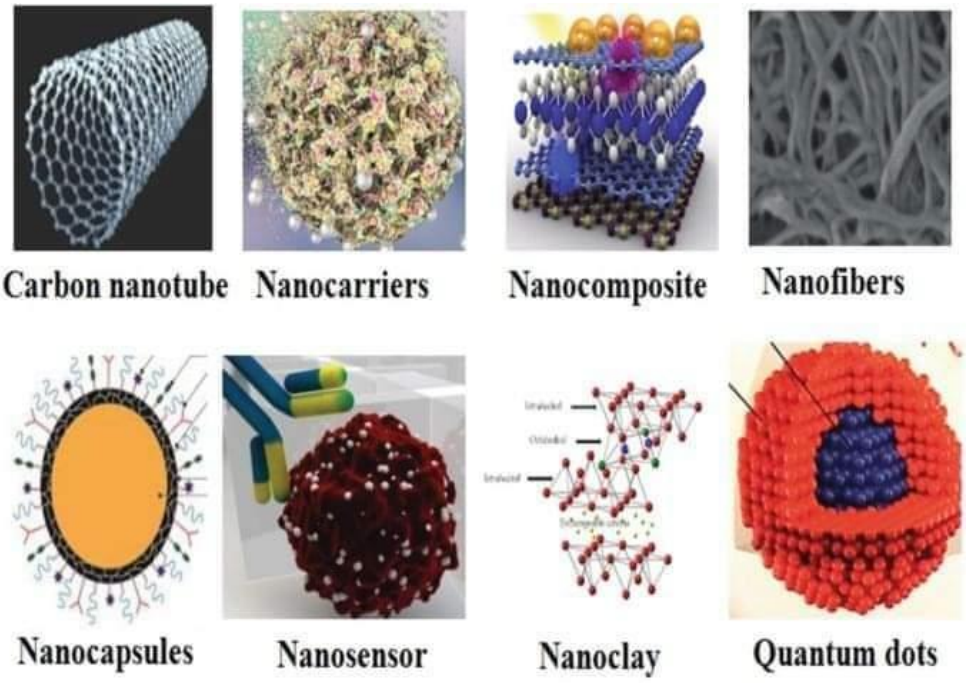
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Ministry of Higher Education and Scientific Research Ibn Khaldoun University–Tiaret-
Faculty of Materials Science Department of Chemistry

Nanomaterials and nanochemistry



Intended for Master 2 students, Materials Chemistry

By

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Foreword

This course handout, entitled "Nanomaterials and nanochemistry", is intended for second year Master's students, specializing in Materials Chemistry, in the Chemistry department of the Faculty of Materials Science at the University of Tiaret.

The topics covered in this handout are:

- Nanomaterials
- Synthesis and development of nanomaterials
- Characterization
- Molecular modeling of nanomaterials
- Nanomaterials and color
- Nanomaterials for biological labeling
- Development and applications I (Energy)
- Application II (Pollution control and catalysis, electromagnetism)
- Nanomedicine
- Electromagnetic applications
- Toxicity. Issues related to nanomaterials

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INTRODUCTION

Nanomaterials constitute the cornerstone of the nanotechnology revolution, referring to structures with at least one dimension ranging between 1 and 100 nm. At this critical scale, matter undergoes a radical modification of its properties driven by a high surface-to-volume ratio and quantum confinement effects granting unprecedented optical, mechanical, magnetic, or catalytic behaviors compared to the bulk state. Their major scientific and technological importance lies in their ability to overcome critical industrial and environmental bottlenecks. Consequently, they find diverse, high-impact applications in fields as varied as energy conversion and storage, depuration, advanced electronics, and nanomedicine. This course aims to explore the physico-chemical foundations of these structures, their preparation methods, and their structure-property relationships to master their design.

We chose to approach this subject from the perspective of future engineers, so we will only discuss research and potential applications (whether completed or still in the planning stages). We will therefore avoid discussing the impact on society or activist reactions.

History

We have been talking about nanotechnology since the beginning of the 2000s and the word itself dates back to the 1970s. In fact, the story began much earlier, we can trace it back 2000 years with the Greek philosophers Leucipe and Democritus who saw matter as composed of indivisible particles which in a way foreshadowed atoms.

But it wasn't until the 19th century that something emerged that was less a philosophical concept and more a scientific theory supported by facts, with Dalton's atomic theory, which sought to explain why chemical reactions always occur with fixed proportions of reactants. Shortly afterward, Loschmidt demonstrated that the atom, if it exists, measures approximately 1 nanometer, which isn't so far from reality.

In the 19th century, scientists were already working with matter at the nanoscale, in ultra-divisible particles; these were called colloids at the time. They weren't directly visible then, but their properties were observed. These colloids were composed of either organic particles from living organisms or metals.

The atom itself, which is at the center of all these ideas, only took shape in the 20th century. It all began in 1897 with Thomson's discovery of the electron, which led him quite quickly to propose a model of atoms in the shape of a pudding, with a positive jelly filled with negative electrons so that the whole thing is neutral.

Then in 1911, with Rutherford's discovery of the nucleus, the model of the atom became more complex, leading to the image of a positive and dense nucleus at the center surrounded by a cloud of electrons, a model that was gradually refined in the 20th century with the advent of quantum mechanics.

And in the 1930s, we had a good understanding of what an atom is, what a molecule is, and also of the forces that act between molecules. We must also talk about visualization methods.

We have been able to observe this matter at the nanoscale for a very long time. As early as the beginning of the 20th century, we could indirectly see the atoms aligned in a crystal thanks to X-ray diffraction. Similarly, ultra-divided matter was not seen directly, but indirectly because it scatters light, and at that time, ultrasonic microscopes were already being developed that allowed us to measure the amount of colloid in a liquid.

An important step was the invention of the electron microscope in 1930, a device that made it possible to see matter directly at this scale, at the time about ten nanometers, and nowadays these devices achieve a resolution that is less than the atom.

Nanotechnology

The term "nanotechnology" was first used in 1974. In the 1980s, with the discovery of the scanning tunneling microscope (STM) and then the atomic force microscope (AFM), the nanoworld truly opened up to researchers. The reference unit of the nanoworld is the nanometer (abbreviated nm). The prefix "nano" comes from the Greek word nannos, meaning dwarf. One nanometer is equivalent to one billionth of a meter ($1\ nm = 10^{-9}\ m$). Nanotechnology encompasses the design, characterization, production, and application of structures, devices, and systems by controlling their shape and size at the nanoscale. It is a branch of science dedicated to the study and fabrication of structures (called nano-objects) with dimensions ranging from 1 to 1,000 nanometers (nm).

Nanoscience

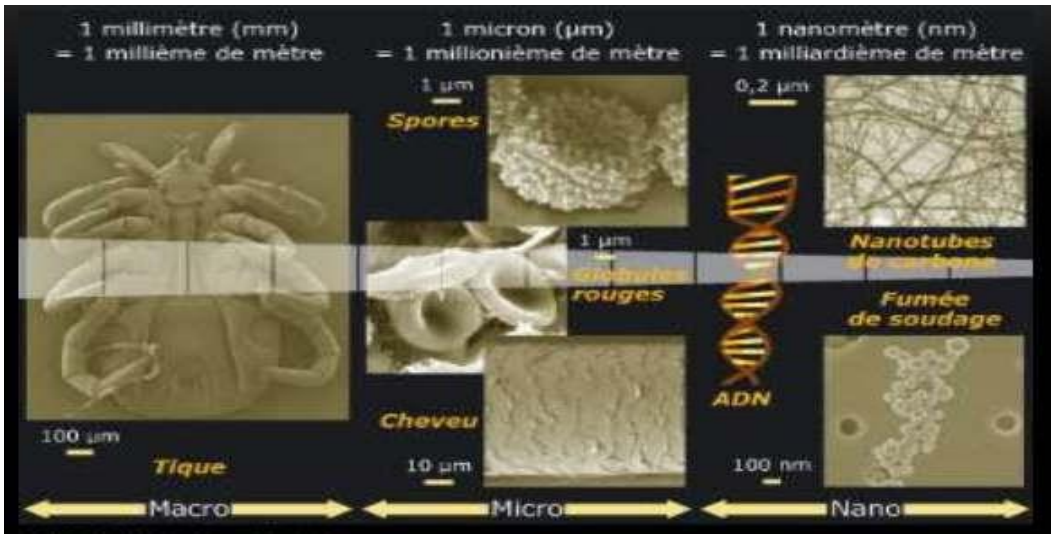
Concerns the study of phenomena observed for objects whose size is a few nanometers and whose properties derive specifically from this nanometric size.

