5. NANOTECHNOLOGY IN GREEN CHEMISTRY

5.1 BASIC CONCEPTS OF NANOSCIENCE & NANOTECHNOLOGY

Nanometer: The term "nano" comes from ancient Greek, and it means "dwarf" (nános = dwarf). It is used as a prefix. Nanometer (nm) is one-billionth of a meter(**1 *nm* = 10^{-9} *m***). Atoms, molecules and aggregates of atoms or molecules are in size of nanometer.

Nanoscale: Nanoscale is the size range between approximately 1 to 100 nm.

Nanoparticle: A nanoparticle is a small particle that has the size in nanometer scale (**1 to 100 nm**).

Nanomaterial: Nanomaterials are the materials with at least one external dimension is in nanoscale (1 to 100 nm).

Nanoscience: Nanoscience is a convergence of chemistry, physics, materials science and biology, which deals with study, manipulation and engineering of matter, particles and structures on the nanoscale.

Nanotechnology: Nanotechnology is science, engineering, and technology conducted at the nanoscale. It is the ability to observe, measure, manipulate, assemble, control, and manufacture matter at the nanoscale.

Nanoscience is the study of material on the scale of nanometers, and nanotechnology is the application of nanoscience. Nanoscience and nanotechnology are the study and application of extremely small things and can be used across all the other science fields, such as chemistry, biology, physics, materials science, technology and engineering.

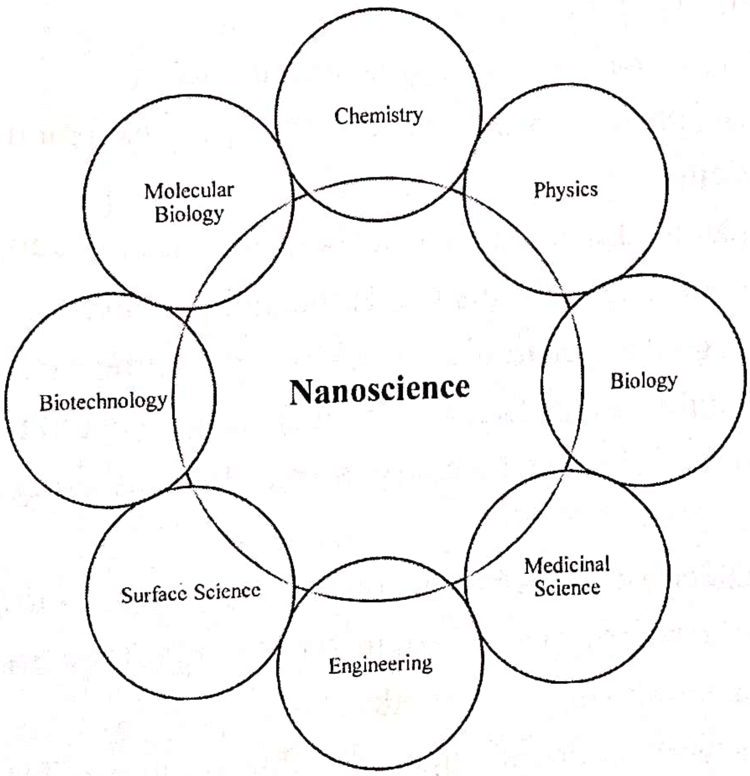


Fig. 5.1.a Relationship between nanoscience and major fields

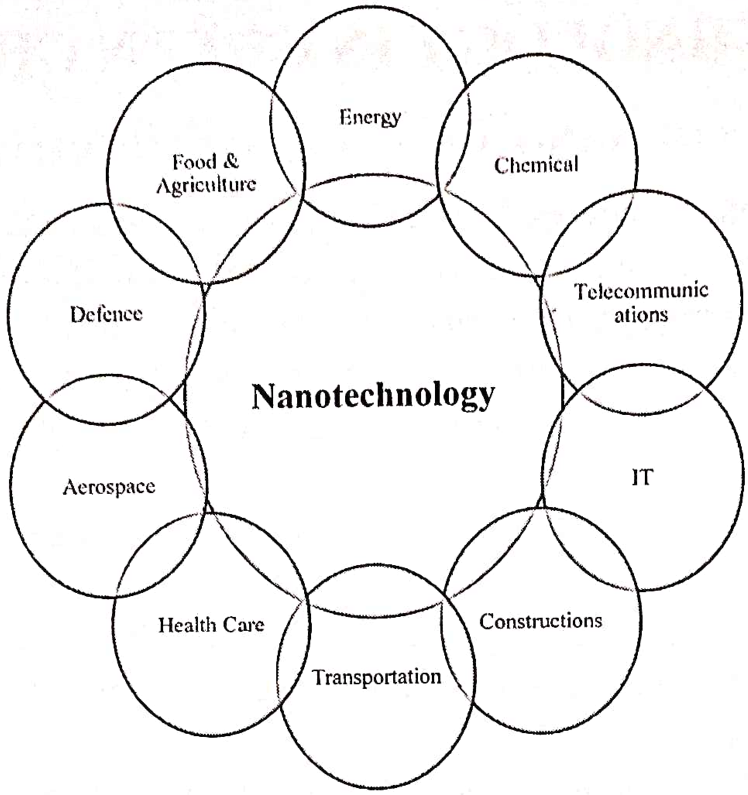


Fig. 5.1.b Relationship between nanotechnology and major fields

History and Background of Nanoscience & Technology

The concept of nanoscience and nanotechnology started with a talk entitled "**There's Plenty of Room at the Bottom**" by physicist **Richard Feynman** at an American Physical Society meeting at the California Institute of Technology on December 29, 1959. In his talk, Feynman described a process in which scientists would be able to manipulate and control individual atoms and molecules.

- The exact history of nanotechnology is still unknown.
- Prior to Feynman, nanomaterials were already being used for different applications, such as in medicine.
- John Utynam patented gold nanoparticle-based glass in 1449.
- In the 16th century, Theophrastus von Hohenheim, a Swiss doctor better known as Paracelsus, used gold nanoparticles to treat patients suffering from various ailments.
- Richard Zsigmondy was the first to introduce the concept of the nanometer, and he received the Noble Prize in Chemistry in 1925 for measuring the size of particles, such as gold
- **Norio Taniguchi** coined the term "nanotechnology" in 1974 to describe the different processing mechanisms of nanosized materials and for the description of accuracy of super thin materials up to nanoscale.
- The birth of clusters in colloidal science and the invention of the Scanning Tunneling Microscope (STM) encouraged more work in nanotechnology.

Therefore, the field of nanoscience and technology is not new, but its methods have advanced over time.

