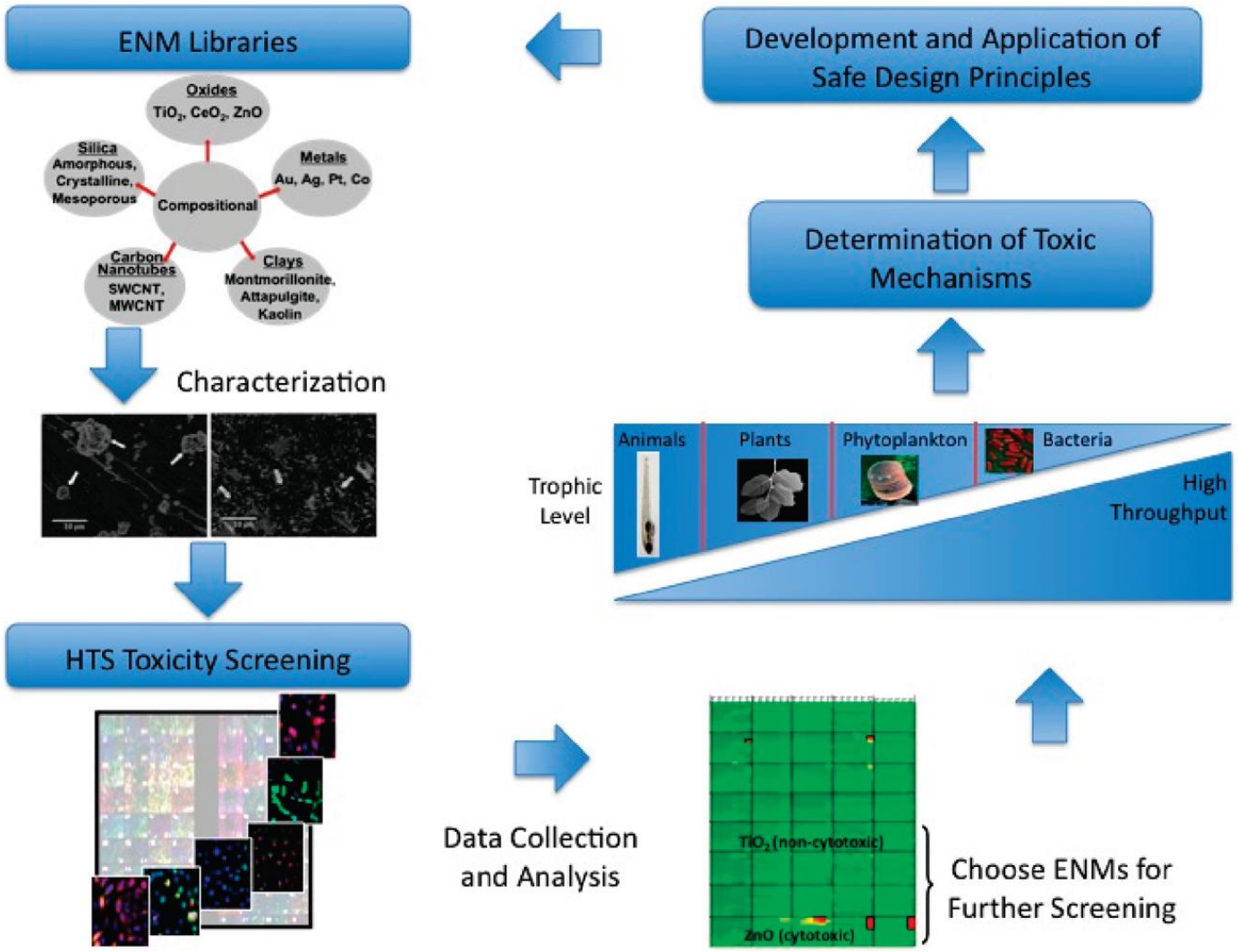
**Table 4**
Few examples of risk profiles of nanoproducts and/or applications containing different NMs at the disposal life cycle phase.

| Application | NMs | Hazard | Exposure potency | Risk at disposal | Potential nanowaste class |
|---|---|---|---|---|---|
| Personal care pro. | Ag | Medium | High | Medium | Class II/Class III |
| | Fullerenes | High | High | High | Class IV/Class V |
| | $Fe_2O_3$ | Medium | High | Medium | Class II/Class III |
| | $TiO_2$ | Low | High | Low | Class I |
| Food/ beverages | $TiO_2$ | Low | Medium | Low | Class I |
| | ZnO | Medium | Medium | Medium | Class II/Class III |
| | Fullerenes | High | Medium | High | Class IV/Class V |
| | Dendrimers | Medium | Medium | Medium | Class II/Class III |
| Sunscreen lotions | ZnO | Medium | High | Medium | Class II/Class III |
| | $TiO_2$ | Low | High | Low | Class I |
| | Fullerenes | High | High | High | Class IV/Class V |
| | Dendrimers | Medium | High | Medium | Class II/Class III |
| Automobile parts | SWNCT | High | Medium | Medium | Class II/Class III |
| | MWNCT | High | Medium | Medium | Class II/Class III |
| | Nanoclays | Low | Medium | Low | Class I |
| | Fullerenes | High | Medium | Medium | Class II/Class III |
| Polishing agents | $TiO_2$ | Low | High | Low | Class I |
| | ZnO | Medium | High | Medium | Class II/Class III |