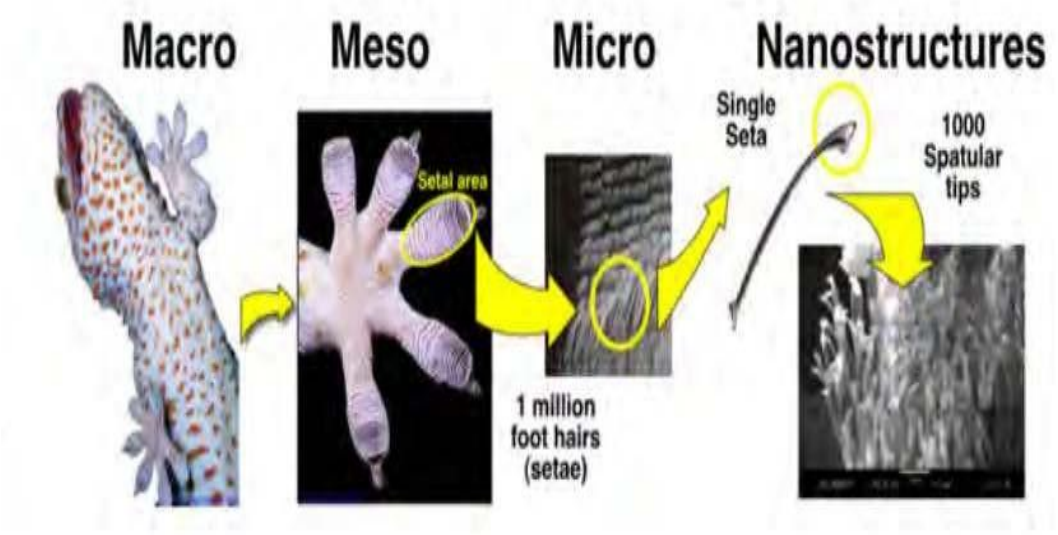
Nanosciences are the fundamental sciences devoted to the study of phenomena observed in structures and systems at the atomic, subatomic, molecular and macromolecular scales, and nanotechnologies are the application of these, which allow the design, characterization, production and application of structures, objects and systems by controlling the shape and size at a nanometric scale.

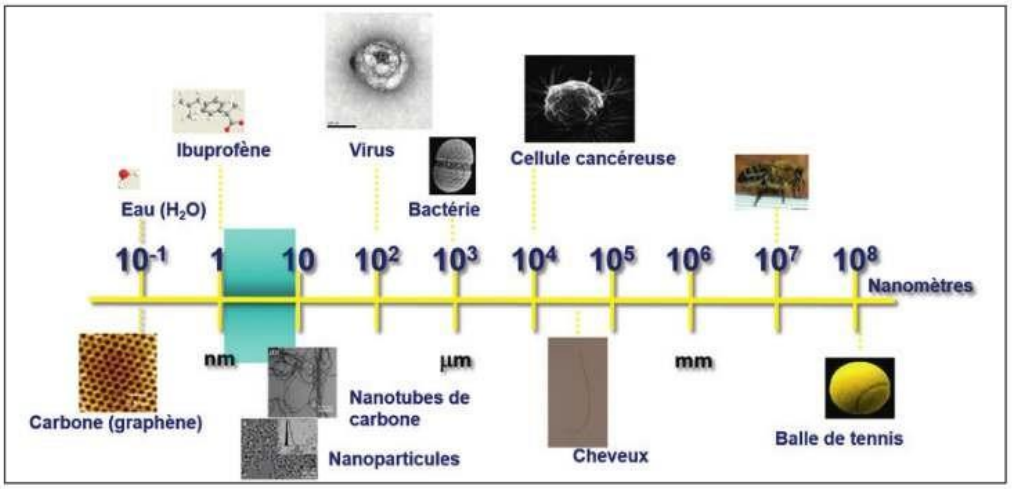
Calibration

- 0.1 nanometer: diameter of a hydrogen atom.
- 2.5 nanometers: width of a DNA molecule.
- 45-90 nanometers: current microelectronic circuits.
- 800 nanometers: red blood cell of a human being.
- 1.7 billion nanometers: average height of a human being.

The following figures show the different sizes and structures.







Figures of calibration of nanomaterials.

Objective

- Miniaturize
- Reduce costs
- Exploiting different properties

Definition of nanomaterials NMs

A nanomaterial is a material of which at least one dimension is on the nanometric scale, that is to say approximately between 1 nm and 100 nm, or which has an internal or surface structure on the nanometric scale.

Sources of nanomaterials

a) **Natural origin**: sea spray, volcanic activity, forest fires

b) **Human activities**: cooking fumes, barbecue smoke, plant dust

c) **Derivatives of industrial processes** Dust and fumes that may originate from:

- *Thermal*: foundry work, welding, oxy-fuel cutting, surface treatment (metallization, resin application…)
- *Mechanical:* milling, sanding, drilling, polishing...
- *Combustion*: engines (diesel, petrol or gas), food smoking, gas heating, incineration
- *Spreading of plant protection products, fumigation gas...*

d) **Intentional production and use** for industrial and research purposes.

Properties of nanomaterials

The study and use of nanostructured materials are experiencing considerable growth due to their unique properties. All major material families are involved: metals, ceramics, dielectrics, magnetic oxides, silicate frameworks, carbons, polymers, etc.

1.Mechanical properties:

With regard to mechanical properties, the effect of the nanostructure results in a phenomenon of superplasticity. Nanomaterials make it possible to improve the strength of materials without compromising their ductility because the size of the nanoparticles limits the concentrations of stress. The example below shows an extremely large elongation for a nanocrystalline copper material.

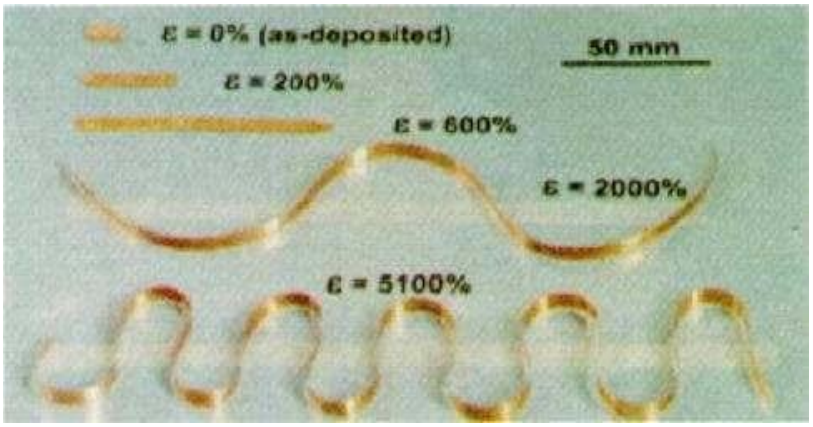


Figure: Superplastic deformation of a bulk Cu-based nanomaterial

2.Electrical properties

Nanomaterials possess unique electrical properties due to their nanometric size: they can exhibit increased conductivity, quantum confinement effects, and semiconducting or metallic behaviors that can be modulated according to their structure. These characteristics are exploited in transistors, sensors, batteries, and quantum devices.

