

## ii. Synthesis of nanomaterials using different methods...

ii. Synthesis of nanomaterials using different methods, Molecular basis of biosynthesis of nanomaterials, assessment of plant, animal and mineral-based drugs for nanomaterials

## Synthesis of Nanomaterials Using Different Methods

Broadly, nanomaterials can be created via **top-down** or **bottom-up** approaches. Top-down methods reduce bulk materials to the nanoscale (e.g., mechanical milling), whereas bottom-up methods assemble nanoparticles from atomic or molecular precursors. These methods can be **physical**, **chemical**, or **biological/green**.

### Physical Methods

#### 1. Evaporation-Condensation (Inert Gas Condensation)

- **Process:** A metal or other material is heated in a low-pressure chamber until it evaporates; the vapor then cools and condenses into nanoparticles.
- **Example:** Production of metal oxide nanoparticles (e.g., ZnO, TiO<sub>2</sub>) in a high-temperature furnace, collected on a cold surface.
- **Advantages:** Relatively pure particles, controlled size by tuning pressure/temperature.
- **Disadvantages:** High energy consumption, specialized equipment.

#### 2. Laser Ablation

- **Process:** A pulsed laser beam strikes a solid target immersed in a liquid or gas, ejecting nanoscale material.
- **Applications:** Generating stable colloidal solutions of gold or silver nanoparticles (AuNPs, AgNPs) without chemical reducing agents.
- **Challenges:** Equipment cost, difficulty scaling up.

#### 3. Sputtering and Mechanical Milling

- **Sputtering:** High-energy ions knock atoms off a solid target, depositing them as a nanomaterial on a substrate.
- **High-Energy Milling:** Ball milling bulk materials into nanosized powders. Top-down approach with less control over uniformity and morphology.

### Chemical Methods

#### 1. Sol-Gel Process

- **Key Idea:** Hydrolysis and condensation of precursors (e.g., metal alkoxides) form colloidal sol, which transitions to a gel and then is calcined to form nanoparticles.
- **Uses:** Synthesis of silica, titanium oxide, and various ceramic nanomaterials with controllable porosity.

#### 2. Chemical Reduction and Precipitation

- **Example:** Noble metal nanoparticles (Au, Ag) produced by reducing metal salts (e.g., HAuCl<sub>4</sub>) with agents like sodium borohydride (NaBH<sub>4</sub>), citrate, or hydrazine.
- **Surfactants or stabilizers** (e.g., PVP, CTAB) often used to control particle growth and prevent aggregation.
- **Tunability:** Reaction conditions (pH, temperature, reagent ratios) adjust size and shape.

#### 3. Hydrothermal and Solvothermal Techniques

- **Process:** Precursors sealed under high pressure and temperature, promoting crystal growth in water or organic solvents.
- **Advantages:** Produces crystalline nanoparticles of metal oxides, sulfides, or composites with fewer defects.
- **Challenges:** Pressure vessel needed, optimization can be intricate.

#### 4. Emulsion and Microemulsion Methods

- **Concept:** Use water-oil systems stabilized by surfactants. Nanoparticles precipitate in microreactors (micelles).
- **Applications:** Polymeric nanoparticles, controlled morphologies, and well-defined core-shell structures.

### Biological (Green) Methods

#### 1. Microbial Synthesis

- Bacteria, fungi, or algae secrete enzymes that reduce metal ions to nanoparticles.
  - **Examples:** *Fusarium oxysporum* or *Pseudomonas stutzeri* producing AgNPs, AuNPs.
  - **Benefits:** Mild conditions, often water-based, minimal toxic byproducts.
2. **Phytosynthesis (Plant Extracts)**
- Plant extracts (rich in polyphenols, flavonoids) act as reducing/stabilizing agents, forming metal or metal oxide nanoparticles.
  - **Examples:** *Azadirachta indica* (neem) for AgNPs, *Ocimum sanctum* (tulsi) for AuNPs.
  - Environmentally friendly, cost-effective, fosters synergy with Ayurvedic pharmacopeia.

## Molecular Basis of Biosynthesis of Nanomaterials

The “green” or **biogenic** nanoparticle synthesis hinges on the ability of biological systems (plants, microbes) to reduce metal ions and stabilize nascent nanostructures.

