Characterization of Nanomaterials Under the Special Aspect of Migration from Packaging Materials into Food

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Workshop on Outlook and Challenges of Nanotechnologies for Food Packaging

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Introduction

The Issue at Hand:

- A packaging system contains nanostructured entities that enhance functionality of the packaging system.
- The nanomaterial (e.g., spherical or non-spherical particles, monolayers) itself may be "simple" to characterize.
- Once it is incorporated into the packaging matrix, this task becomes more difficult.
- Determining what happens over time may be extremely difficult.

Food packaging based on polymer nanomaterials Progress in Polymer Science, Volume 36, Issue 12, December 2011, Pages 1766-1782
Clara Silvestre, Donatella Duraccio, Sossio Cimmino
Why Do We Need to Know What Happens?

- Nanomaterials have shown to interact especially with biological entities (such as ourselves) in unforeseen ways
- If the nanostructures are liberated from the packaging materials, they will interact with their environment, which may be us
- In order to assess risk and safety, we need to ensure that no or minimal migration takes place


TEM images revealing attachment of nanoparticles to the surface of *P. fluorescens*: SiO₂ (B), ZnO (D).
What Do We Need To Know ?

• Is there a liberation of nanostructures from the packaging material?
  – Changes in concentration, composition, structure of the packaging material containing the nanoentities
  – Uptake of the nanoentities by food – concentration, composition, structure in the food matrix
  – Uptake by the body upon consumption of food? – Interaction with digestive system, in extreme case permeation through membranes?
  – Environmental impacts upon decomposition?
Why is This Such a Difficult Issue?

- Ordinarily, detecting the presence and concentration of a potentially hazardous material may be sufficient to draw conclusions about risk.
- In nanomaterials: physicochemical properties and structure alter behavior (e.g. reactivity).
- Thus structure has to be determined as well!
- Structure analysis (in situ) on nanometer lengthscales is difficult at best impossible at worst.

Conversion of CO oxidation (black bars) and the activity of glucose oxidation (grey bars) over gold nanoparticles.

**Gold catalysis: Effect of particle size on reactivity towards various substrates**
*Catalysis Today, Volume 181, Issue 1, 12 February 2012, Pages 26-32* László Guczi, Andrea Beck, Zoltán Pászti
Overview General Analytical Tools

• Compositional Analysis:
  – Spectroscopic or chemical methods
  – Substantial variations on limits of detectable concentrations
  – Chemical methods are not “in situ” – typically involve “destruction” of material – if structure is changes so may chemical reactivity

• Structural Analysis:
  – Imaging / Microscopic Methods
  – Scattering Methods
  – May require preparation methods that may alter material

• Physicochemical Property Analysis:
  – Wide variety of techniques
  – Electrophoretic mobility, thermal analysis, adsorption behavior
  – Often suited to “free” nanoentities but not “embedded” nanoentities
A. Spectroscopy

**Definition:**
Analytical techniques that provide information about material properties by measuring the interaction of radiation with matter

Radiation Source ➔ Material ➔ Radiation Detector

**Information:** Composition, Structure, Dynamics
General Spectroscopy Principles (I)

Energy Form:
- Electronic
- Vibrational
- Rotational
- Nuclear
- Translational

Each material has a unique set of energy levels depending on the type of atoms and molecules present.

Unique Energy Levels:
- $E_0$
- $E_1$
- $E_2$
- $E_3$
General Spectroscopy Principles (II)

Radiation

\( h\nu \)

\( \rightarrow \)

Material

Material with specific energy levels

\( E_0 \)
\( E_1 \)
\( E_2 \)
\( E_3 \)