Example:

The introduction of nanoparticles and/or nanotubes can drastically alter the electrical conductivity of materials considered to be insulators. In the example below, the electrical conductivity reaches 3345 S/m for the addition of 15% vol. of single-walled carbon nanotubes in an alumina matrix, corresponding to a change of 13 orders of magnitude from the initial value.

Painting: Modification of the electrical conductivity of Al_2O_3 following the addition of carbon nanotubes.

Materials	Manufacturing conditions	Relative density (%TD)	Grain size (nm)	Electrical conductivity (S/m)
Pure Al_2O_3	SPS 1150 °C/ 3 min	100	350	10-12
5.7 vol % carbon black / Al_2O_3	SPS 1150 °C/ 3 min	100	200	15
5.7 vol% single-walled NTC / Al_2O_3	SPS 1150 °C/ 3 min	100	200	1050
10 vol % single-sheet NTC / Al_2O_3	SPS 1200 °C / 3 min	99	100	1510
15 vol % single-sheet NTC / Al_2O_3	SPS 1150 °C/ 3 min	99	100	3345
8.5 vol% NTC / 4.3 vol% Fe / Al_2O_3	HP 1150 °C / 15 min	88.7	300	40-80
10 vol % NTC / 4.3 vol % Fe / Al_2O_3	HP 1150 °C / 15 min	87.5	300	280-400
20 vol % NTC / multi-layered / polymer	…..	…	…	30

NTC: *nanotube of* carbon

3.Optical properties

Nanoparticles have dimensions smaller than the wavelengths of visible light (380 – 780 nm), which allows for the improvement of the unique optical properties of the material linked to their nanometric size: they can absorb, scatter and emit light differently from bulk materials, paving the way for applications in optoelectronics, bio-imaging and sensors.

Quantum size effect:

At the nanoscale, electrons are confined, which alters energy levels. This leads to phenomena such as photoluminescence (the emission of light after excitation).

Surface plasmon resonance (SPR):

Observed mainly in metallic nanoparticles (e.g., gold, silver). Free electrons oscillate collectively under the effect of light, producing intense colors that depend on the size and shape of the particles.

4.Heat transfer properties

The thermal transfer properties of nanomaterials refer to how heat is conducted, stored, or dissipated at the nanoscale. They differ significantly from those of bulk materials, as surface phenomena, small size, and quantum confinement become dominant.

In nanomaterials, heat transfer is primarily governed by:

- *The phonons* (quanta of vibrations of the crystal lattice).
- *Electrons* (in metals and semiconductors).
- *The interfaces* (contacts between nanoparticles, nanolayers or nanofibers).

These mechanisms are modified by the nanometric size, resulting in novel thermal behaviors.

5.Barrier properties

Barrier properties in nanomaterials refer to a material's ability to prevent or limit the passage of certain substances (gases, water vapor, ions, molecules) through its structure. Barrier properties correspond to a nanomaterial's ability to act as a protective barrier against:

- *The diffusion of gases (oxygen, carbon dioxide, water vapor).*
- *The migration of ions or molecules in polymers and composites.*
- *Corrosion and oxidation are prevented by limiting the access of chemical agents to the surface.*

Example:

In polymer matrix nanocomposites, the incorporation of clay increases the barrier properties against water and gases due to the increased distance that diffusing molecules must travel. The silicate lamellae are impermeable to water and gases.

6.Flammability

Flammability in nanomaterials refers to their ability to ignite and burn when exposed to a heat source or flame. As with conventional materials, this is a crucial property for fire safety, but it takes on a particular significance at the nanoscale because the small size of the particles and their high specific surface area can alter their behavior in the face of fire.

Example:

The flame-retardant properties of polymers are enhanced by the use of silicate-polymer nanocomposites. The introduction of nanometer-sized clay flakes into a polymer matrix delays its degradation and allows the formation of a carbonized surface layer that does not fracture but instead forms a multilayer silicate nanostructure, improving barrier and resistance properties, acting as an insulator, and reducing emissions of volatile combustion products.

7.Magnetic properties

Magnetic properties in nanomaterials refer to how these materials respond to an external magnetic field or generate their own magnetism. At the nanoscale, magnetic behavior differs significantly from that of bulk materials, as size effects, high specific surface area, and quantum interactions become dominant. In nanomaterials, size reduction leads to unique phenomena such as superparamagnetism, increased magnetic anisotropy, and coercivity variation.

8.Catalytic properties

The catalytic properties of nanomaterials refer to their ability to accelerate or facilitate a chemical reaction without being consumed by that reaction. At the nanoscale, these properties are greatly enhanced due to the small size of the particles, their high specific surface area, and quantum effects that modify the reactivity of the surface atoms. For example, the modification of the catalytic properties of manufactured nanoparticles is illustrated by the example of gold nanoparticles.

Type of nanomaterials:

Nanomaterials are classified using different methods; we distinguish:

- Intentionally generated (manufactured) nanomaterials.
- Unintentionally generated nanomaterials.
- Nanomaterials generated according to their dimensions.
- Nanoparticles generated according to their composition.

1.Intentionally generated (manufactured) nanomaterials.

a) **Nano-objects**: which are materials where at least one of the external dimensions is between 1 and 100 nanometers. The number of nanometer dimensions is three for nanoparticles, two for nanotubes or nanowires, one for nanosheets or two-dimensional (2D) materials.

i. *Nanoparticles:* refer to nano-objects whose three external dimensions are on the nanometric scale: latex nanoparticles, zinc oxide, iron and cerium nanoparticles, alumina and titanium dioxide nanoparticles, sodium carbonate nanoparticles, etc.

ii. *Nanofibers, nanotubes, nanofilaments or nanobatonets*: These terms refer to nano-objects where two external dimensions are on the nanometer scale and the third dimension is significantly larger (carbon nanotubes, polyester nanofibers, boron nanotubes, etc.). They designate elongated nano-objects with a cross-section between 1 and a few tens of nm and a length between 500 and 10,000 nm.

iii. *Nanosheets, nanoplates, or nanoplatelets:* which define nano-objects whose external dimension is on the nanometric scale and whose other dimensions are significantly larger (clay nanosheets, cadmium selenide nanoplatelets, etc.).

Noticed:

Nano-objects can be used as such in the form of powder, suspension, solution or gel.



b) **Nanostructured materials:** which, while having macroscopic dimensions, possess a structure internal or surface at the nanometric scale. Nanoporous materials (whose pore diameter is less than or on the order of 100 nm) belong to this family as do aggregates and agglomerates, nanocomposites.

i. *Aggregates and agglomerates of nano-objects:* Nano-objects can be in individual form (i.e., in the form of primary particles), or in the form of aggregates or agglomerates whose size is significantly greater than 100 nm.

ii. *Nanocomposites:* These materials are composed, to a large extent, of nano-objects that give them enhanced or nanoscale-specific properties. The nano-objects are incorporated

into a matrix or onto a surface to provide new functionality or modify certain mechanical, magnetic, thermal, or other properties. Carbon nanotube-loaded polymers used in the sporting goods industry to improve mechanical strength and reduce weight are an example of nanocomposites.

iii. *Nanoporous materials:* These materials have pores of nanometric size. Silica aerogels are nanoporous materials that exhibit excellent thermal insulation properties.