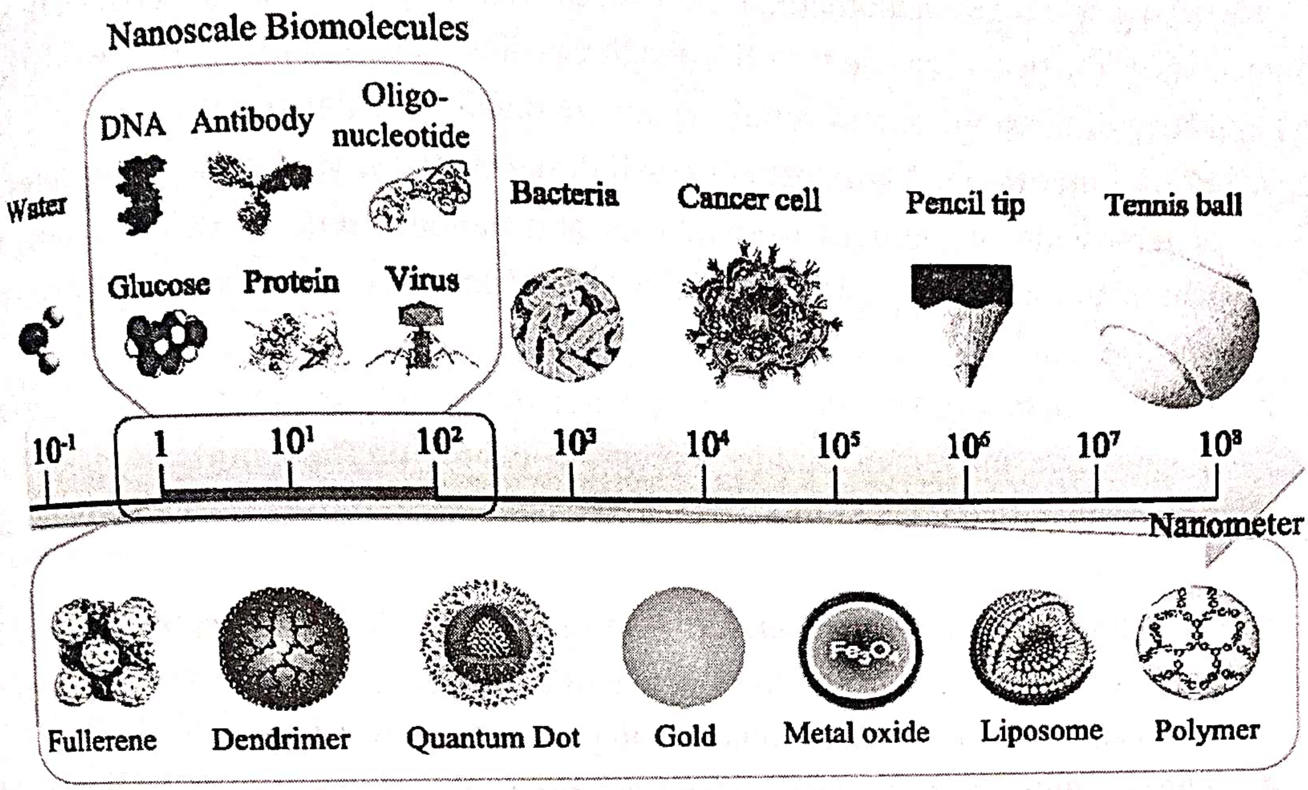
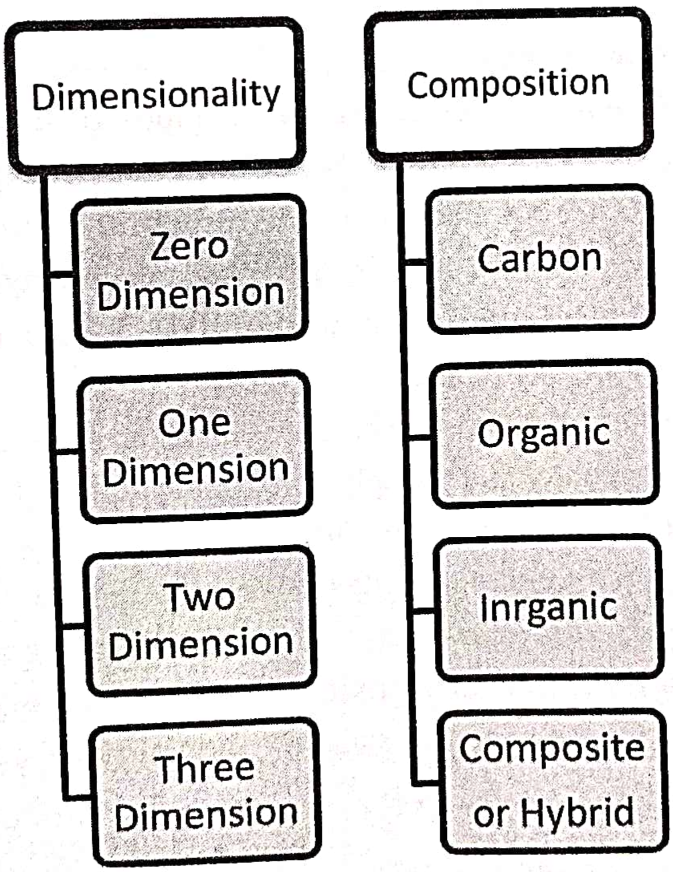


Fig. 5.1.c Comparison of Nanomaterials Sizes

5.2 CLASSIFICATION OF NANOMATERIALS



Nanomaterials can be classified based on dimensionality and composition.

Based on Dimensionality

According to Siegel, nanomaterials are classified into zero-dimensional (0D), one-dimensional (1D), two- dimensional (2D) and three- dimensional (3D) nanomaterials based on number of dimensions of a material, which are outside the nanoscale range.

1. ***Zero-dimensional Nanomaterials:*** All dimensions (x, y, z) of nanostructures are at nanoscale. It includes nanospheres and nanoclusters. Most commonly 0D nanomaterials are nanoparticles. E.g.: quantum dots, graphene, fullerenes and polymer dots.
2. ***One-dimensional Nanomaterials:*** Any two dimensions (x, y) or (y, z) or (x, z) are at nanoscale and remaining **one dimension is outside the nanoscale.** They have needle shape nanostructures. It includes nanofibers, nanotubes, nanorods and nanowires.
3. ***Two-dimensional Nanomaterials:*** Any one-dimension x or y or z at nanoscale and the remaining **two dimensions are outside the nanoscale**. They have plate like shape. It includes nanofilms, nanolayers, and nanocoatings.
4. ***Three-dimensional Nanomaterials:*** All **three dimensions are at outside side nanoscale range**. It can contain bulk powders, dispersion of nanoparticles, bundles of nanowires, nanotubes, and multi-nanolayers.

Based on Composition

1. ***Carbon-based Nanomaterials:*** These are composed of carbon. These include graphene, fullerene, single-walled carbon nanotube (SWCN), multi-walled carbon nanotube (MWCN), carbon fiber, activated carbon, and carbon black.
2. ***Organic-based Nanomaterials:*** Organic-based nanomaterials are formed from organic materials excluding carbon materials. These include dendrimers, cyclodextrin, liposome, and micelle.
3. ***Inorganic-based Nanomaterials:*** These are elemental metal and non-metal, oxides, hydroxides, chalcogenides and phosphates of metals and non-metals. These include silver (Ag), gold (Au), copper (Cu), etc., metal nanomaterials, zinc oxide (ZnO), copper oxide (CuO), titanium dioxide (TiO_2), etc., metal oxides.
4. ***Composite-based Nanomaterials:*** The composite nanomaterials are any combination of metal-based, metal oxide-based, carbon-based, and organic-based nanomaterials, and these nanomaterials have complicated structures like a metal-organic framework.

5.3 APPROACHES OF SYNTHESIS OF NANOMATERIALS

There are two general approaches for the synthesis of nanomaterials: 1. Top-down approach 2. Bottom-up approach.

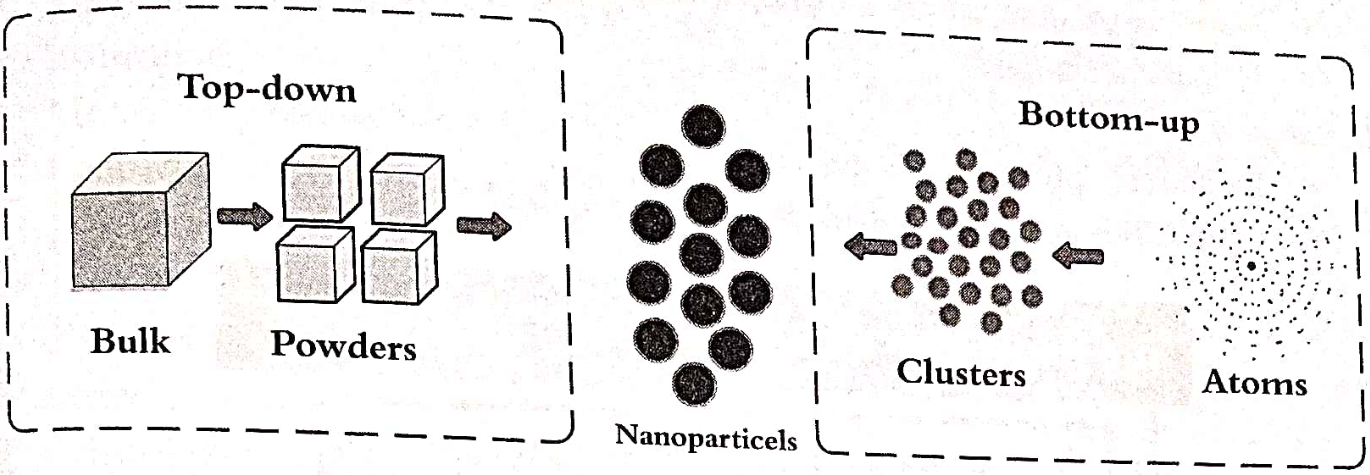


Fig. 5.3. Top-down and bottom-up approaches in synthesis of nanomaterials

5.3.1 Top-down Approach

It involves taking of bulk material and then repeatedly breaking down of it into smaller and small nanosized structures or particles. This can be achieved by physical and chemical methods. It can produce nanostructures with long range order.

Advantages:

- It is used in large scale production of nanomaterials.
- The method doesn't require chemical purification.

Disadvantages:

- Broad size distribution of nanoparticles ranges from 10 to 1000 nm.
- Broad range of particle shapes or geometry.
- Control over deposition parameters is difficult to achieve.
- Stresses, defects and imperfections get introduced.
- Expensive technique.

