Single Particle ICP-MS for the Characterization and Study of Nanoparticles in the Environment

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Robert Thomas,
Scientific Solutions
Gaithersburg, MD
Definition of a Nanomaterial

- The International Standards Organization (ISO) defines a **nano-object** as a material with at least one, two or three external dimensions in the nanoscale range of 1 to 100 nm.
- A **nanoparticle** is specifically a nano-object with all three external dimensions in the 1 to 100 nm range which exhibits a property not evident in the bulk material.
- However, there are also nanotubes, nanowires, nanofibers and nanoplates, and nanocrystals.
Different Types of Nanomaterials

Table 1. Nanomaterial types and dimension characteristics.

<table>
<thead>
<tr>
<th>Type of Nanomaterial</th>
<th>Number of dimensions and size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nanoparticle</td>
<td>Three dimensions in the 1 to 100 nanometers (nm) range</td>
</tr>
<tr>
<td>Nanotubes/nanowires</td>
<td>Two dimensions in the 1 to 100 nm range</td>
</tr>
<tr>
<td>Nanofibers</td>
<td>Length ranges between 50 nm and 300 nm with diameter &lt;50 nm</td>
</tr>
<tr>
<td>Nanofilms</td>
<td>One dimension in the 1 to 100 nm range</td>
</tr>
<tr>
<td>Nanoplates</td>
<td>Two dimensions in the 1 to 100 nm range</td>
</tr>
</tbody>
</table>
Nanotechnology-Based Consumer Products are EVERYWHERE
The Market Size for Nanotechnology Products

The National Institute of Standards and Technologies reported that nanotechnology-based consumer products are currently entering the market at a rate of 3 to 4 per week and it is estimated that $2.6 trillion in manufactured goods will be manufactured using some kind of nano technology in 2015.
In the US, Funding for Nanotechnology Research is Approx $5 Billion

According to the U.S. National Nanotechnology Initiative (NNI), Federal Government funding in the United States, for nanotechnology, has increased from approximately $464 million in 2001 to nearly $1.9 billion for the 2010 fiscal year. Private industry is investing at least as much as the government, according to estimates. The United States is not the only country to recognize the tremendous economic potential of nanotechnology. While it is difficult to measure accurately, estimates from 2005 showed the European Union (EU) and Japan are investing approximately $1.5 billion and $1.8 billion, respectively, in nanotechnology. Behind them were Korea, China and Taiwan with $300 million, $250 million and $110 million respectively, invested in nanotechnology research and development.⁶
### Table 2. Selection of nanomaterials and usage or application area.