2.Unintentionally generated nanomaterials

Type of process	Examples
Thermal	- Metal foundry and refining (steel, aluminum, iron, etc.) - Metallization (galvanizing, etc.) - Welding and gouging - Metal cutting (laser, thermal torch, etc.) - Surface heat treatment (laser, thermal spraying, etc.) - Application of resins, waxes, etc.
Mechanical	- Machining - Sanding - Drilling - Polishing
Combustion	- Emissions from diesel, petrol or gas engines - Incineration plant, thermal, cremation - Food smoking - Gas heating

3.Nanomaterials generated according to their dimensions

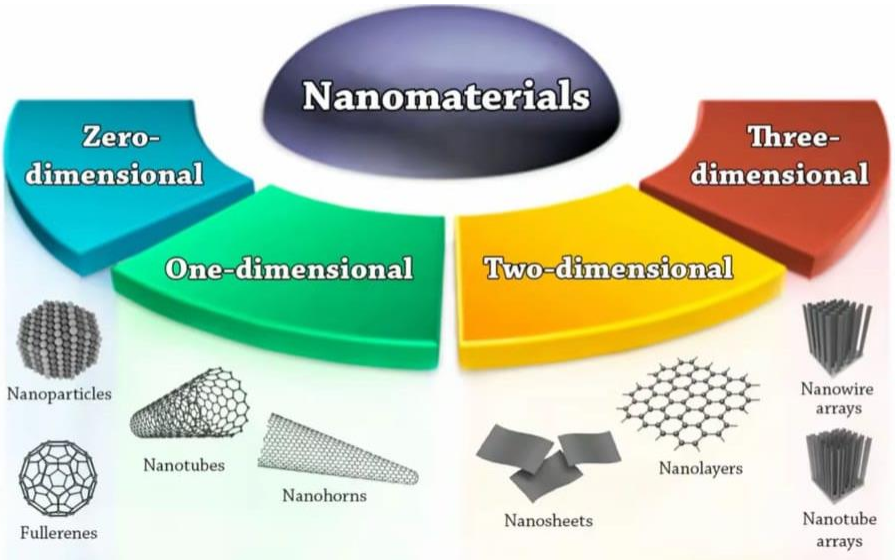


Figure: Classification of nanomaterials based on their dimensions

➢ ***0D: Nanoparticles***

All their three dimensions are in the nanometer range include nanoparticles, fullerenes, and quantum dots.

➢ ***1D: Nanowires and nanotubes***

one dimension is outside the nanoscale, while the other two are inside the nanoscale. This classification includes nanofibers, nanorods, nanotubes, nanowires, and nanohorns.

➢ ***2D: Nanolayers and thin films***

Nanosheets, and nanolayers have two dimensions beyond the nanoscale. Example: graphene, thin films of TiO_2.

➢ ***3D: Complex Nanostructures***

The most common examples of three-dimensional nanomaterials (3–D) or bulk nanomaterials are core shells, arrays of nanotubes, and nanowires. In this category, the materials are not in the nanoscale in any dimension. Example: nanocomposites.

4. Nanomaterials generated according to their composition

Nanoparticles can also be divided according to their composition, meaning according to the material from which they are produced. These include in particular organic, inorganic, and carbon-based nanoparticles.

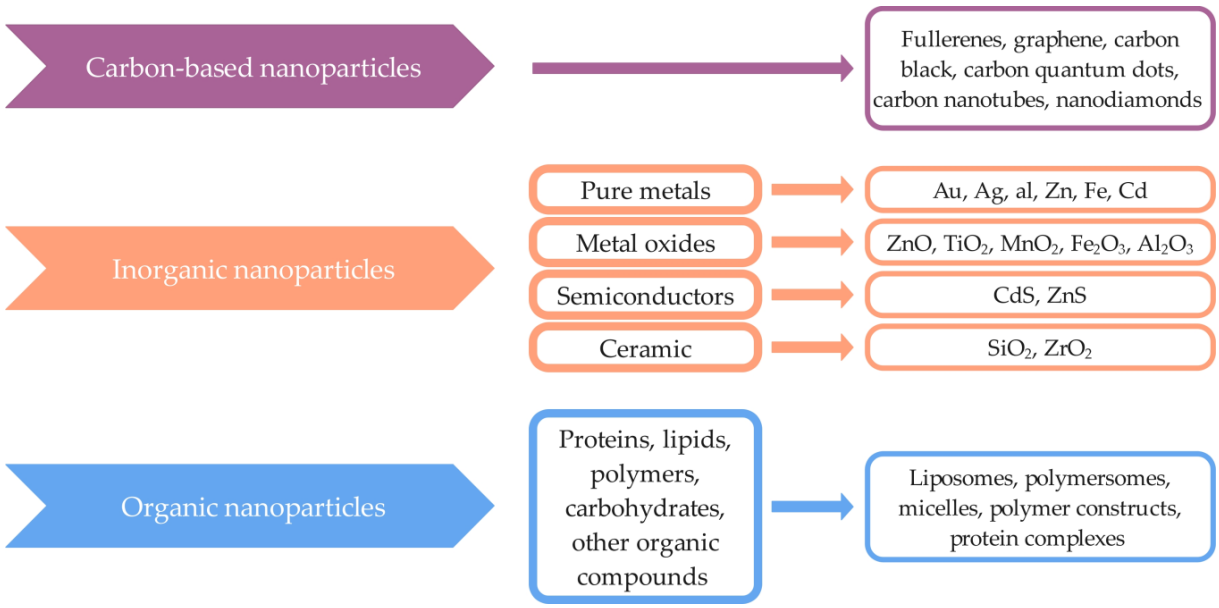


Figure: Classification of nanomaterials based on their chemical composition

Nanomaterial manufacturing processes:

Manufactured nanomaterials can be synthesized using two different approaches. It is therefore necessary to differentiate between the so-called "bottom-up" method and the so-called "top-down" method.

1.The approach "ascending" (Top-own):

It consists of building nanomaterials atom by atom, molecule by molecule, or aggregate by aggregate. The assembly or positioning of atoms, molecules, or aggregates is carried out in a precise, controlled, and exponential manner, thus enabling the development of functional materials whose structure is completely controlled.

2.The approach " descending » (Bottom-up):

It consists of reducing, and more specifically miniaturizing, current systems by optimizing existing industrial technologies. Devices or structures are thus gradually downsized or fragmented until they reach nanometric dimensions.

The following figure shows the two approaches.