Class I has lowest risk profile, Classes II and III exhibits moderate (medium) risk levels, and Classes IV and V have the highest degree of risk.

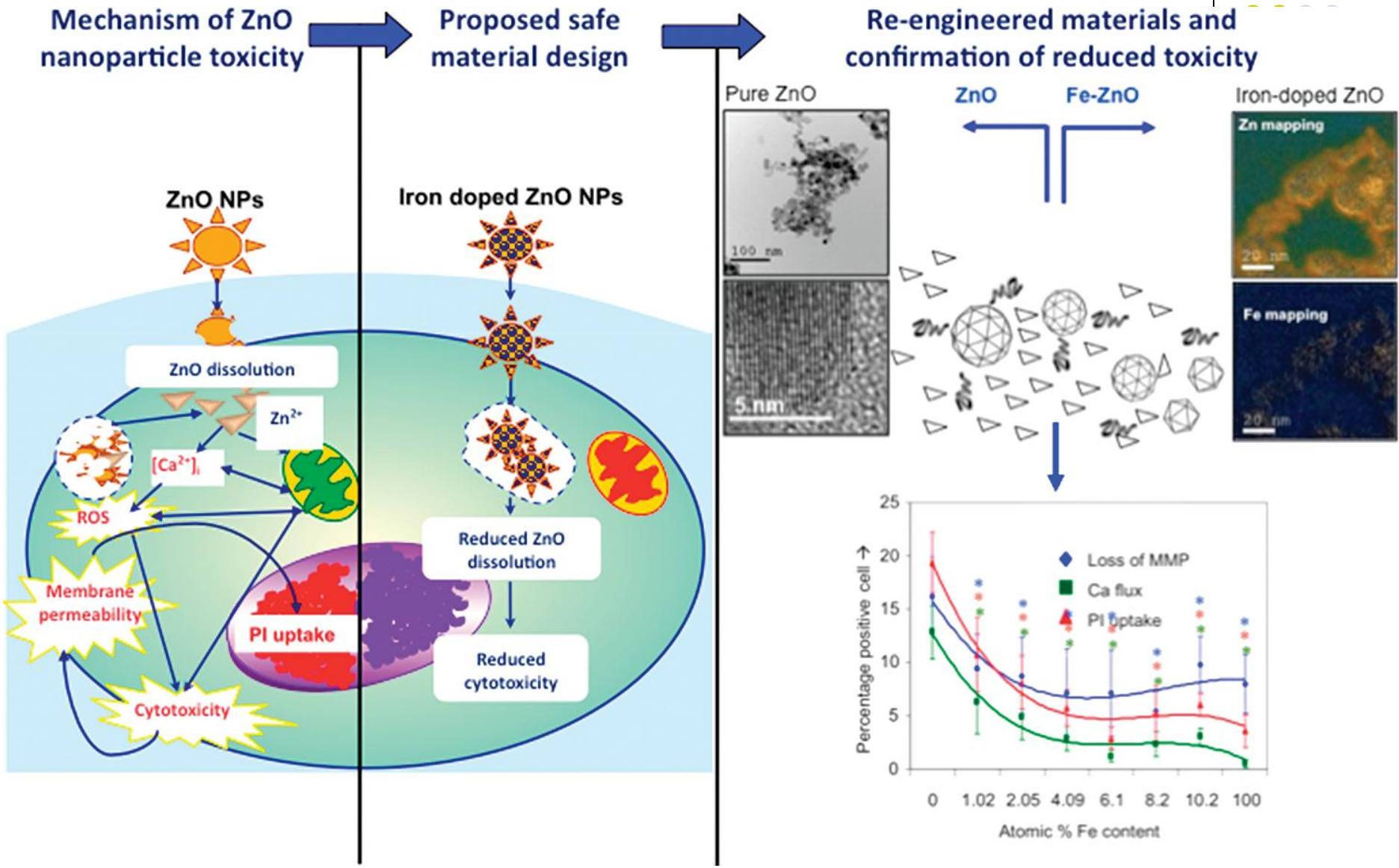
*Musee, Environ Int. 2011; Musee, Hum Health Exp Toxicol, 2011*