5.3.2 Bottom-up Approach:

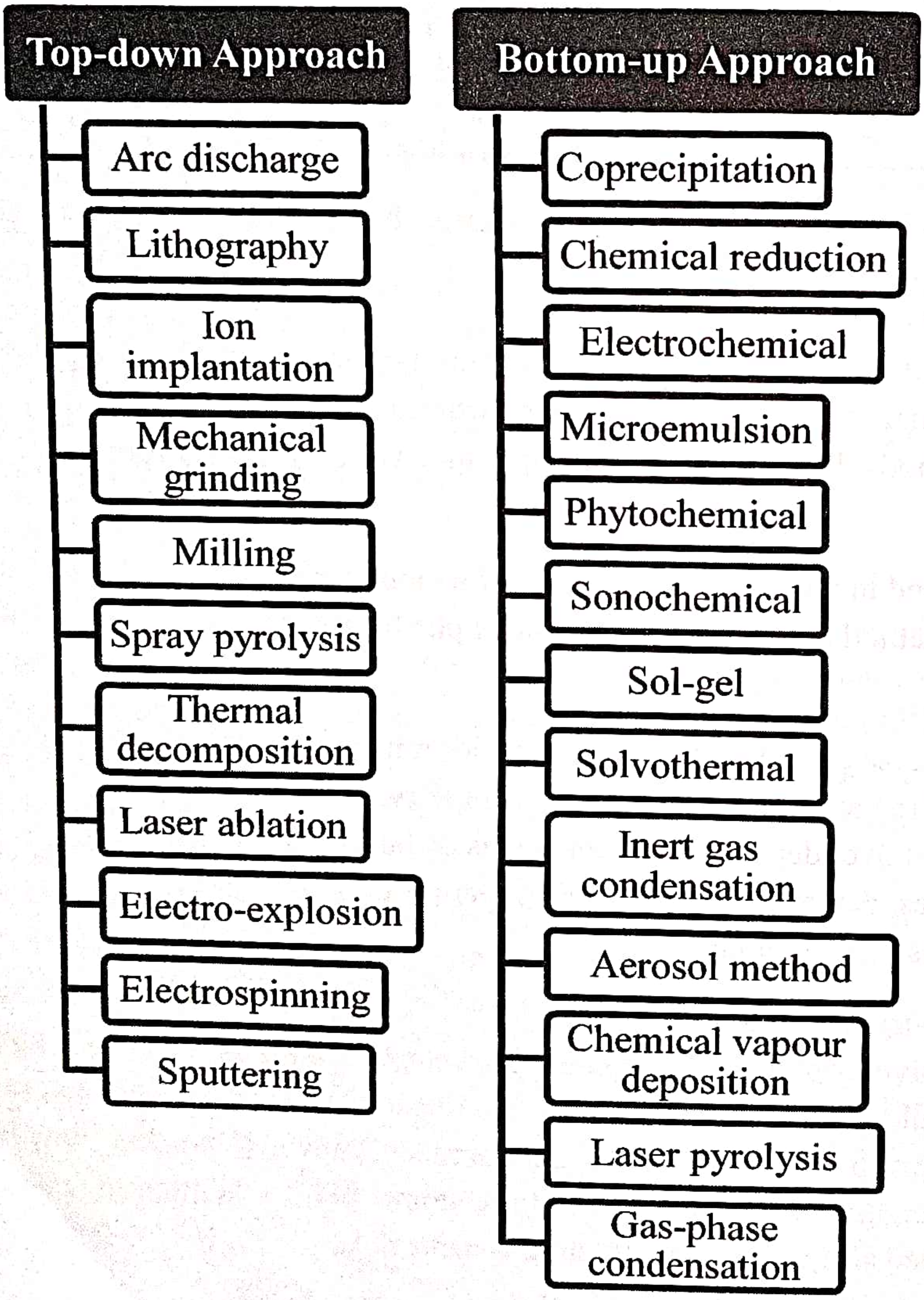
It involves formation of larger nanostructures from smaller building blocks such as atoms, molecules and clusters. It involves chemical and biological methods. Nucleation is the main working principle involved in this approach. It involves breaking down a substance to atomic level, afterward, the growth of the atomic particle is monitored and controlled until the desired size of the nanostructure is achieved.

Advantages:

- Ultra-fine nanoparticles and nanostructures can be prepared.
- Deposition parameters can be controlled.
- Narrow size distribution of nanoparticles ranges from 1 to 20 nm.
- Cheaper technique.

Disadvantages:

- Large scale production is difficult.
- Chemical purification of nanoparticles is required.



Difference between top-down and bottom-up approaches

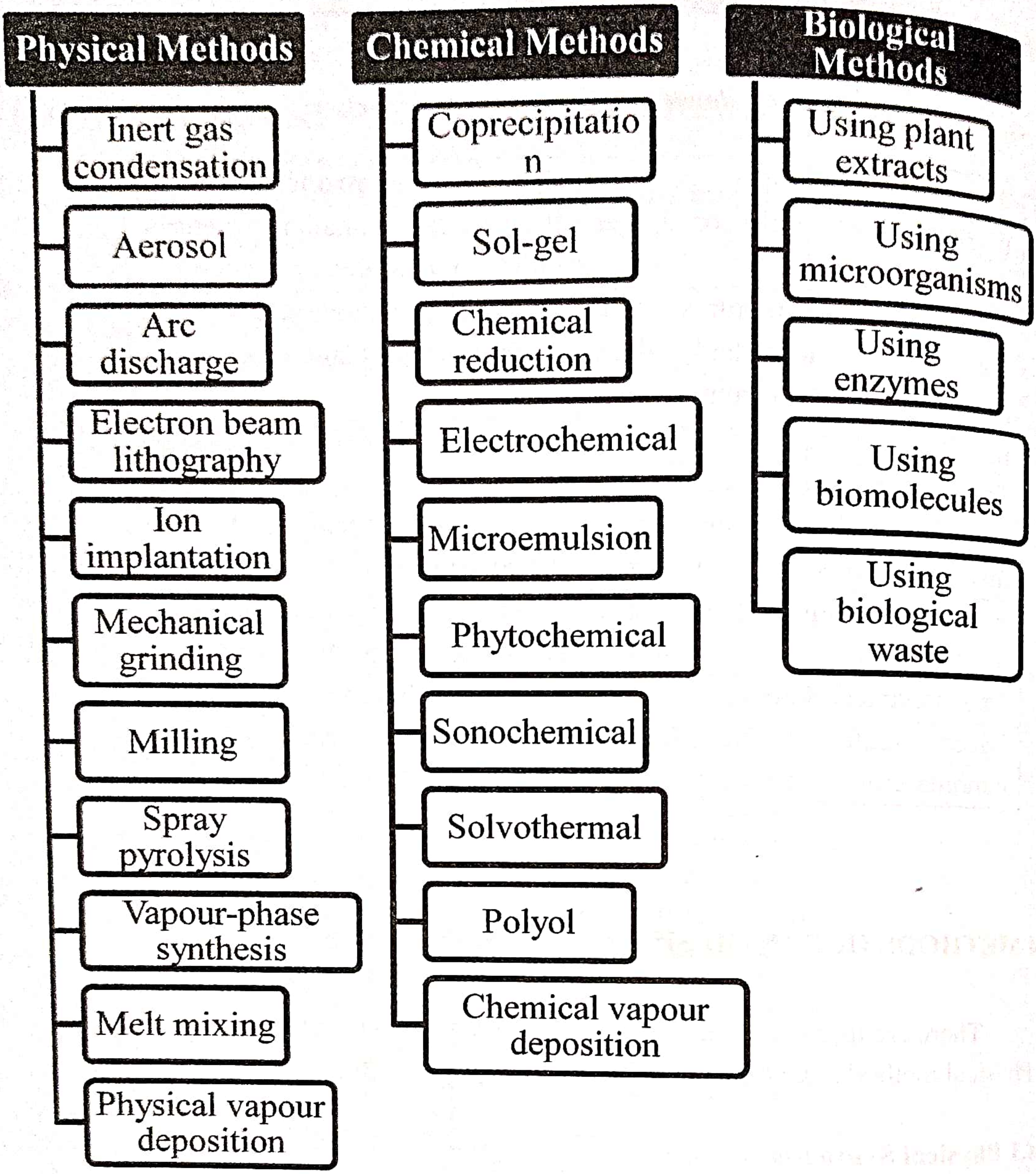
Top-down Approach	Bottom-up Approach
It starts from bulk or larger structures	It starts from smaller structures (atoms, molecules or clusters)
It forms nanostructures with imperfect surfaces and edges (wrinkly or contain cavities)	It can form nanostructures with perfect surfaces and edges
It is an old approach	It is a newer approach
The nanostructures have low precision and accuracy. Broad distribution of size of particles	The nanostructures have high precision and accuracy. Narrow distribution of size of particles
It involves removal of some material part	It does not involve removal of some material part
Expensive technique	Cheaper technique
Large scale production of nanomaterials is possible	Large scale production of nanomaterials is difficult

5.4 METHODS OF SYNTHESIS OF NANOMATERIALS

There are three synthetic methods to synthesize nanomaterials:
1. Physical method 2. Chemical method 3. Biological method

5.4.1 Physical Synthesis

Physical synthesis involves mechanical pressure, high energy radiations, use of thermal energy or electrical energy to cause materials abrasion, melting, evaporation or condensation to generate nanoparticles. Most of these methods come under top-down approach and are advantageous due to involvement of no solvent and formation of monodisperse NPs. Inert gas condensation, aerosol method, high energy ball milling, laser ablation, electro spraying, physical vapour deposition, laser pyrolysis, flash spray pyrolysis, melt mixing are some of the most commonly used physical methods to generate NPs.