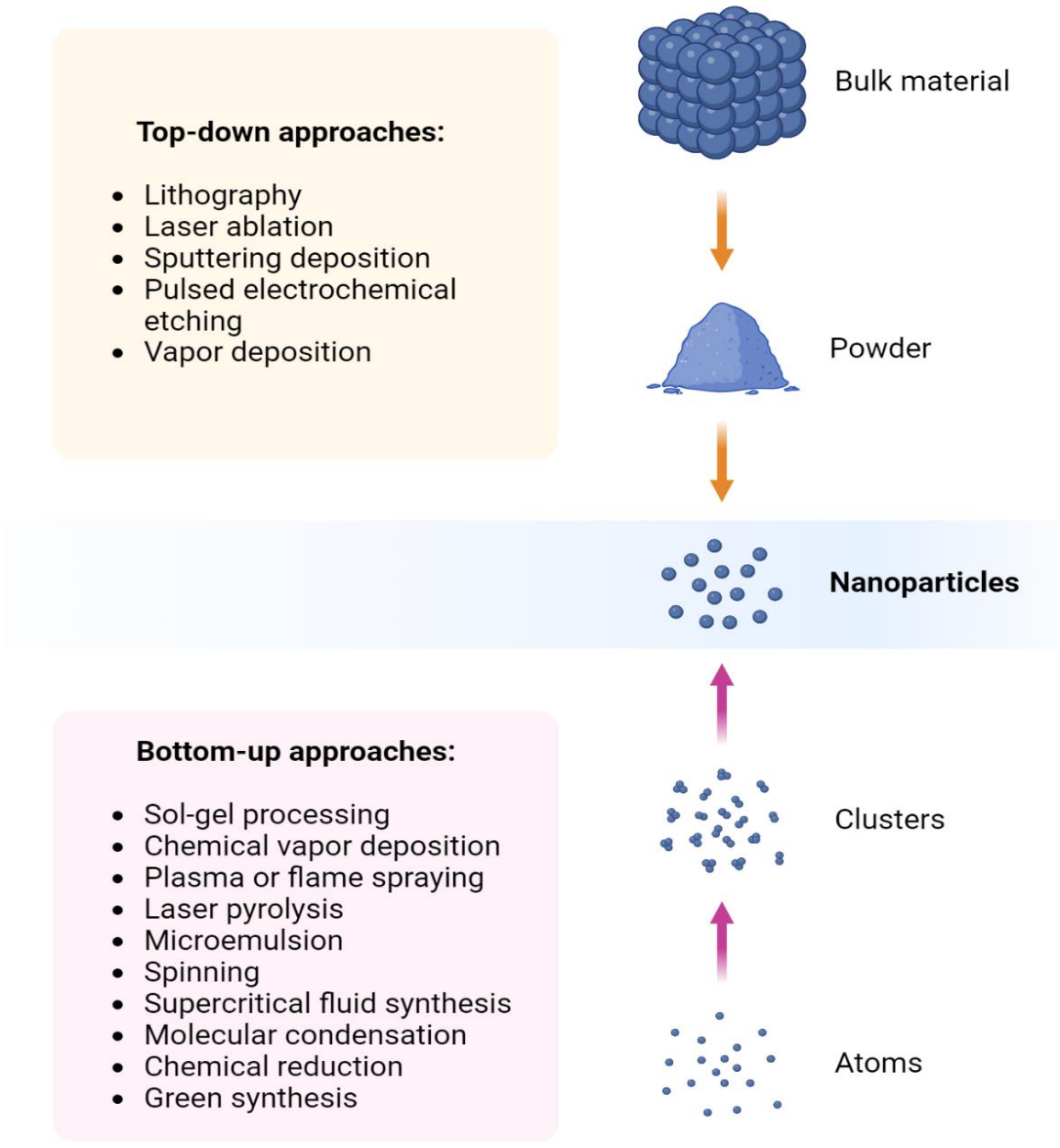


Figure of nanomaterial manufacturing processes

The table below shows the different manufacturing methods for nanomaterials.

Synthesis Method	Key Features	Advantages	Disadvantages	Typical Applications	Trial Outcomes
Chemical vapor deposition (CVD)	Uses high temperature to vaporize a precursor, which reacts to form nanoparticles	High purity, controlled size, and shape.	High energy consumption, complex equipment, potential environmental concerns.	Semiconductor manufacturing, sensors, catalysis	Used in drug delivery systems for targeted therapies; trials show controlled release in cancer treatments.
Sol-gel process	Involves transitioning from a liquid solution to a gel phase to create	Low cost, relatively simple, can produce large quantities.	Long processing times, potential for high solvent use.	Coatings, catalysis, drug delivery	Trials show success in the delivery of anti-cancer agents, though stability can be a concern.
Green synthesis	Uses plant extracts, bacteria, or fungi to reduce metal salts into nanoparticles	Environmentally friendly, low cost, less toxic byproducts, sustainability.	Slower process, sometimes inconsistent results.	Environmental cleanup, biosensors, drug delivery	Trials have shown promising results in using plant-based nanoparticles for improved bioavailability in oral drugs.
Laser ablation	Laser is used to break a bulk material into nanoparticles in liquid or vacuum.	High purity, no chemical reagents required, can produce nanoparticles with specific properties.	Expensive equipment, energy intensive.	Optical applications, medical imaging	Effective in the preparation of nanoparticles for MRI contrast agents, with reduced toxicity in trials.
Hydrothermal synthesis	Involves using water at high pressure and temperature to synthesize nanoparticles from precursor materials.	High quality, controlled size and morphology, scalable.	Energy and time consuming, requires precise temperature and pressure control.	Energy storage, catalysis, sensors	Clinical trials are ongoing for using hydrothermal nanoparticles in drug delivery, especially for gene therapies.
Microemulsion Method	Uses surfactants and co-surfactants to form a stable microemulsion that encapsulates the precursors for nanoparticle formation.	Precise control over particle size and shape, suitable for water-insoluble drugs.	Requires use of surfactants, which can lead to toxicity concerns.	Cosmetics, drug delivery, diagnostics	Trials for oral drug formulations have shown increased absorption rates and enhanced therapeutic effects.

Molecular modeling of nanomaterials

Molecular modeling of nanomaterials is now a cornerstone of nanoscience and nanotechnology research. It enables the prediction, understanding, and optimization of the structural, electronic, thermal, and mechanical properties of materials with dimensions ranging from 1 to 100 nanometers. At this scale, surface effects, quantum confinement, and the interdependence of spatial and temporal scales give nanomaterials unprecedented properties, paving the way for revolutionary applications in medicine, energy, electronics, the environment, and many other fields. It involves using computational methods (classical and quantum) to predict and analyze their structural, electronic, and mechanical properties at the atomic scale. This allows us to understand the unique behavior of nanometric materials and to guide their design for applications in medicine, energy, and electronics.

Morphological characterization and modeling

The characterization and morphological modeling of nanomaterials are two complementary approaches that allow us to understand and predict their physical, chemical and functional properties. Characterization involves experimentally analyzing the shape, size, structure, and distribution of nanomaterials.

Main techniques:

- **Transmission electron microscopy (TEM):** Allows observation of the size and internal structure of nanoparticles.
- **Scanning electron microscopy (SEM):** Provides surface and morphology images.
- **Atomic force microscopy (AFM):** Analyzes topography and roughness at the nanoscale.
- **X-ray diffraction (XRD):** Determine the crystal structure and size of the crystallites.
- **Spectroscopy (Raman, FTIR, UV-Vis)** : Provides information on chemical bonds and surface interactions.

These techniques allow us to measure: average size, particle size distribution, shape (spherical, tubular, laminated), specific surface area and porosity. Modeling aims to predict and simulate the morphology and properties of nanomaterials using mathematical and computer models.

Main approaches:

- ***Atomistic modeling (molecular simulation, molecular dynamics, Monte Carlo)*** Studies the behavior of atoms and molecules in nanostructures.
- ***Density Functional Theory (DFT):*** Allows calculation of electronic and structural properties.
- ***Geometric and statistical models:*** They describe the size distribution and growth of nanoparticles.
- ***Multi-scale modeling:*** Relates atomic properties to macroscopic behaviors (mechanical, thermal, optical).

Modeling helps to understand how morphology (size, shape, surface) influences optical, electrical, mechanical, and catalytic properties.

Nanomaterial and color

Nanomaterials and color are intimately linked, because at the nanoscale the way light interacts with matter changes radically. The colors observed do not only originate from chemical pigments, but also from physical phenomena related to the size, shape, and structure of the nanomaterials.

Surface plasmon resonance (SPR)

In metallic nanoparticles (gold, silver), free electrons oscillate collectively under the influence of light. This produces intense and variable colors depending on the size and shape of the particles. For example, gold nanoparticles appear red, purple, or blue depending on their size.