<table>
<thead>
<tr>
<th>Market</th>
<th>Industry Segment</th>
<th>Type of Nanomaterial</th>
<th>Use/Application Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environmental</td>
<td>Water</td>
<td>Nano zero valent iron (nZVI)</td>
<td>Being tested for the remediation of ground and surface waters exposed to chlorinated hydrocarbons&lt;sup&gt;17&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Gold nanoparticles</td>
<td>Various gold nanomaterials are used to enhance imaging properties of a variety of MRI and CT-based contrast agents&lt;sup&gt;18&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>UV absorbing nanomaterials</td>
<td>Improved and sustainable water based surface coatings to protect and preserve wood, concrete and metal surfaces used in construction&lt;sup&gt;19&lt;/sup&gt;</td>
</tr>
<tr>
<td>Safety and Security</td>
<td>Food</td>
<td>Clay</td>
<td>Nanomaterials are being used in food packaging. The penetration of light, moisture, or gases can alter the sensory characteristics of food products, as well as increase spoilage. Nanomaterials enhance packaging barrier properties&lt;sup&gt;20&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>Energy</td>
<td>Pd and V doped carbon nanotubes</td>
<td>Enhance hydrogen fuel cells by increasing storage capacities and showing faster hydrogen absorption kinetics&lt;sup&gt;21&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>Medical</td>
<td>Various materials</td>
<td>Nanomaterials coated with pharmaceutical compounds are being considered as novel inhalation delivery systems for medications difficult to administer by other means&lt;sup&gt;22&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>Textiles/Apparel</td>
<td>Silver nanoparticles</td>
<td>Integrated with sports clothing to prevent microbial growth, and odor&lt;sup&gt;23,24&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>Cosmetics/</td>
<td>Nano titanium dioxide and nano zinc oxide</td>
<td>Used in some cosmetics. The applications include: eye liners, moisturizers, lipsticks, make-up foundations, soaps, sunscreen, mascara, and nail polish&lt;sup&gt;16&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>Personal Care</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Industrial</td>
<td>Defense CNTs</td>
<td>Body armor – multilayer-epoxy composites manufactured with CN sheets, the size of a piece of plywood 4’ x 8’ foot, provide a shield that can stop a 9 mm bullet and weighs no more than a pack of playing cards&lt;sup&gt;25&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>Aerospace</td>
<td>Clay nanoparticles</td>
<td>Incorporated with thermoplastics to create improved fire retardant aircraft interiors&lt;sup&gt;26&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>Automotive</td>
<td>10 nm Cerium oxide nanoparticles</td>
<td>Forms part of the Envirox™ diesel fuel catalyst which improves combustion due to the increased surface area of the cerium oxide nanoparticles&lt;sup&gt;27&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>Recreation/</td>
<td>Unknown</td>
<td>Holmenkol® AG supply a chemical nanotechnology coating system under the brand name ‘Nanowax®’ to replace conventional ski and snowboard waxes&lt;sup&gt;28&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>Manufacturing</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sports equipment</td>
<td>CNTs/Yarn</td>
<td>High end golf club shafts are made with nano-composites to make the shaft stronger and more flexible. Racing bicycle components&lt;sup&gt;29&lt;/sup&gt;</td>
</tr>
</tbody>
</table>
Characterization of Nanomaterials

- It is important to understand that the unique capabilities and applications of nanomaterials are based on the fact that, because of their very small size, the characteristics and behavior are quite different to bulk materials with the same composition.

- As a result, the range of parameters that has to be assessed to characterize them is typically larger than the characterization of the bulk material.
What are the Important Metrics Used to Characterize Nanomaterials?
## Analytical Techniques Used for Nanometrology

<table>
<thead>
<tr>
<th>Analytical Technique</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inductively Coupled Plasma – Mass Spectrometry</td>
</tr>
<tr>
<td>Field-flow Fractionation + ICP-MS</td>
</tr>
<tr>
<td>Liquid Chromatography – Mass Spectrometry</td>
</tr>
<tr>
<td>Optical Spectroscopy – UV/Vis</td>
</tr>
<tr>
<td>Fluorescence Spectroscopy</td>
</tr>
<tr>
<td>Turbidity</td>
</tr>
<tr>
<td>Scanning Electron Microscopy</td>
</tr>
<tr>
<td>Transmission Electron Microscopy (+EDX)</td>
</tr>
<tr>
<td>Atomic Force Microscopy</td>
</tr>
<tr>
<td>Confocal Microscopy</td>
</tr>
<tr>
<td>Field Flow Fractionation</td>
</tr>
<tr>
<td>Dynamic Light Scattering</td>
</tr>
<tr>
<td>Static Light Scattering</td>
</tr>
<tr>
<td>Molecular Gas Adsorption (BET)</td>
</tr>
<tr>
<td>Dialysis</td>
</tr>
<tr>
<td>Electrophoresis and Capillary Electrophoresis</td>
</tr>
<tr>
<td>Ultrafiltration</td>
</tr>
<tr>
<td>Centrifugation</td>
</tr>
<tr>
<td>Filtration</td>
</tr>
<tr>
<td>Nanoparticle Tracking Analysis</td>
</tr>
<tr>
<td>Size Exclusion Chromatography</td>
</tr>
<tr>
<td>Selected Area Electron Diffraction</td>
</tr>
<tr>
<td>Zeta Potential by DLS</td>
</tr>
<tr>
<td>X-ray Diffraction</td>
</tr>
<tr>
<td>Thermogravimetric Analysis</td>
</tr>
<tr>
<td>Quartz Microbalances</td>
</tr>
<tr>
<td>Differential Scanning Calorimetry</td>
</tr>
<tr>
<td>Dynamic Mechanical Analysis</td>
</tr>
<tr>
<td>Fourier Transform Infrared Spectroscopy</td>
</tr>
<tr>
<td>FT-IR Imaging</td>
</tr>
<tr>
<td>Raman Spectroscopy</td>
</tr>
<tr>
<td>TGA coupled with Gas Chromatography – Mass Spectrometry</td>
</tr>
<tr>
<td>Laser Induced Plasma Spectroscopy</td>
</tr>
<tr>
<td>Hydrodynamic Chromatography</td>
</tr>
<tr>
<td>Laser Induced Breakdown Detection</td>
</tr>
<tr>
<td>X-ray Photoelectron Spectroscopy</td>
</tr>
<tr>
<td>Electron Energy Loss Spectroscopy</td>
</tr>
</tbody>
</table>
Implications of Nanomaterials Getting into the Environment