Interaction

If \( h\nu = \Delta E \)
- Absorption of Photon
- Atom or Molecule Excited

If \( h\nu \neq \Delta E \)
- No Absorption of Photon
- Photon Passes Through

Measurement Modes: Absorption or Emission
Spectroscopic Methods

- UV / NIR: Visible or near infrared spectra
- Infrared: Raman: Depends on the polarizability of molecules and causes an excitation of their vibrational modes, FTIR
- MS:
  - Conversion to ions by electrospray ionization (ESI), matrix-assisted laser desorption ionization (MALDI), laser desorption/ionization (LDI) or inductively coupled plasma (ICP). Subsequent analysis of mass-to-charge ratio by time-of-flight (TOF), ion-trap (IT), quadrupole linear ion-trap (QLIT), quadrupole time-of-flight (QTOF), and secondary ion mass spectrometry (SIMS)
- NMR:
  - Pulsed Field (PF-NMR), nuclear resonance scattering (NRS) using synchrotron radiation, positron annihilation spectroscopy (PAS), muon spin resonance spectroscopy (muon-SR), and perturbed angular correlation (PAC)
<table>
<thead>
<tr>
<th>Characterization Technique</th>
<th>Detectable Properties</th>
<th>Advantages and Disadvantages</th>
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<tbody>
<tr>
<td><strong>UV-Visible, Near Infrared (NIR) Spectroscopy</strong></td>
<td>Aggregation, Chemical composition</td>
<td>Advantages: Inexpensive, little sample preparation, turbid samples in reflectance mode Disadvantages: Insensitive, structure information only for sizes &gt; 300nm</td>
</tr>
<tr>
<td><strong>Raman Spectroscopy</strong></td>
<td>Composition, some structural information especially for proteins</td>
<td>Advantages: Little sample preparation, aqueous systems Disadvantages: Only dilute systems</td>
</tr>
<tr>
<td><strong>Fourier Transform Infrared Spectroscopy (FTIR)</strong></td>
<td>Qualitative chemical composition</td>
<td>Advantages: Rapid measurement Disadvantages: Dry systems only, quantitation difficult</td>
</tr>
<tr>
<td><strong>Mass Spectrometry (MS): Secondary ion (SIMS), single particle (SPMS), Time of flight (TOF)</strong></td>
<td>Quantitative chemical composition</td>
<td>Advantages: In combination with aerosol time of flight technique size information as well Disadvantages: Sample preparation, column interactions, destructive, potentially unwanted solvent</td>
</tr>
<tr>
<td><strong>Nuclear Magnetic Resonance Spectroscopy (NMR), Pulsed Field (PF-NMR)</strong></td>
<td>Diffusion coefficient, size, some structure information extractable</td>
<td>Advantages: Suitable for both hydrated or dry Disadvantages: Interpretation difficult</td>
</tr>
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B. Microscopy / Imaging

Definition:
Microscopy involves the interaction of electromagnetic radiation or electron beams with a specific portion of the sample and a collection of that radiation to create an spatially resolved image -

Information: Composition, Structure, Dynamics
Light and Electron Microscopy

\[ d = \frac{\lambda}{2N_A} \]

\[ \Rightarrow d_{\text{min}} \approx 200 \text{ nm} \]

\[ \lambda = \frac{E}{mv} \]

**Electron Wavelength Data:**
- 1 keV \( \lambda = 0.04 \text{ nm} \)
- 10 keV \( \lambda = 0.01 \text{ nm} \)
- 100 keV \( \lambda = 0.004 \text{ nm} \)

Radiation Source
Condensor
Sample
Objective Lens
Projective
Screen
Electron Microscopy

- Scanning EM: Secondary and backscattered electrons are collected
- Transmission EM: Direct transmission of electrons
- Energy Dispersive X-Ray (EDX): Collection of "kicked out" electrons (X-ray spectra collection)
- Environmental SEM
Probe Microscopy (AFM)

- Utilizes interaction (attraction or repulsion) of a probe as it is scanned across the sample surface.
- The attractive or repulsive forces can be determined by measuring the deflection of the probe and knowing the spring constant of the probe holder.