Quantum size effect

In semiconductors (quantum dots), the color of the luminescence depends directly on the size of the nanoparticles. The smaller the particle, the higher the emitted energy → blue color; the larger it is → red color.

Selective diffusion and absorption

Nanomaterials scatter and absorb certain wavelengths of light more efficiently than others. This alters the perceived color.

Nanominerals and their colors

The following table shows some examples of nanominerals with their observed colors.

Nanomineral	Origin of the color	Color observed
Gold nanoparticles	Plasmon resonance	Red, purple, blue
TiO_2 nanocrystals	Selective distribution	Bright white
Cadmium sulfide quantum dots	Quantum confinement	From blue to red
Iron oxide nanocrystals (Fe_2O_3, Fe_3O_4)	Electronic transitions	Brown, red, black

Applications of nanomaterials

Nanomaterials can be used in different fields; they can be selected according to several areas:

- Scope of application by type of nanomaterial
- Application of nanomaterials in different field

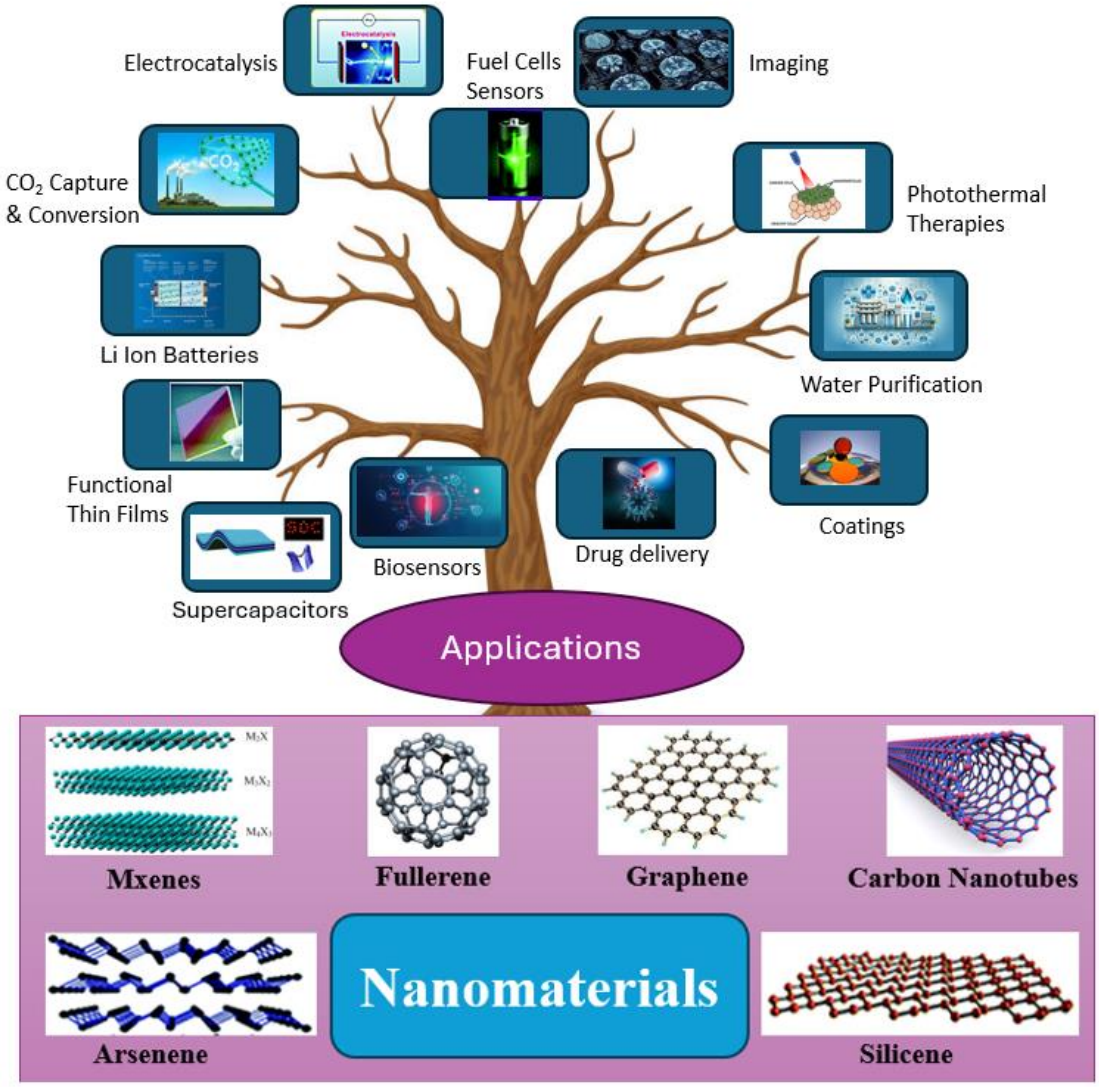
1.Scope of application by type of nanomaterial

The table below show different area of application by type of NMs.

Nanomaterials	Areas of application
Nanoceramics	Structural composite materials - UV-resistant components - Mechanochemical polishing of substrates (wafers) in microelectronics - Photocatalytic applications
Nanometallic	Antimicrobial sector - Catalysis - Conductive layers for screens - Sensors - Energetic materials
Nanoporous	Aerogels for thermal insulation in the fields of electronics, optics and catalysis - Biomedical field for applications such as vectorization or implants
Nanotubes	Electrically conductive nanocomposites - Structural materials - single-walled nanotubes for applications in electronics and displays
Bulky nanomaterials	Hard coatings - Structural components for the aerospace, automotive, oil and gas pipeline, sports, and corrosion protection industries
Dendrimers	Medical field (drug administration, rapid detection) - Cosmetic field
Quanta Dots	Optoelectronic applications (displays) - Photovoltaic cells - Inks and paints for anti-counterfeiting marking applications
Fullerenes	Sports (nanocomposites) and cosmetics sectors
Nanowires	Applications include the conductive layers of screens or solar cells, as well as electronic devices.

2.Application of nanomaterials in different field

The figure below shows different main application of NMs.



The figure of different main application of NMs.

a) Nanomedicine

Nanomedicine involves applying the principles of nanoscience to:

- *View*: detecting and imaging cells or tissues using fluorescent or magnetic nanoparticles.
- *Diagnose*: to identify diseases early via nanosensors or biological markers.
- *To treat*: delivering drugs in a targeted manner using nanovectors.
- *Regenerate*: using nanomaterials to repair or stimulate tissue growth (nanobiomaterials).

Main areas of nanomedicine

a) *Nanodiagnostics:* This involves using nanosensors and nanoparticles to detect biomarkers. Example: rapid tests based on gold nanoparticles.

b) *Drug delivery nanosystems:* These are nanocapsules, liposomes, dendrimers, or polymeric nanoparticles that transport a drug directly to the target cell. Their role is to reduce side effects and increase efficacy.

c) *Medical Nano-imaging*: these are fluorescent quantum dots or magnetic nanoparticles to improve imaging (MRI, fluorescence).

d) *Nanotherapy:*

- Magnetic hyperthermia: nanoparticles heated by a magnetic field to destroy cancer cells.
- Photodynamic therapy: nanoparticles activated by light to kill pathological cells.

e) *Nanobiomaterials*: These are implants and prostheses coated with nanolayers to improve biocompatibility and reduce rejection.