5.4.1.1 Inert Gas Condensation (IGC):

It is a physical synthesis method under bottom-up approach. IGC is the first and simplest method for the preparation of the ultrafine metallic nanoparticles and nanocomposites. It involves two steps: 1. Vapourization 2. Condensation.

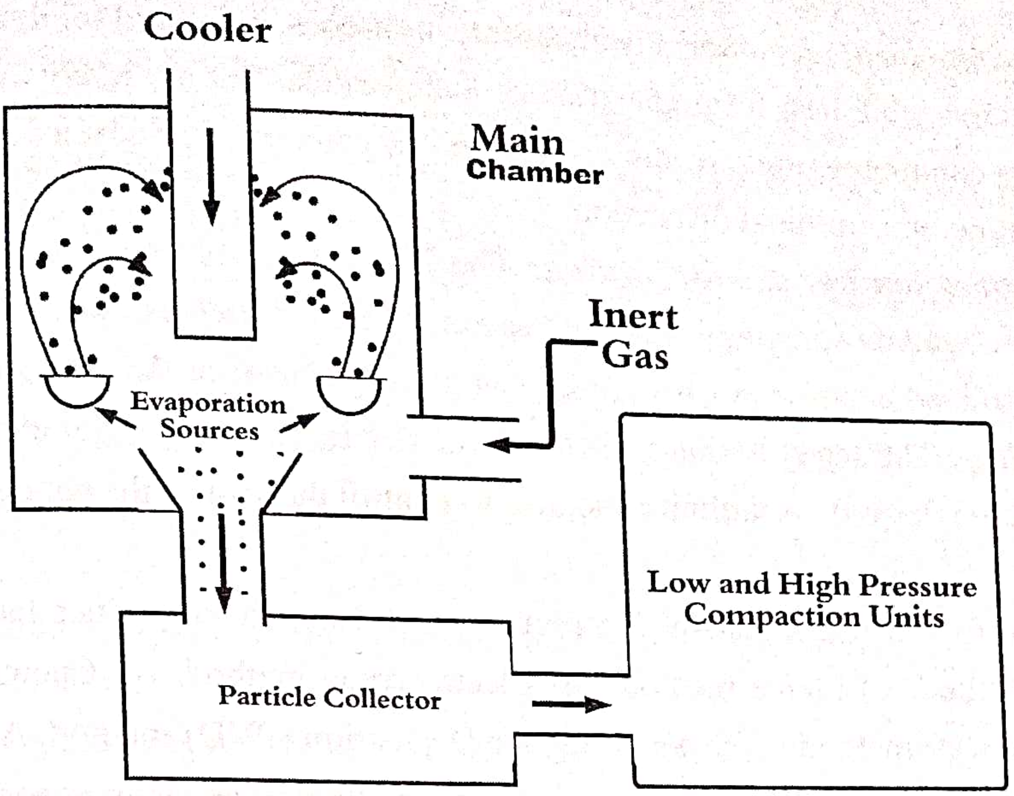


Fig. 5.4.1.1 Schematic diagram of inert gas condensation

1. ***Vapourization:*** It involves evaporation of metal or inorganic substance into atoms in presence of an inert gas from vaporizing source. The vaporization of the material can be carried out by vaporizing source such as sputtering, plasma heating, laser vaporization, electric arc discharge or thermal vaporization. The source to form atoms is in either solid or gaseous state.
2. ***Condensation:*** It involves condensation of the vaporized atoms of the metal or inorganic material on a cold surface. This step is the key step to control size of the nanoparticles. The required spontaneous condensation is carried out by the collection of the vaporized nanoparticles on surface with relatively low temperatures.

The production of the required size of the nanoparticles are determined by the nature of the inert gas (He, Xe or Ar) present in the chamber, the pressure of the gas in the chamber, temperature and rate of cooling. This process is the basis of the chemical vapor deposition process.

5.4.1.2 Aerosol Method

It is a physical method under bottom-up approach. It can form polycrystalline nanoparticles. The range of size of the particles formed by aerosol method is from molecules up to 100 μm. The preparation of nanoparticles by using aerosol method involves the following steps: 1. Preparation of precursor, 2. Evaporation and aerosolization, 3. Cooling.

1. ***Preparation of precursor:*** Precursors are in gaseous, liquid and solid state. Gaseous precursors are best for preparation of nanoparticles but are rarely available. The most commonly used precursors are liquid precursors. It can be a simple mixture solution or a colloidal dispersion.
2. ***Evaporation and Aerosolization:*** The liquid precursors are evaporated and aerosolized by spraying it into the reactor. The solid precursors are sublimed and aerosolized by using hot-wall reactor or plasma reactor or flame reactor.
3. ***Cooling:*** The aerosols obtained must be cooled to stop the growth of the particles, to obtain desired crystallinity and also to control the size of the nanoparticle.

There are five different aerosol techniques are developed to produce nanoparticles: i) Furnace method, ii) Flame method, iii) Electro spray method, iv) Chemical Vapour Deposition (CVD) method v) Physical Vapour Deposition (PVD) method. Among these methods, electro spray method is the most accurate method to generate nanoparticles.

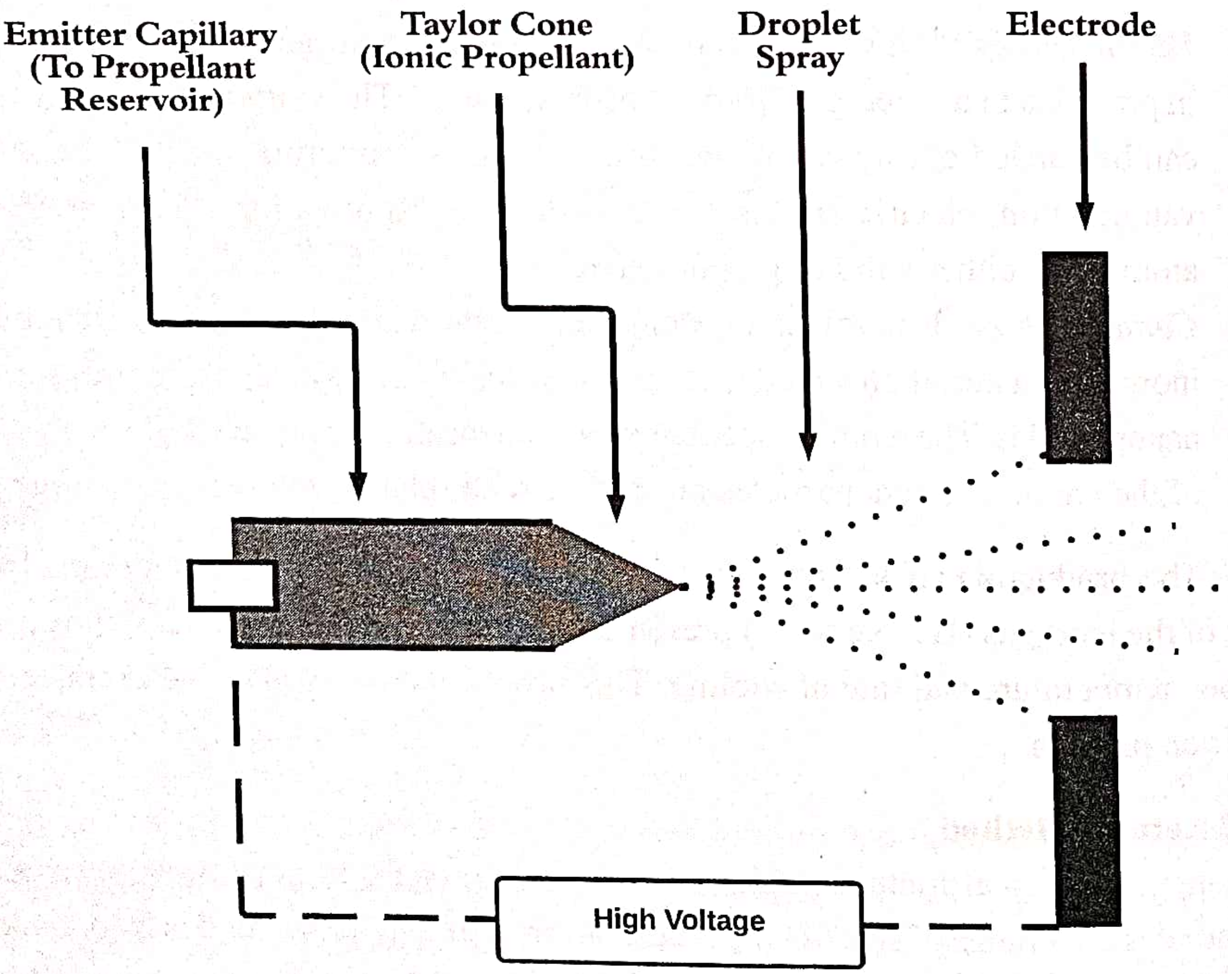


Fig. 5.4.1.2 Schematic diagram of electro spray device

Advantages:

- The method is simple and low cost.
- The method has good control over particle shape and size.
- It can generate high purity nanoparticles with a minimal effect on the environment since it generates low waste.
- It involves a limited number of fabrication steps when compared with wet chemical methods.
- It is widely used in commercial production of nanoparticles since it allows continuous direct collection of nanoparticles without involving purification and separation.