- Processing waste has always been a manufacturing issue. It is slightly different today when nanoparticles are considered, as they are different to bulk material waste.
- It’s been seen in laboratory experiments that nanomaterials can enter the human body by dermal exposure, inhalation, and ingestion.
- While there are very few specific nanomaterial regulations, yet, there is increasing review and concern both within the industry and in the environmental field as to the fate and behavior of these materials in the environment.
Environmental Impact on Human Health

- Many nanomaterial manufacturers are working with the EPA to establish nanomaterial guidelines for health and safety for the workers and for the end users.
- The EPA has therefore declared that the manufacturers of nanomaterials must show proof that they are safe when entering the environment.
- For example, the safety of airborne nanoparticles, nanoparticles in water, and skin exposure to nanomaterials are currently being studied by various research groups and universities.
- A key aspect of this work is the need for methods and analytical techniques that can separate, identify and quantitate ENPs at very low levels in the presence of naturally occurring nanoparticles.
Government Initiatives

- Within the United States, the EPA and other government agencies are proactive in regards to nanotechnology.
- The Federal Government has established the National Nanomaterial Initiative (NNI) where government agencies and private industry meet to discuss to better understand nanomaterial impact on the environment and human health.
The Transfer of Engineered Nanomaterials (EN) from Wastewater & Storm Water to Rivers

The following issues require clarification:

• Which Engineered Nanomaterials are released?
• What amounts are being released?
• How persistent are they?
• To what extent do they cause in situ toxicity?

Reasons for knowledge gaps are a lack of suitable high sensitivity analytical methods, insufficient databases on usage and release, and the absence of comprehensive monitoring networks to advance scientific knowledge on release and fate of engineered nanomaterials in the urban water cycle.
“A Lack of Suitable High Sensitivity Analytical Methods”

• **Single Particle ICP-MS**: a novel analytical technique that allows ICP-MS to monitor single nanoparticles in a sample, together with the dissolved ions to get information about the number, size, and size distribution of the particles.

It is rapidly becoming common nanometrology practice in various laboratories: drug delivery, environmental release, silica dioxide, element oxide slurries, and other application areas.

It is being shown that SP-ICP-MS is capable of generating data that is not possible with any other single analytical technique.
Concept of Single Particle-ICP-MS

Steady-state Signal

Particle Size Information

Individual Signal Events

Differentiation Between Dissolved and Particles Signal
### How does it work?

<table>
<thead>
<tr>
<th>Sample</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Sample" /></td>
</tr>
<tr>
<td>Sample containing dissolved metals</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Plasma</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Plasma" /></td>
</tr>
<tr>
<td>constant stream of charged ions</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Result" /></td>
</tr>
<tr>
<td>Dwell time</td>
</tr>
<tr>
<td>Constant signal</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sample</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Sample" /></td>
</tr>
<tr>
<td>Sample containing metal NPs</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Plasma</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Plasma" /></td>
</tr>
<tr>
<td>pulses of charged ions</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Result" /></td>
</tr>
<tr>
<td>Dwell time</td>
</tr>
<tr>
<td>individual pulses</td>
</tr>
</tbody>
</table>
Factors Influencing Transient Signal Data Quality

Optimization of Measurement Protocol

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Transient Signal Data Quality for Multielement Analysis