Application	Nanomaterial used	Objective
MRI Imaging	Iron oxide nanoparticles	Improved contrast
Cancer	Gold nanoparticles	Targeted photothermal therapy
Vaccines	Lipid nanoparticles	mRNA transport (Example: COVID-19 vaccines)
Cardiology	Coated nanostents	Reduced rejection and improved healing
Neurology	Polymeric nanocapsules	Crossing the blood-brain barrier

Nanomaterials for biolabeling

Nanomaterials for biolabeling are materials at the nanoscale used as probes, tracers, or tags to identify, track, and analyze biological molecules (proteins, DNA, cells) in complex systems. Their value lies in their small size, functionalizable surface area, and unique optical, magnetic, or electrical properties. It consists of attaching a "marker" to a biological target in order to make it visible, detectable or traceable.

Types of nanomaterials used for biomarking:

a) Quantum dots: These are fluorescent semiconductor nanocrystals that emit light of a color that can be controlled according to their size. They are used for the fluorescent labeling of proteins, cells, and tissues.

b) Gold and silver nanoparticles: They exploit surface plasmonic resonance and produce intense and stable optical signals. They are used in imaging and biomolecular detection (biosensors).

c) Magnetic nanoparticles (Fe_3O_4, γ-Fe_2O_3): They allow for the labeling and magnetic separation of cells. They are used in MRI as contrast agents.

d) Functionalized carbon nanotubes and graphene: it is a modifiable surface for binding antibodies or DNA. They are used in electrochemical biosensors.

e) Silica nanoparticles: They are porous and can encapsulate dyes or biomarkers. They are stable and biocompatible for cell imaging.

Domain	Application
Biomedical imaging	Quantum dots for visualizing cancer cells
Diagnosis	Gold nanoparticles for rapid testing (e.g., viral detection)
Targeted therapy	Magnetic nanoparticles to guide drugs
Basic research	Fluorescent labeling of proteins to track their interactions
Biosensors	Graphene and nanotubes to detect specific biomolecules



Figure of different application in nanomedicine

b) Environmental field

In environmental matters, the use of nanomaterials is being considered for reducing pollutant emissions, treating effluents (particularly through photocatalysis) and purifying gases, producing ultrapure water from seawater, improving resource use, recovery, and. improved recycling of existing resources, specific and multi-substance real-time chemical analyzers, etc. Nanomaterials could be developed in particular in the form of nano-functional organic membranes, catalysts, filters, nanoporous ceramics and aerogels.

Their effectiveness is based on their high specific surface area, chemical reactivity, and unique optical or catalytic properties.

a) *Water treatment and purification*

- Titanium dioxide (TiO_2) nanoparticles: used in photocatalysis to degrade organic pollutants and industrial dyes.
- Zero-valent iron nanoparticles (nZVI): effective for groundwater decontamination (reduction of heavy metals, pesticides).
- Nanofiltration and nanostructured membranes: enable advanced purification of drinking water by eliminating bacteria, viruses and micropollutants.
- Silver nanoparticles (AgNPs): antibacterial action to purify water.

b) *Air purification*

- Metallic nanocatalysts (Pt, Pd, Au): used in filters and catalysts to reduce emissions of toxic gases (NOx, CO, VOCs).
- Carbon nanotubes and graphene: absorb fine particles and improve air filters.
- Photocatalytic TiO_2: decomposes atmospheric pollutants under UV light.

c) *Waste and contaminated soil management*

- Nanoclay and nanocomposites: used to stabilize polluted soils and limit the migration of contaminants.
- Magnetic nanoparticles: facilitate the recovery and separation of pollutants in sludge and liquid waste.
- Nanoremediation: an emerging technique using nanomaterials to restore soils contaminated by hydrocarbons or heavy metals.

c) Catalysis

a) *Heterogeneous catalysis*

- Platinum, palladium, rhodium nanoparticles: catalysts for industrial reactions (hydrogenation, oxidation).
- Gold nanoparticles: active at low temperature for CO oxidation.
- Nanoceramics: stable and efficient for environmental catalysis.

b) *Photocatalysis*

- Nanostructured TiO_2: degradation of organic pollutants and production of hydrogen by photolysis of water.

- ZnO and doped graphene: catalysts for pollution control and solar energy.

d) Electrochemical catalysis

- Carbon nanotubes and graphene: electrocatalysts for fuel cells and batteries.
- Ni, Co, Fe nanoparticles: catalysts for oxygen or hydrogen reduction reactions.

e) Renewable energy and sustainability

- Nanomaterials for solar cells: quantum dots and nanolayers improve photovoltaic conversion efficiency.
- Nanocatalysts: increase the performance of fuel cells and batteries.
- Photocatalytic nanomaterials: used to produce hydrogen from water (clean energy).

d) Electromagnetism

The electromagnetic applications of nanomaterials, from nano to macro, rely on their ability to manipulate electric and magnetic fields through unique properties such as tunable permittivity, anisotropic conductivity of nanotubes and the design of metamaterials capable of controlling wave propagation.

e) Energy

Nanomaterials play a key role in the energy sector, as their unique properties (high specific surface area, quantum effects, improved conductivity, chemical stability) allow for more efficient and sustainable energy production, storage, and conversion.

a) Energy Production

Nanostructured solar cells

- Quantum dots and TiO_2 or ZnO nanolayers improve photovoltaic conversion efficiency.
- Graphene and carbon nanotubes used as transparent and conductive electrodes.

Photocatalysis for hydrogen

- TiO_2 nanoparticles, doped or coupled to metals, produce hydrogen by photolysis of water.

b) Energy storage

Lithium-ion batteries

- Nanoparticles of Si, Sn or Fe_3O_4 increase the capacity and lifespan of the electrodes.
- Carbon nanotubes and graphene improve conductivity and stability.

Supercapacitors

- Graphene or nanocomposite electrodes offer high energy density and fast charging.

c) Conversion and energy efficiency

Fuel cells

- Nanocatalysts (Pt, Pd, Au) reduce the number of precious metals needed and increase efficiency.

Nanostructured thermoelectrics

- Semiconductor nanomaterials (Bi_2Te_3, Sb_2Te_3) convert lost heat into electricity.

Insulating nanostructured coatings

- They improve the energy efficiency of buildings by reducing heat loss.

Challenges of nanomaterials

The toxicity of nanomaterials and the associated challenges constitute a crucial area, as their nanometric size gives them extraordinary properties but also potential risks to human health and the environment.

Toxicity of nanomaterials

Origins of toxicity

- Large size and high specific surface area: promote penetration into cells and organs.
- Increased chemical reactivity: production of free radicals → oxidative stress.
- Solubility and biodistribution: some nanomaterials can cross the blood-brain barrier or accumulate in tissues.
- Surface effects: uncompensated atoms or doping alter biological interactions.

Observed biological effects

- Cytotoxicity: damage to cell membranes, apoptosis.
- Genotoxicity: alterations to DNA.
- Inflammation: activation of the immune system.
- Bioaccumulation: persistence in organs (liver, lungs, brain).

The challenges of nanomaterials

a) Human health

- The need to assess toxicity before medical or food use.
- Development of biocompatible and biodegradable nanomaterials.

As shown in the following figure, the contamination of nanomaterials and the consequences related to exposure.