Disadvantages

- It requires optimization of many parameters to generate desired nanoparticle characteristics.
- The rapid formation of nanoparticles at elevated temperatures may result undesired properties such as crystallinity, composition, and morphology.

5.4.2 Chemical Processes

Chemical methods are widely used for the synthesis of metal oxide nanoparticles (MONPs). The most important wet chemistry methods to prepare nanoparticles are co-precipitation method, sol-gel method, microemulsion technique, hydrothermal synthesis, polyol synthesis, chemical vapour deposition technique, etc.

5.4.2.1 Co-precipitation Method

It is a wet chemical synthesis method under bottom-up approach. This method is commonly used to synthesize metal oxide nanoparticles, thin films, coatings, microspheres, and nanocomposite materials. In this method the desired component is precipitated from the solution. Co-precipitation is used for simultaneous precipitation of more than one component. The thermal treatment of precipitate can be considered as chemical grinding since it evolves gases which break the particles and decrease the size of the particles. It is relatively easy to scale up.

In general, the metal hydroxides are precipitated from their precursor salt solution because of their low solubility. The precipitation can be performed by starting from an alkaline solution which is acidified or starting from acidic solution by raising the pH.

Usually, metal hydroxides are precipitated from an acidic solution by the addition of an alkaline precipitating agents such as ammonia or sodium bicarbonate. Highly soluble inorganic salts such as nitrates, carbonates, or chlorides are generally used as metal precursors.

Co-precipitation method is one of the well-established synthetic approaches to prepare metal oxide nanoparticles (MONPs). In general, synthesis of MONPs has the following steps: 1. Liquid mixing/supersaturation 2. Precipitation-gelation/nucleation, 3. Particle growth, 4. Agglomeration, 5. Drying and 6. Thermal decomposition.

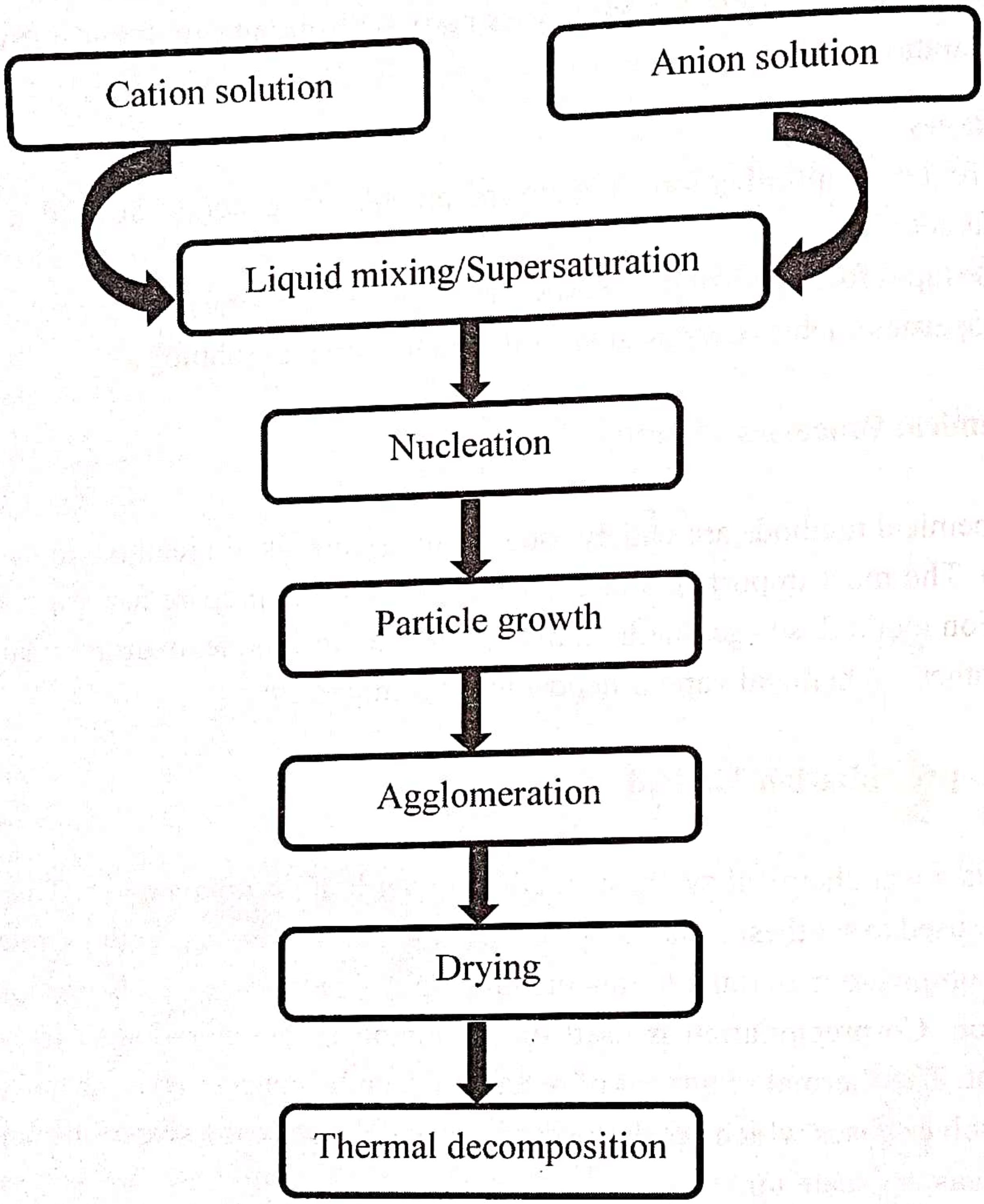


Fig. 5.4.2.1 Flowchart of co-precipitation method

1. ***Liquid Mixing/Supersaturation:*** Mixing of components in the solution has a significant effect on the precipitation. Good mixing of components is required to form homogeneous materials. Rate of stirring and manner of mixing influences nucleation and aggregation.

2. ***Precipitation-Gelation/Nucleation:*** The precipitation involves nucleation of particles. The smallest solid phase aggregate of atoms, molecules, or ions which is formed during precipitation is called as nucleus. The formation of nucleus is called as nucleation. It occurs when the concentration exceeds a critical threshold value. As long as the concentration of the species is above the critical concentration, new particles are formed. The nucleation process ceases when the concentration of species falls below the critical concentration. The nucleation process takes place when the solution is supersaturated. The supersaturation is acquired by increasing the concentration of components by evaporation or lowering the temperature or increase in pH. The increase in pH is the most convenient method for precipitation. The commonly used bases to rise the pH are NaOH, KOH, NH_4OH, carbonates and bicarbonates.

$$M^{n+} + nOH^- \rightleftharpoons M(OH)_n$$

3. ***Particle Growth:*** After a particle is nucleated, growth of particle takes place. The growth of clusters takes place until a critical size is reached. The clusters smaller than the critical size tends to redissolve but larger clusters continue to grow. The dissolution of fine particles and re-precipitation of larger particles is called as Ostwald ripening. It is responsible for growth of the particles. Growth proceeds through adsorption of ions on surface of seed particles. It is a function of concentration, temperature and pH. If nucleation is faster than particle growth, narrow distribution of small particles take place. Fast growth of particles results in narrow distribution of large particles.

4. ***Agglomeration:*** Normally crystals do not occur as single discrete units, but they form bigger clusters. There are two main classes of agglomeration: primary agglomeration and secondary agglomeration. Primary agglomeration is due to the faulty growth of crystals. Secondary is due to crystal-crystal interactions.

5. ***Drying:*** It involves separation of solid phase from the solution media. It requires simultaneous heat and mass transfer. It depends on the temperature and partial pressure of the solvent.

6. ***Thermal Decomposition:*** It involves performance of thermal treatment to decompose metal hydroxides into metal oxides and remove residues and water molecules from the material. The calcination temperature is a very important parameter in controlling the pore size and the density of the material.

Advantages Co-precipitation method

- High yield of material.
- Formation of pure and homogeneous material.
- Easy control of particle size.
- The lack of necessary to use organic solvents.
- Easily reproducible.
- Low cost.