**Quadrupole Scanning/ Settling/Measuring Time**

- **Direction of Mass Scan**

- **Scanning Protocol**
  - Scan to a mass
  - Settle electronics (quad and detector)
  - Dwell for fixed period of time at each point on mass
  - Move to next point on mass, settle and dwell
  - Scan/Hop to next mass
  - Repeat measurement cycle
Principles of Single Particle ICP-MS

Understanding a Transient Peak

Dwell Time

Settling Time
Factors Influencing Transient Peak Data Quality

Measurement Efficiency Cycle at Different Dwell Times as a Function of Settling Time

Settling Time does not contribute to data quality as demonstrated by measurement efficiency (duty) cycle below:

\[
\text{Dwell Time} \times \# \text{Sweeps} \times \# \text{Elements} \times \# \text{Reps} \times \frac{100}{(\text{Dwell time} \times \# \text{Sweeps} \times \# \text{Elements} \times \# \text{Reps}) + (\text{Scanning/Settling Time} \times \# \text{Sweeps} \times \# \text{Elements} \times \# \text{Reps})}
\]

Single point peak hopping, with a total integration time of 1 second/mass
For Rapid Transients (Nanoparticle Pulses), Short Dwell Times are Needed
Using a Long Quadrupole Settling Times Can Easily Miss a Nanoparticle Pulse

The Limitations of Conventional ICP-MS

\[ t_d = \text{Dwell Time} \]

\[ t_d \]

\[ t_d \]

\[ t_d \]

\[ t_d \]

\[ t_d \]

Overlap of ion plume transit with dwell time

Inaccurate particle counting leading to inaccurate particle sizing
ICP-MS Schematic of Analysis of Metal-Based Nanoparticles

- Tune Mass Spec for material
- Intensity of pulse relates to particle mass
- Number of pulses relates to particle concentration
- Baseline = dissolved

Counts at mass 197 (Au)

Dwell Time

Pulse

300-500 µs

Time
Fast Continuous Data Acquisition is Important

Overlap of ion plume transit with dwell time

ICP-MS Counts

Time

Fast Continuous Data Acquisition = No Settling Time

Dwell Time Shorter than the Particle Transient Time
Shorter Dwell Times Means a Better Chance of Detecting a Single Nanoparticle Peak

….and less chance of two nanoparticles being mistaken for one
How Nanoparticle Sizing is Carried out by ICP-MS

1. Nanoparticle release
2. Characterize nanoparticles with ICP-MS
3. Collect SP-ICP-MS data
4. Create size distribution
5. Understand product nano-release

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Characterization Cycle by SP-ICP-MS

Size Distribution

Dilution

Time Resolved Data

SP-ICP-MS Analysis

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Converting Pulse Counts to Diameter

<table>
<thead>
<tr>
<th>Time (seconds)</th>
<th>Signal intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>500 ppt Ag⁺</td>
</tr>
<tr>
<td>100</td>
<td>100 ppt AgNP</td>
</tr>
</tbody>
</table>

Ag⁺ calibration data

“unknown” NP sample; raw data

NP mass converted to diameter: apply element mass fraction and density, assume a geometry

Ref: Pace et al. 2011, Anal. Chem, 83, 9361-9369
This transport efficiency must be calculated for each instrument and under the given run conditions for the mass flux to be accurate. In this way, the resulting calibration curve relates signal intensity (counts/event) to a total mass transported into the plasma per event.

The relationship between analyte concentration and the mass observed per event is called the “mass flux”, which is highly dependent on the transport efficiency.

Finally, the intensity of each individual pulse (counts/event) can then be transformed using the mass flux calibration curve to determine the particle mass, which can then easily be converted to particle diameter, when assuming a spherical geometry of the particle.
SP-ICP-MS: Calculate Instrument Transport Efficiency

- Analyte ions are detected only during an ion plume transits to the detector; otherwise, intensity at the detector is due to background.

\[ f = q n_{\text{trans}} C_{\text{NP}} \]

- Sample flow rate (mL/min)
- NP concentration (particles/mL)
- Observed pulse frequency (particles/min)
- Transport Efficiency