# High throughput screening mechanisms



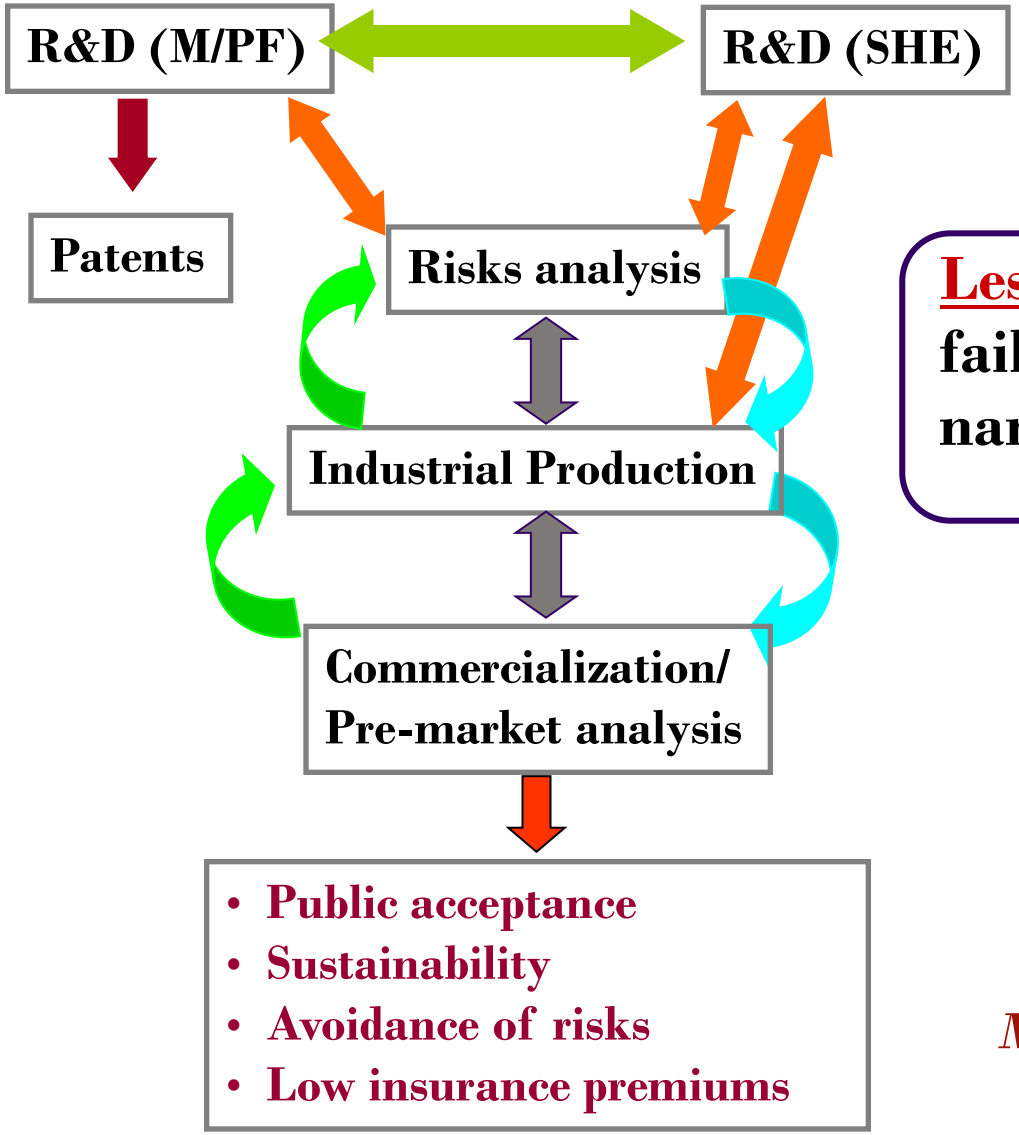

*Thomas et al., ACS Nano, 2011, 5(1) 13–20*

# Safe design of ENMs




*Thomas et al., ACS Nano, 2011, 5(1) 13–20*

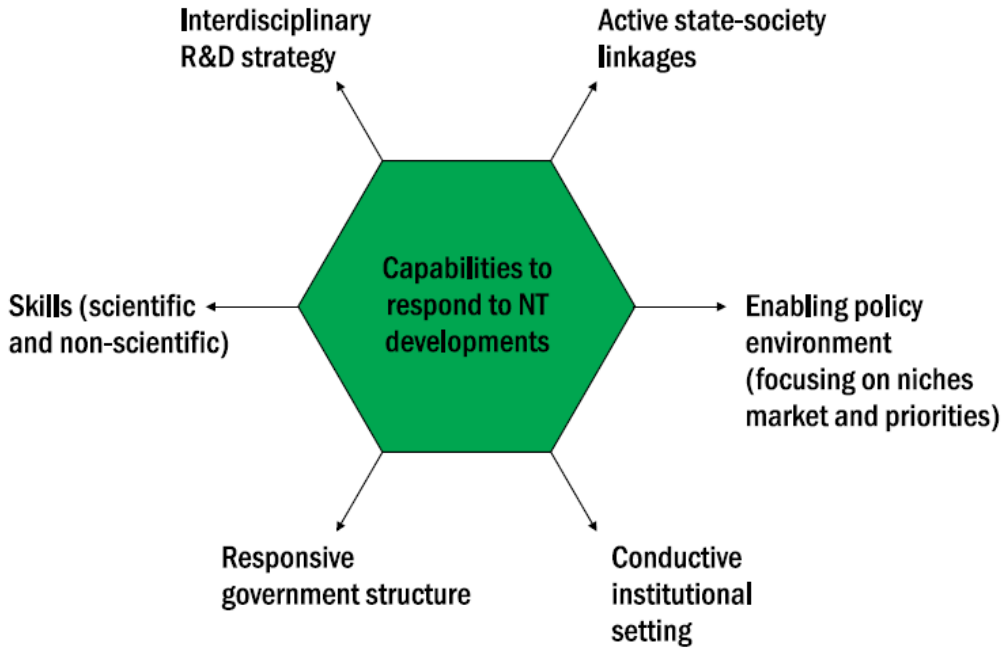
# *Proactive approach to Nanotech Sustainability*

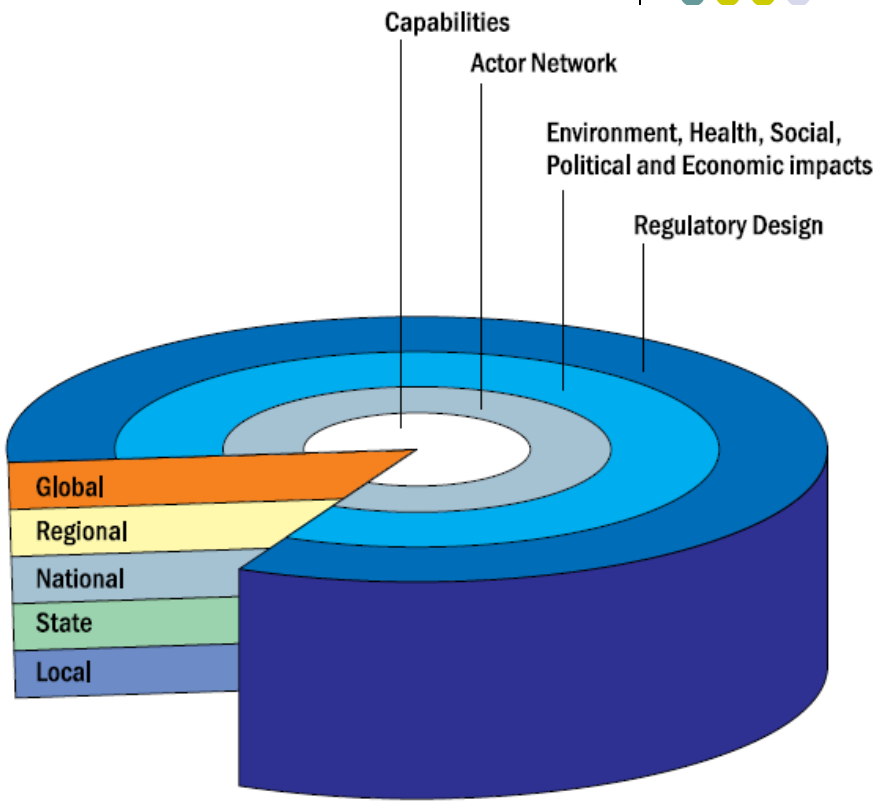



**Lesson:** Past technological failures can be avoided during nanotechnology era.

*Musee et al., S. Afr. J. Sci. 2010*

# Future outlook



# *Paths Forward*

- Focused integration of lab-based risk assessment research to nanoproducts impacts on actual environmental systems
- Formation of collaborations at national, regional, continental and global (including economic groupings) to address nanotech HSE aspects (e.g. policy/decision makers, scientists & engineers)
- Development of nanotech specific regulations to govern research and commercial applications of nanotechnology (e.g. products labeling). Challenges include:
  - Inadequate regulatory capacity
  - Information asymmetry
  - Financial constraints
  - Lack of expertise (technical know-how)
  - Absence of interagency coordination

# *The End….*

# *But… Small Baby Steps moves on …*

# Acknowledgements


CSIR
our future through science

science & technology
Department:
Science and Technology
REPUBLIC OF SOUTH AFRICA

SANi South African Nanotechnology Initiative

UFS UV

**And … colleagues and students**




*Thank you for your attention*