Disadvantages Co-precipitation method

- Necessity of product separation after precipitation.
- Generation of the large volume of salt containing solutions.
- Difficulty in maintain product quality.

5.4.2.2 Sol-Gel Method

The sol-gel process is a wet chemical synthesis method under bottom-up approach. This method is commonly used to synthesize metal nanooxides, thin films, coatings, microspheres, fibers and nanocomposite materials. It involves changing the state from sol to gel by removing the solvent by various processes. A sol is a stable dispersion of colloidal particles or polymers in a solvent. A gel consists of a three-dimensional continuous network, which encloses a liquid phase.

The formation of crystalline materials such as nanoparticles or thin films and non-crystalline materials like ceramics, xerosol, aerosol and glasses depends upon the final heat treatment steps.

Sol–gel method is one of the well-established synthetic approaches to prepare high-quality MONPs. In general, synthesis of metal oxide nanoparticles (MONPs) by sol–gel method has the following steps:

1. Hydrolysis, 2. Polycondensation, 3. Aging, 4. Drying, and 5. Thermal decomposition

1. ***Hydrolysis:*** The synthesis of MONPs requires oxygen which supplied by solvent (water or alcohol or carboxylic acids). The first step involves mixing of metal alkoxide precursors and solvents. The nucleophilic attack of solvent molecules on metal alkoxides forms alcohol functional group (M - OH).

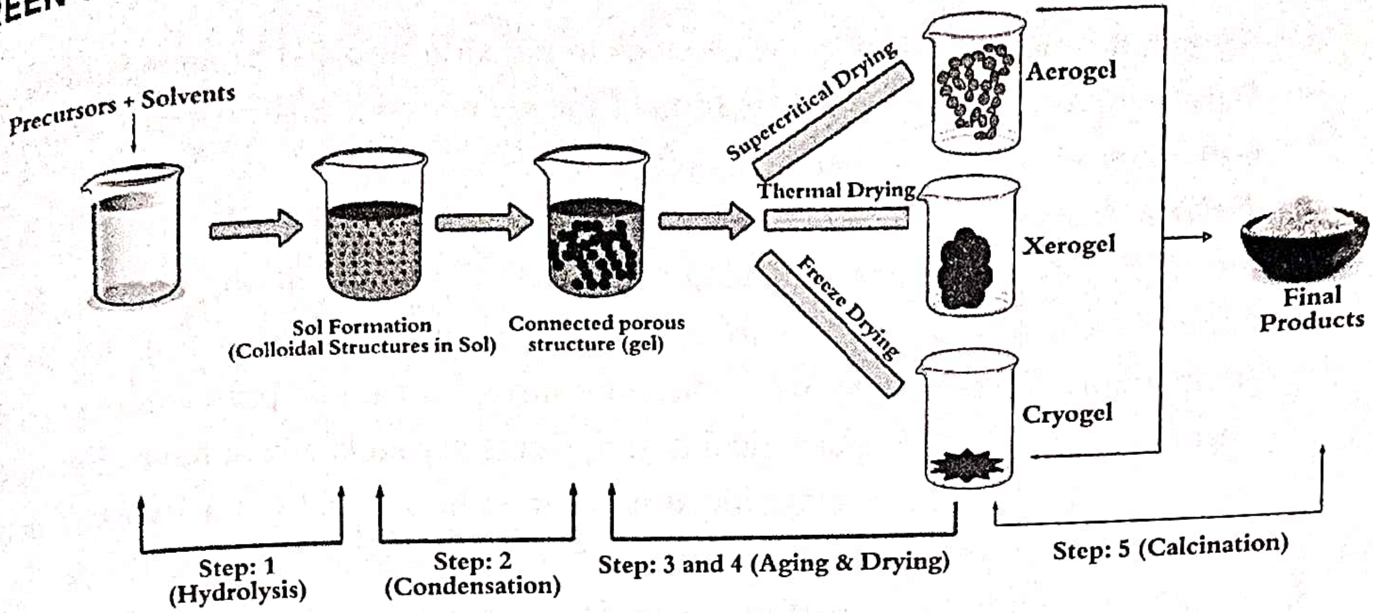


Fig. 5.4.2.2 Steps involved in sol–gel process to synthesize MONPs

$$M-OR + H_2O \longrightarrow M-OH + ROH$$

M = Metal, R = Alkyl group

2. ***Polycondensation:*** This step involves formation of metal oxide linkages by elimination of smaller molecules water/alcohol. Polycondensation leads to growing of polymeric network made of metal alkoxide linkages and forms colloidal solution (sol). Condensation occurs via two processes olation and oxolation. Olation is a process in which hydroxyl (–OH–) bridge is formed between two metal centers (metal–hydroxy-metal bonds) and oxolation is a process in which an oxo (–O–) bridgeis formed between two metal centers (metal–oxo-metal bonds).This process increases the viscosity of the solution as the polymer network grows, forming a porous structure within the liquid phase (gel). The size of the colloidal particles and the cross-linking of polymer mainly depend on the alkoxide precursor and pH of the solution.

The hydrolysis and condensation reactions strongly depend on the parameters such as the nature of the R-group, steric hindrance of alkoxy functional group, temperature, pH, nature of solvent, the ratio of solvent to metal alkoxide, and concentration of catalysts (acid or a base).

$$M-OH + XO-M \longrightarrow M-O-M + XOH$$

X = H or Alkyl group

3. ***Aging:*** It produces continuous changes in the structure and properties of the gel. Polycondensation and reprecipitation of the gel network finally decreases porosity and increases thickness between colloidal particles.
4. ***Drying:*** It involves detaching of water and organic components from gel. There are three different types of drying processes: i) thermal/atmospheric drying, ii) supercritical drying and iii) freeze-drying. Heating of the porous gel at high temperature forms xerogel which has low surface area, low pore volume and high shrinkage of the gel. Supercritical drying forms aerogels which have high surface area, high pore volume with almost no change in original gel network structure. Freezing of the gel forms cryogel which has shrinkage of the gel network.
5. ***Calcination:*** It involves performance of thermal treatment to drive of the residues and water molecules from the gel. The calcination temperature is a very important parameter in controlling the pore size and the density of the material.

Advantages of sol-gel method

- It is useful to synthesize special products such as powders, films, coatings, microspheres, fibers, etc.
- It forms new solids with enhancement of physical and chemical properties.
- The obtained materials have high purity and homogeneity of size of particles (narrow particle size distribution).
- Full control over the particle size and morphology.
- It involves consumption of less energy. Compared with the solid-phase reaction, the chemical reaction is simpler and only requires a lower synthesis temperature (< 220 °C).

Disadvantages of sol-gel method

- It is very sensible to moisture.
- Difficult to scale up.
- It is time-consuming process since it involves several number of steps.

5.5 PHYSICAL PROPERTIES OF NANOMATERIALS

The dimensions of nano scaled materials are close to individual atoms or molecules than to the bulk materials. Therefore, their behaviour is described by quantum mechanics. The properties of nanomaterials are different than bulk materials due to the following factors:

- **Larger surface area to volume ratio.**
- **Quantum confinement effect.**
- Domination of electromagnetic forces over gravitational forces.
- Wave-particle duality.
- Quantum tunneling effect.
- Quantization of energy.
- Random motion of particles.
- Energy of confinement electrons.
- Reduced imperfections.
- Surface plasmon resonance.

1. Surface Properties

The surface properties influence physical, chemical and biological activity of the materials. Nanomaterials have large surface areas. When the bulk material is repeatedly divided into smaller and smaller pieces, total volume of all the pieces together does not change, but the surface area is greatly enhanced. Therefore, the surface-area to volume ratio is significantly increased.

2. Thermal Properties

Melting Point: As the size of nanoparticles decreases surface area increases, which increases surface energy, decreases stability and increases disorder of material. It decreases the coordination numbers and cohesive energy, which makes the nanoparticles thermally unstable which leads to decrease in melting point.