Compute this for NP standard
Solve for this
SP-ICP-MS: Calculate Mass Flux

- The analyte signal intensity is proportional to the ion flux
- The number of ions detected for each plume transit is proportional to the analyte mass in the particle

\[ W = \left( \eta_n \right) \left( q_{liq} \right) \left( C \right) \]

Transport Efficiency
Sample Flow Rate (mL/sec)
Sample Concentration (μg/L)
Mass Flux (μg/sec)

\[ y = 228x + 0.9 \quad R^2 = 0.9999 \]

\[ y = 1259x + 0.9 \quad R^2 = 0.9999 \]
SP-ICP-MS: Relating Pulse Height to Nanoparticle Mass/Size

\[ m_{ENP} = f_M^{-1} \left[ \frac{(I_{pulse} - I_{Bkgd})}{m} \right] \]

- \( f_M^{-1} \) = mass fraction metal in NP.
- \( m \) = dissolved mass calibration curve slope.

![Graph showing number of events for 50 nm and 80 nm nanoparticles]
SP-ICP-MS: Relating Mass to Particle Shape

For Sphere (most common): \[ d_{ENP} = \left( \frac{6 \ast m_{ENP}}{\pi \ast \rho} \right)^{1/3} \]

For wire/rod: \[ L_{wire} = \frac{m}{\rho \ast \pi \ast r^2} \]
Data Processing Options of Converting Pulse Counts to Nanoparticle Diameter

Ref: Pace et al. 2011, Anal. Chem, 83, 9361-9369

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Data Processing Options for Converting Pulse Counts to Nanoparticle Diameter

- Data Exported and Data Processing Calculations done via an External Spreadsheet
- Data Processing and Calculations Exported Carried out by the ICP-MS Software
- Data Processing and Calculations Carried out Interactively in Real Time, while the Nanoparticle Pulses are being Generated
- Commercial Instruments use one or more of these approaches
The PKI Nano Application Module is specifically designed for the analysis of Nano Particles on the NexION ICP-MS.

The Nano Application Module can be used to rapidly determine:

- Most common particle diameter (nm)
- Mean particle diameter (nm)
- Distribution of nanoparticle diameters
- Particle concentration (particles /mL) (total or by distribution)
- Dissolved concentration of analyte (ppb)
PKI Nano Application Module: Interactive Real Time Display

Real Time Nanoparticle Pulse Data

Real Time Distribution Histogram of Particle Size
PKI Nano Application Module: Interactive
Real Time Display: Expansion of Pulses

Analytical Parameters
Method Parameters
Calibration

Real Time Distribution Histogram
Real Time Nanoparticle Pulse Data Expanded
Nano Application Module: Interactive
Real Time Display: Dissolved and Nanoparticle Calibration

Sample & Table Export

File Information

Method Parameters

Dissolved Calibration

Particle Calibration

Scrolling list of results

Data Reprocessing

Adjustable Integration Window

Size Distribution Histogram

File Options

Particle Information

Real Time Display: Dissolved and Nanoparticle Calibration

Nano Application Module: Interactive

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Real-Time Display Showing Three Different Sized Nanoparticles

20 nm
50 nm
80 nm
Calibration and Transport Efficiency

- Requires both Dissolved and Particle standards to be measured
- Dissolved Calibration
  - Must be same element as the analyte
  - Required to determine the dissolved analyte concentration in the sample
  - The blank is the particle diluent (typically DI)
- Particle Calibration
  - Can be same or different element than the analyte
- Typical Transport Efficiency = 5-10%
Method Development for Optimum Particle Concentrations

- Dilute sample solutions are required
  - Ideally 100,000 – 200,000 particles/mL
  - Decreases the chance of 2 particles arriving at the plasma at the same time
    - If sample is too dilute, it requires longer total measurement time to see enough particles to get meaningful results
- Ideally, 1,000 – 3,000 peaks are needed in the distribution for reliable results
- For unknown samples, the typical analysis time is typically 1-2 minutes
  - This generates the recommended particle concentration and the optimum number of nanoparticle pulses
  - If number of peaks is outside the recommended range, adjust analysis time and/or dilute sample more
Nano Application Limitations