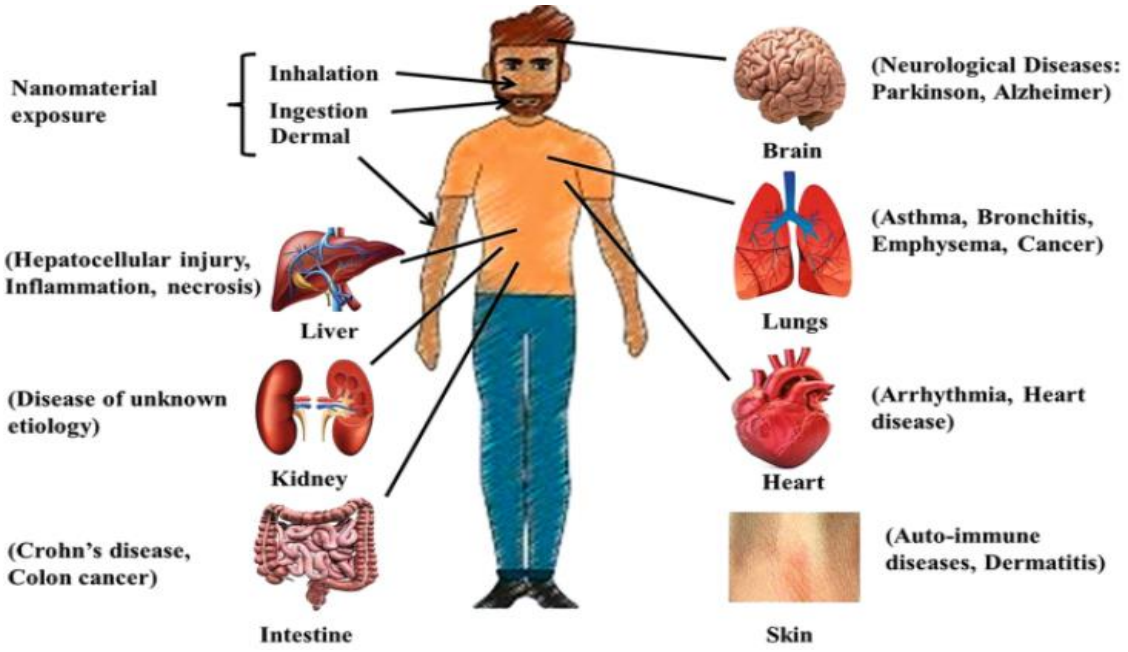


Figure of contamination of NMs in human health

b) <u>Environment</u>

- Risk of soil and water contamination by persistent nanoparticles.
- Impact on aquatic wildlife and food chains.

The following figures show how nanomaterials spread and affect the environment.

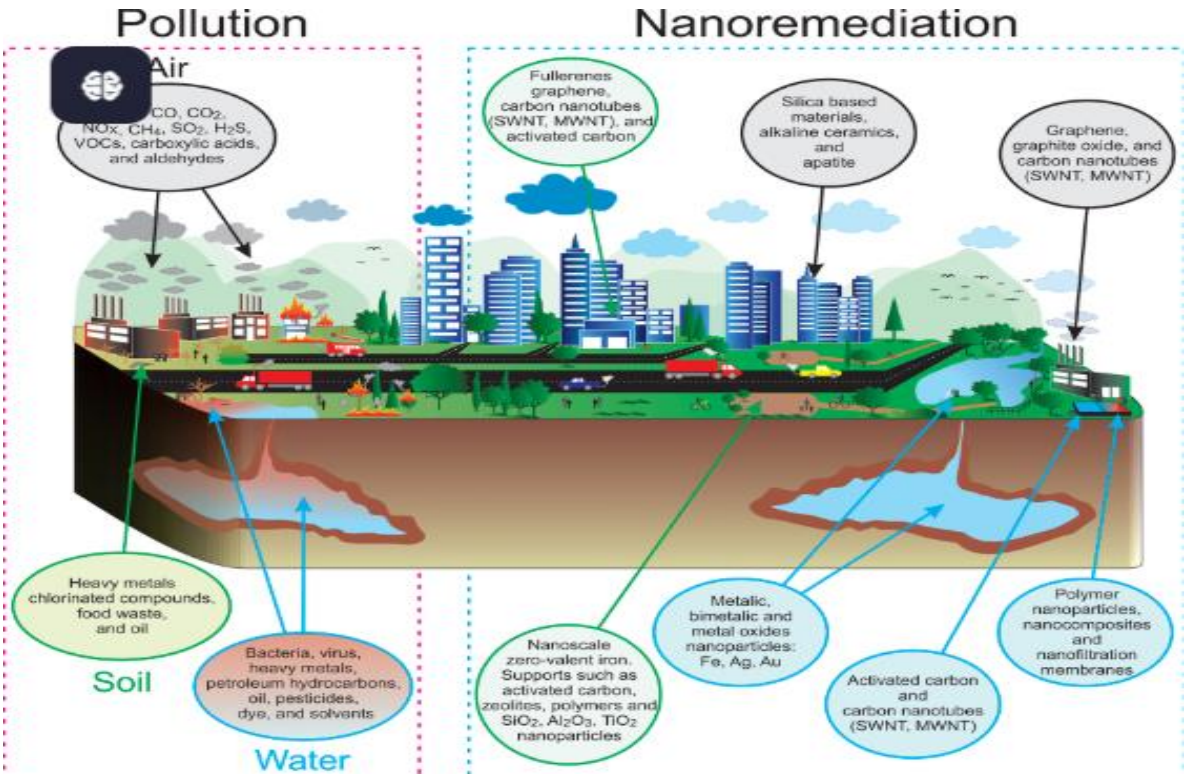


Figure of contamination of NMs in human environment

Pictogram related to nanomaterials

Here are pictograms related to NMs.

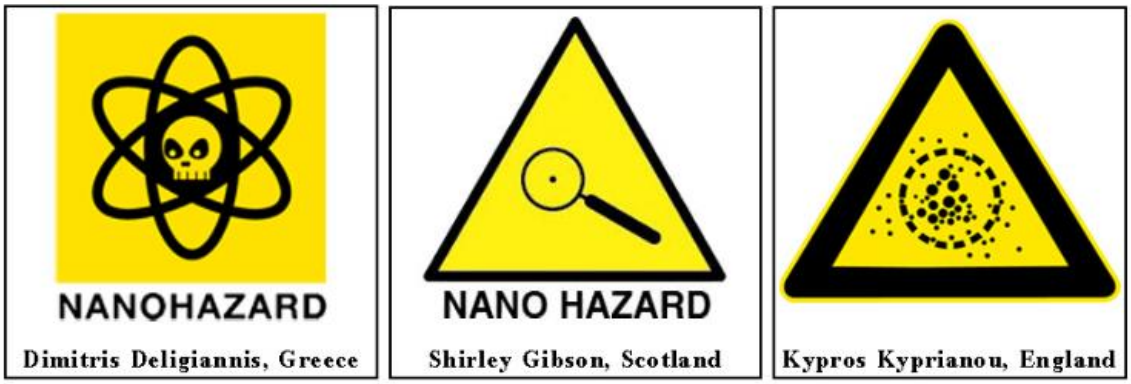


Figure of different pictograms of NMs

Conclusion

the study of nanomaterials bridges fundamental scientific principles and advanced technological applications, fundamentally transforming fields from materials science to nanomedicine and environmental engineering. As we have explored throughout this course, reducing dimensions to the nanoscale unlocks extraordinary quantum, optical, mechanical, and surface properties that differ dramatically from those of bulk materials. However, unlocking this immense potential requires a balanced understanding of both the unprecedented opportunities and the inherent challenges. The high reactivity, large surface-area-to-volume ratio, and unique interactions of engineered nanoparticles also introduce critical considerations regarding toxicity, environmental fate, and safety regulation, as highlighted by international hazard symbols and ongoing toxicological evaluations. Ultimately, future scientists and engineers must champion responsible innovation, rigorous characterization, and sustainable design principles to ensure that nanotechnology advances safely. By mastering the synthesis, behavior, and characterization of these advanced systems, researchers are well-equipped to drive the next wave of technological breakthroughs while safeguarding human health and the global environment.

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