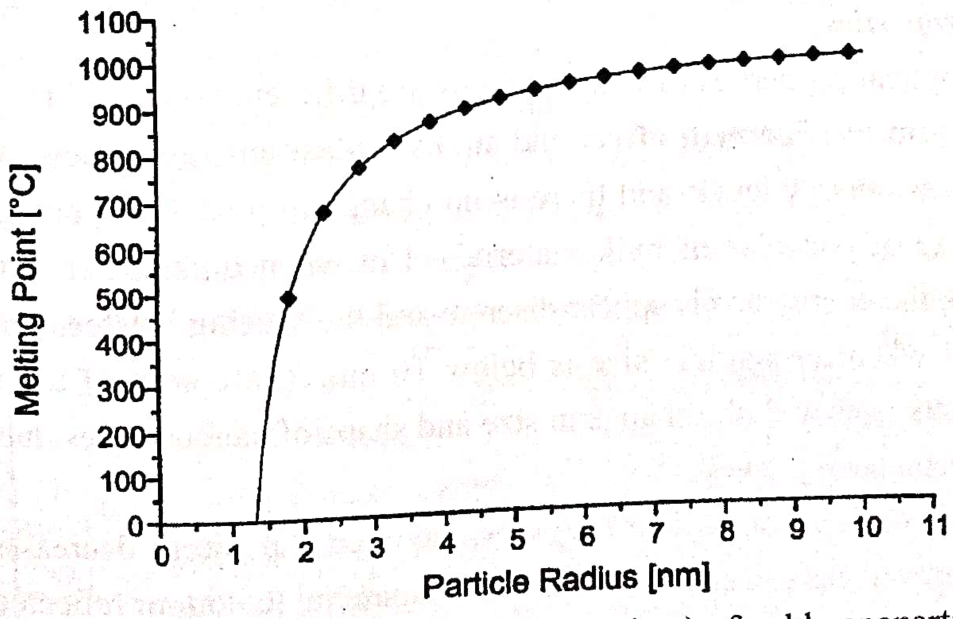


Fig. 5.5.2 Melting point (K) vs particle size (nm) of gold nanoparticles)

i. ***Heat Capacity:*** It increases with decrease in size of the nanoparticles is due to increase in thermal vibration energy of atoms and availability of free volume.

ii. ***Curie Temperature:*** It is the temperature at which ferroelectric converts into paraelectric. It decreases with decrease in particle size.The Curie temperature of barium titanate in bulk form is 130 °C and it decreases to 75 °C for size of 120 nm.

iii. ***Thermal Conductivity:*** It increases with decrease in size of the nanomaterials.

3. Mechanical Properties

The mechanical strength of the nanomaterials increases with decrease in size of the nanomaterials due to enhancement of internal and external perfection. Nanomaterials exhibit lower elastic modulus and more hardness compared to bulk materials. Ultrahigh hardness is shown by the metallic or ceramic nanoscale multilayered materials.

4. Electrical Properties

i. ***Electrical Conductivity:*** The decrease in grain size of nanoparticles increases electrical resistivity due to increased surface scattering. Nano materials with size less than 10 nm exhibit 7–20 times higher electrical resistivity than bulk materials. So, the electrical conductivity decreases with decrease in size of the nanomaterials.

ii. ***Electrical Energy Storage:*** Nanomaterials have ability to store more energy compared to bulk materials due to large surface area. Hence, nanomaterials can be used in batteries to obtain higher efficiency.

5. Optical Properties

The optical properties of nanomaterials are different compared to bulk materials due to **quantum confinement effect** and **surface plasmon resonance.** Bulk materials have continuous energy levels and there is no change in position of energy levels with change in size of particles of bulk materials. But when bulk material is reduced to nanomaterial, the energy levels appear discrete and the spacing between energy levels is so prominent when the particle size is below 10 nm. The colour of the nanoparticles significantly changes with the change in size and shape of nanoparticles due to change in spacing between energy levels.

As size of the nanoparticle increases, the band gap energy decreases, absorption shifts to longer wavelength and the colour of the material (colour of reflected light) shifts to shorter wavelength.

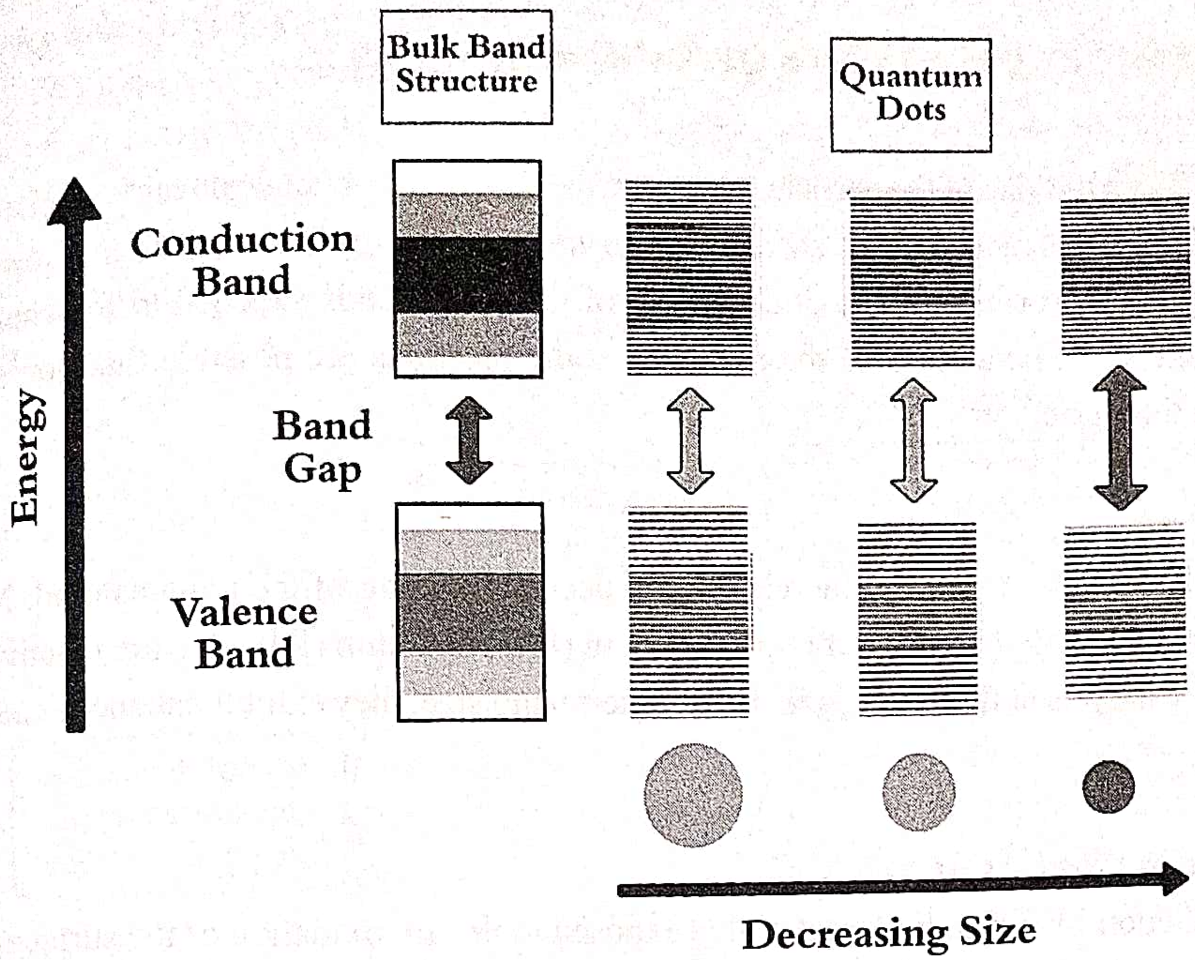


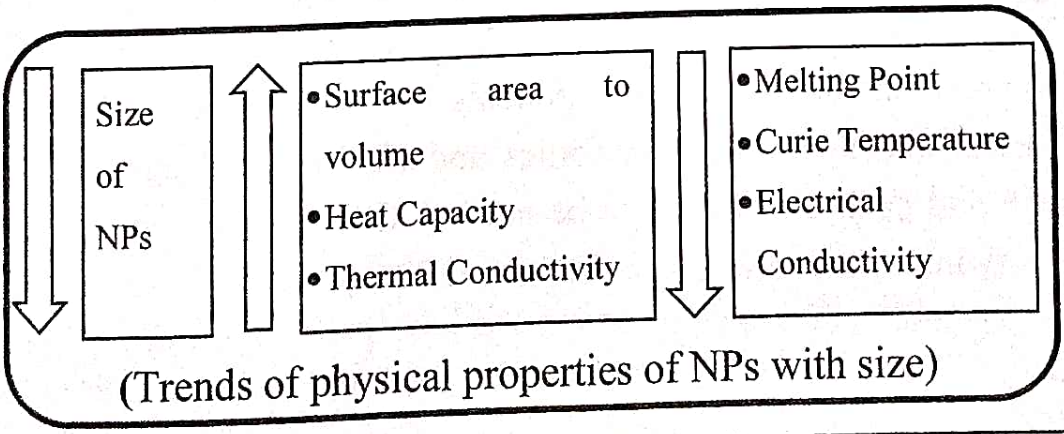
Fig. 5.5.5 Band gap energy vs Size of the particles

5. Magnetic Properties

When the size of the magnetic material decreases to nanosize, it exhibits the following properties: i) Superparamagnetic behaviour ii) Giant magnetoresistance.

i. ***Superparamagnetic nanoparticles*** are not magnetic when placed in a zero magnetic field. But they are quickly magnetized in presence of magnetic field. It is one of the most important property of nanoparticles used for drug delivery, bio separation, in-vitro diagnostics, and therapeutic treatment.

ii. ***Giant Magnetoresistance (GMR):*** It is the large change in electrical resistance in metallic multilayers containing alternating ferromagnetic and non-magnetic conductive layers in presence of applied magnetic field.