1. **Enzymatic Reduction**
  - **NADH/NADPH-dependent reductases** in microbes or plant cells donate electrons to metal ions (e.g.,  $\text{Ag}^+$ ,  $\text{Au}^{3+}$ ) → elemental metal ( $\text{Ag}^0$ ,  $\text{Au}^0$ ).
  - **Cytochrome** or other metalloproteins may also participate, forming stable nucleation centers.
2. **Phytochemicals as Reductants**
  - **Polyphenols, flavonoids, terpenoids** provide the electron-donating capacity.
  - **Functional Groups** (-OH, -CHO) can chelate metal ions, controlling nucleation/growth.
  - Secondary metabolites (e.g., ascorbic acid, anthocyanins) further enhance or modulate particle shape/size.
3. **Capping and Stabilization**
  - Biological macromolecules (proteins, polysaccharides) or small molecules anchor onto nanoparticle surfaces, preventing agglomeration.
  - This **bio-capping** can impart biocompatibility, potential specificity for biological targets, and extended colloidal stability.
4. **Genetic and Environmental Influences**
  - Microbes can upregulate reductase enzymes under metal stress (self-protection) → nanoparticle formation.
  - Reaction environment (pH, ionic strength) dictates whether smaller or larger aggregates form.

## Assessment of Plant, Animal, and Mineral-Based Drugs for Nanomaterials

### Plant-Based (Phytogenic) Nanomaterials

1. **Phytopharmaceuticals**
  - Traditional herbal extracts or decoctions can be directly leveraged to synthesize nanoparticles.
  - Example: **Green synthesis** of gold nanoparticles using *Terminalia arjuna* bark extract, combining cardiotoxic properties with plasmonic potential.
2. **Advantages**
  - Natural capping ligands typically enhance biocompatibility and reduce toxicity.
  - Possible synergy with **pharmacologically active** phytoconstituents, opening new avenues in drug delivery or combined therapies (e.g., herbal-metal nanoformulations).
3. **Challenges**
  - **Standardization:** Variable chemical profiles in plants due to geographic, seasonal factors.
  - **Scalability:** Large-scale extraction, reproducible reaction conditions.

### Animal-Based (Zoogenic) Nanomaterials

1. **Chitosan and Other Biopolymers**
  - Derived from crustacean shells or insect cuticles.
  - Biodegradable, mucoadhesive, can form nanoparticles for gene/drug delivery.
2. **Proteins (e.g., Silk Fibroin, Collagen)**
  - Self-assembly of silk fibroin into nanoparticles, used for controlled release.



- Collagen-based nanoparticles for regenerative medicine.

### 3. Challenges

- Ethical sourcing, risk of immunogenicity, ensuring consistent quality.

## Mineral-Based (Geogenic) Nanomaterials

### 1. Classical Ayurvedic Bhasmas

- Repeated calcination of metals/minerals (e.g., Suvarna bhasma from gold, Lauha bhasma from iron).
- Modern characterization reveals nano-/submicron-sized metal oxides or carbonates.

### 2. Biomedical Potential

- Proposed enhanced bioavailability, possibly lower toxicity if properly detoxified (shodhana).
- Integration with advanced **toxicity** and **efficacy** assays crucial to meet modern regulatory standards.

### 3. Key Issues

- **Standardization:** Variation in raw materials, incomplete knowledge of reaction pathways.
- Need for mechanistic insights: identifying roles of trace herbal components, controlling final nanoparticle size and morphology.

## Concluding Remarks

The **synthesis of nanomaterials** comprises a rich spectrum of techniques—ranging from physical/chemical methods (sol-gel, hydrothermal, laser ablation) to **biological/green** approaches harnessing microbial enzymes or phytochemicals. The **molecular basis** of biosynthesis involves redox-active biomolecules (enzymes, secondary metabolites) directing nucleation, growth, and capping of nanoparticles.

Simultaneously, **plant-, animal-, and mineral-based pharmaceuticals**—especially from the Ayurvedic tradition—present unique opportunities to create **hybrid nanoformulations** that merge **ancient medicinal wisdom** with **modern nanotechnology**. Rigorous **characterization** (particle size, morphology, surface chemistry), **biocompatibility**, and **efficacy** studies are essential to unlock safe, reproducible, and scalable nanomedicines. This synergy underscores the promise of sustainable and culturally rooted approaches in advancing next-generation healthcare solutions.