## Microscopic / Imaging Methods

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<td><strong>Electron Microscopy:</strong> (Cryo) Transmission (TEM), (Environmental) Scanning (E-SEM), Scanning Transmission (STEM), Analytical (EDX &amp; EELS), Auger (AES)</td>
<td>Aggregation, particle number and size, surface topography and composition,</td>
<td>Advantages: Very high resolutions, imaging of intact (frozen) specimens, combination with analytical techniques possible  Disadvantages: Expensive, sample preparation difficult, some techniques in full vacuum not suitable for hydrated samples</td>
</tr>
<tr>
<td><strong>Near Field Scanning Optical Microscopy (NSOM)</strong></td>
<td>Size, shape, some chemical information</td>
<td>Advantages: Expansion of optical microscopy to spatial resolutions of tens of nanometers  Disadvantages: Suitable for thin samples only</td>
</tr>
<tr>
<td><strong>Atomic Force Microscopy</strong></td>
<td>Size, shape, some compositional information</td>
<td>Advantages: Hydrated and dehydrated samples, 3D structures, surface topology, rheological information extractable  Disadvantages: Time consuming, Samples must be fixed to prevent distortions due to movement.</td>
</tr>
<tr>
<td><strong>X-Ray Microscopy (XRM), X-Ray Diffraction (XRD), X-Ray Photoelectron (XPS)</strong></td>
<td>Size, shape, composition</td>
<td>Advantages: Very high resolution  Disadvantages: Radiation damage possible, resolution best for metals not organic materials, no information on hydrogen</td>
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C. Scattering

Definition:
The process whereby a radiation (light or sound) deviate from their straight path due to the presence of an entity that is suspended in the medium through which the radiation wave travels.
Scattering Methods

• Light Scattering:
  – Dynamic or static

• Ultrasound:
  – Velocity or attenuation analysis

• Neutron Scattering
  – Diffraction: SANS, Reflectometry
  – Inelastic scattering: Triple-axis, time-of-flight, backscattering, spin echo, resonance spin echo
### Scattering Methods

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<td>Small Angle Neutron Scattering (SANS)</td>
<td>Charge density, size, shape, concentration</td>
<td>Advantages: Possible for fully hydrated samples, internal structure information can be obtained by deuteration. Disadvantages: Only available in central (governmental) institutions, interpretation of scattering data difficult, resolution depending on strength of neutron sources.</td>
</tr>
<tr>
<td>Static and Dynamic Light Scattering</td>
<td>Size, shape, molecular weight, radius of gyration</td>
<td>Advantages: Inexpensive, simple sample preparation. Disadvantages: Requires dilution to prevent multiple scattering.</td>
</tr>
<tr>
<td>Ultrasound Scattering</td>
<td>Size, concentration</td>
<td>Advantages: Feasible for concentrated systems as well. Disadvantage: Analysis requires knowledge of a large amount of physical properties. In complex systems signals are difficult to analyze and interpret.</td>
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In most cases, samples have to be prepared for analysis, especially if the structures to be investigated are included in a matrix.

This may involve digestion or removal of the matrix prior to analysis (e.g. by solvents, chemically, enzymatically, or by thermal degradation.

Samples may also have to be concentrated or fractionated in order to obtain sufficient quantities of material.

Key techniques for fractionation of particles after dissolution / removal of matrix: FFF

Research ongoing, e.g. NanoLyse project at Wageningen UR
Proposed Analytical Scheme

- Extraction of nanoentity to be analyzed is included in a matrix
- Enrichment of concentration is insufficient
- Fractionation if large variations in size of entities so that a single technique can not be used
- Subsequent analysis by the previously mentioned methods
Conclusions

• The difficulty of characterizing structure, concentration and composition of nanomaterials remains one of the key issues that inhibit production, use and distribution of such materials.

• Many techniques (not just one) are needed to properly characterize a nanomaterial especially if embedded in a matrix.

• Techniques are expensive and difficult to use → a problem for both industry and regulators.

• Lots of unknowns as to potential alterations due to sample preparation → do we really get data of the actual sample or only of an artifact?

• For dynamic processes such as migration, the issue becomes even more difficult as we have to consider the time factor.