- In nano mode, only one isotope can be measured.
- Maximum sample time determined by dwell time (6M data points/acquisition)
  - 10 minutes @ 100us dwell time
  - 5 minutes @ 50us dwell time
  - 1 minute @ 10us dwell time
Overall Benefits of Single Particle ICP-MS Characterization for Nanoparticle

- **Shape**
- **Pulse shape?**
- **Porosity**
- **Structure**

**SP-ICP-MS**

**Concentration**

**Composition**

**Agglomeration**

**Size Distribution**

**Size**

**Coating thickness from element ratios**

**Measured mass compared to TEM size**

ICP-MS

Instrumentation

Conventional ICP-MS
SP-ICP-MS Publications (1)

- Silver Particle Characterization Using Single Particle ICP-MS (SP-ICP-MS) and Asymmetrical Flow Field Flow Fractionation ICP-MS: D.M. Mitrano, A. Barber, A. Bednar, P. Westerhoff, C.P. Higgins, and J.F. Ranville; Journal of Analytical Atomic Spectrometry, 27, 1131-1142, (2012)


SP-ICP-MS Publications (2)

SP-ICP-MS Publications (3)

- Gold Nanoparticle Uptake of Tomato Plants Characterized by **Single Particle ICP-MS**: Y. Dan, W. Zhang, X. Ma, H. Shi, C. Stephan; PerkinElmer Application Note (2015)
PKI SP-ICP-MS Nano Application Publications

- **PKI SP-ICP-MS Nano Application Materials:**
  - Single Particle ICP-MS Theory white paper
  - Nano Application Module for SP-ICP-MS
  - Iron Nanoparticles SP-ICP-MS app brief
  - Gold Nanoparticles SP-ICP-MS app note
  - Silver Nanoparticles in surface water SP-ICP-MS app note
  - Element Oxide Slurries Nanoparticles SP-ICP-MS app note
  - Silver Nanoparticles Dissolution SP-ICP-MS app note
  - SP-ICP-MS for Characterization of Nanoparticles in Biological Tissues
The Benefits of Single-Particle ICP-MS to Better Understand the Fate and Behavior of Engineered Nanoparticles in Environmental Water Samples

Single-particle inductively coupled plasma–mass spectrometry (SP-ICP-MS) is an exciting new technique for detecting and characterizing metal nanoparticles at very low concentrations. It is fast and can provide significantly more information than other traditional techniques, including particle number concentration, particle size, and size distribution, in addition to the concentration of dissolved metals in solution. The added benefit of using ICP-MS is that it can distinguish between particles of different elemental compositions. The study will investigate the use of SP-ICP-MS to track the release of engineered nanoparticles (ENPs) into the environment and to better understand their fate and behavior specifically in drinking, surface, and wastewater samples.

The unique properties of engineered nanoparticles (ENPs) have created intense awareness in their environmental behavior. Because of the increased use of nanotechnology in consumer products, industrial applications, and healthcare technology, nanoparticles are more likely to enter the environment. For this reason, it is not only important to know the type, size, and distribution of nanoparticles in soils, potable water, and wastewater, but it is also crucial to understand their impact on the growing mechanism of crops used for human consumption. Therefore, to ensure the future development of nanotechnology products, there is clearly a need to evaluate the risks posed by these ENPs, which will require proper tools to fully understand their toxicological impact on human health. Current approaches to assess exposure levels include predictions based on computer modeling, together with direct measurement techniques. Predictions through modeling are based on knowledge of how they are emitted into the environment and by their behavior in the samples being studied. Although the life cycles of ENPs are now starting to be understood, very little is known about their environmental behavior. Prediction through life-cycle assessment modeling requires validation through measurement as environmentally significant concentrations. For ENPs that are being released into the environment, currently sensitive methods are required to ensure that direct observations are representative in time and space. ENPs differ from most conventional “dissolved” chemicals in terms of their heterogeneous distributions in size, shape, surface charge, composition, and degree of dispersion. For this reason, it is not only important to determine their concentrations, but also these other important metrics, particularly when they are discharged and interact with their real-world surroundings.

Impact of Nanoparticles Released into the Environment

When nanoparticles enter the environment, they can undergo a number of potential transformations that depend not only on the properties of the nanoparticles but also on the medium they are being released into. These changes typically involve chemical and physi-