(Trends of physical properties of NPs with size)

5.6 CHEMICAL PROPERTIES OF NANOMATERIALS

When the size of the particle decreases, the speed of the chemical reactions increases exponentially due to increase in surface area to volume ratio, number of atoms or molecules on the surface, surface energy and number of dangling bonds exposed to the chemical environment. At nanoscale of the particles, some reactions are possible that don't take place in bulk size.

1. Catalysis

The catalytic activity increases with decrease in size of the nanomaterial. Noble metals such as gold (Au), silver (Ag), platinum (Pt), palladium (Pd), etc., are inactive and are poor catalysts at their bulk size. But, at their nano size, they exhibit enhanced catalytic activity.

2. Oxidation Process At Nanoscale

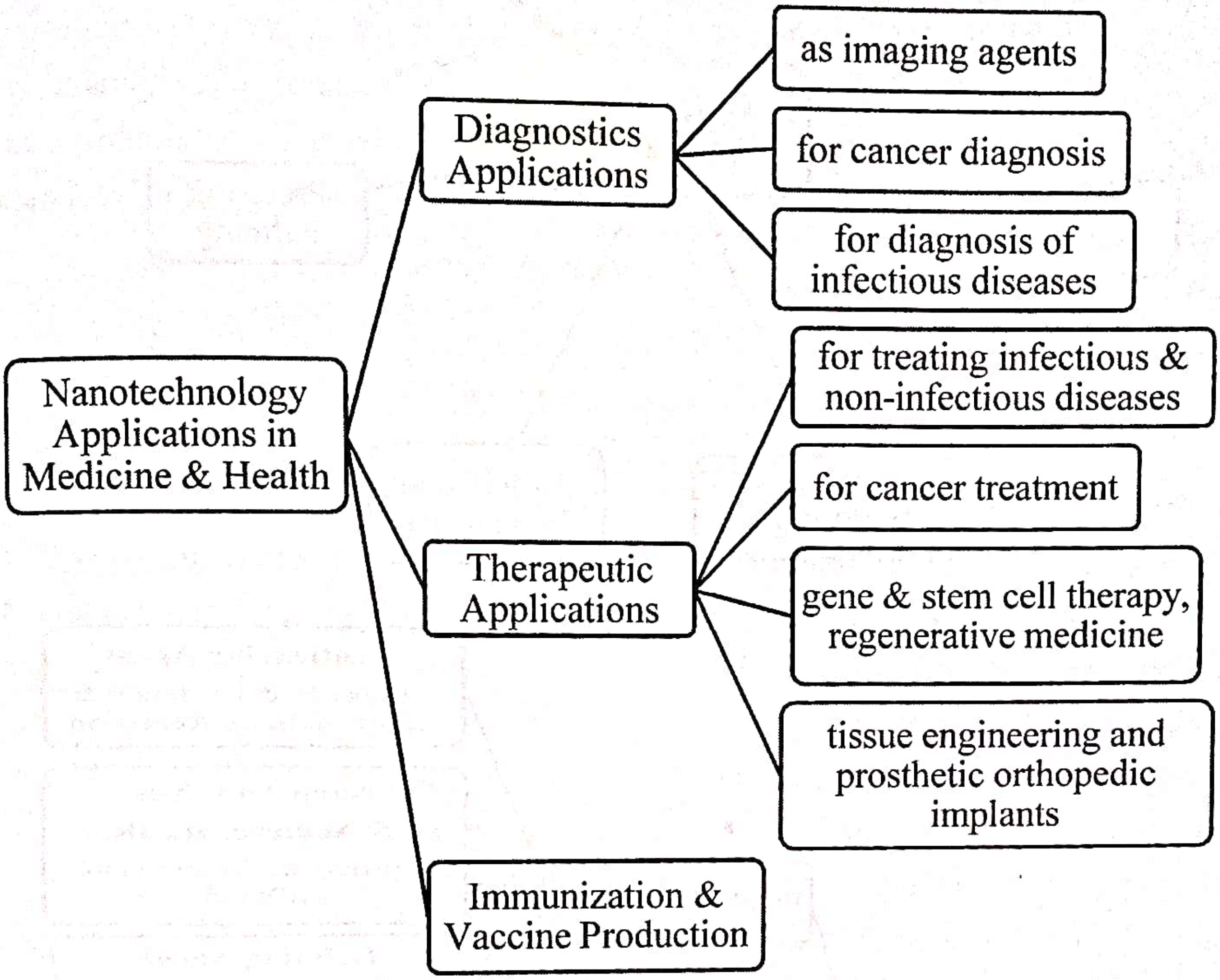
Generally, when bulk material is exposed to the air, oxidation of the surface takes place. The recent studies have shown that the oxidation process is not taken place in case of metal nanoparticles at low temperature but it is observed at elevated temperature. There is no oxidation at low temperature is due to formation of a thin layer on the surface of the nanoparticles due to adsorption of gases. When temperature reaches threshold temperature or above it, desorption of gases takes place and materials undergo oxidation. Threshold temperature is the temperature at which oxidation on nanoparticles surface takes place. The binding of gas and nanoparticles surface determines the threshold temperature. The less reactive nanometals like Zn, Sn, and Cu have weak bonds with the gas molecules and have low threshold temperature, whereas more reactive nanometals like Fe, Mo, etc., form strong bonds with the gas molecules, hence they have high threshold temperature.

5.7 APPLICATIONS OF NANOMATERIALS

Nanomaterials are integral components in a wide variety of applications in the fields of health and medicine, electronics and IT, food and agriculture, energy and environment, and catalysis. They can be used as fillers or coatings for UV protection, which are very important in windows, lenses, and sunscreens.

1. Health and Medicine

The physical, chemical and biological properties of nanomaterials are different compared to bulk materials. Nanomedicine is an application of nanoscience and technology to the field of health and medicine. Nanomedicines are economic, rapid, efficient and more specific. Nanomedicines are used in diagnosis, therapeutic treatment, immunization and vaccine production.

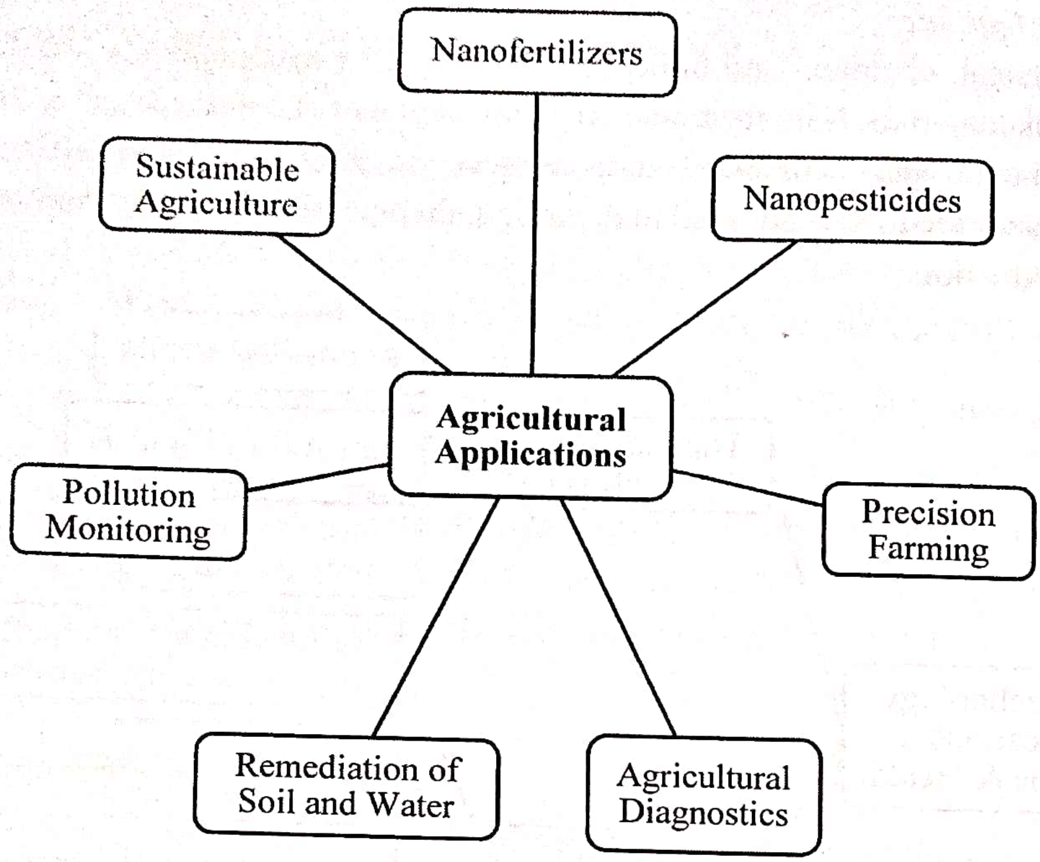


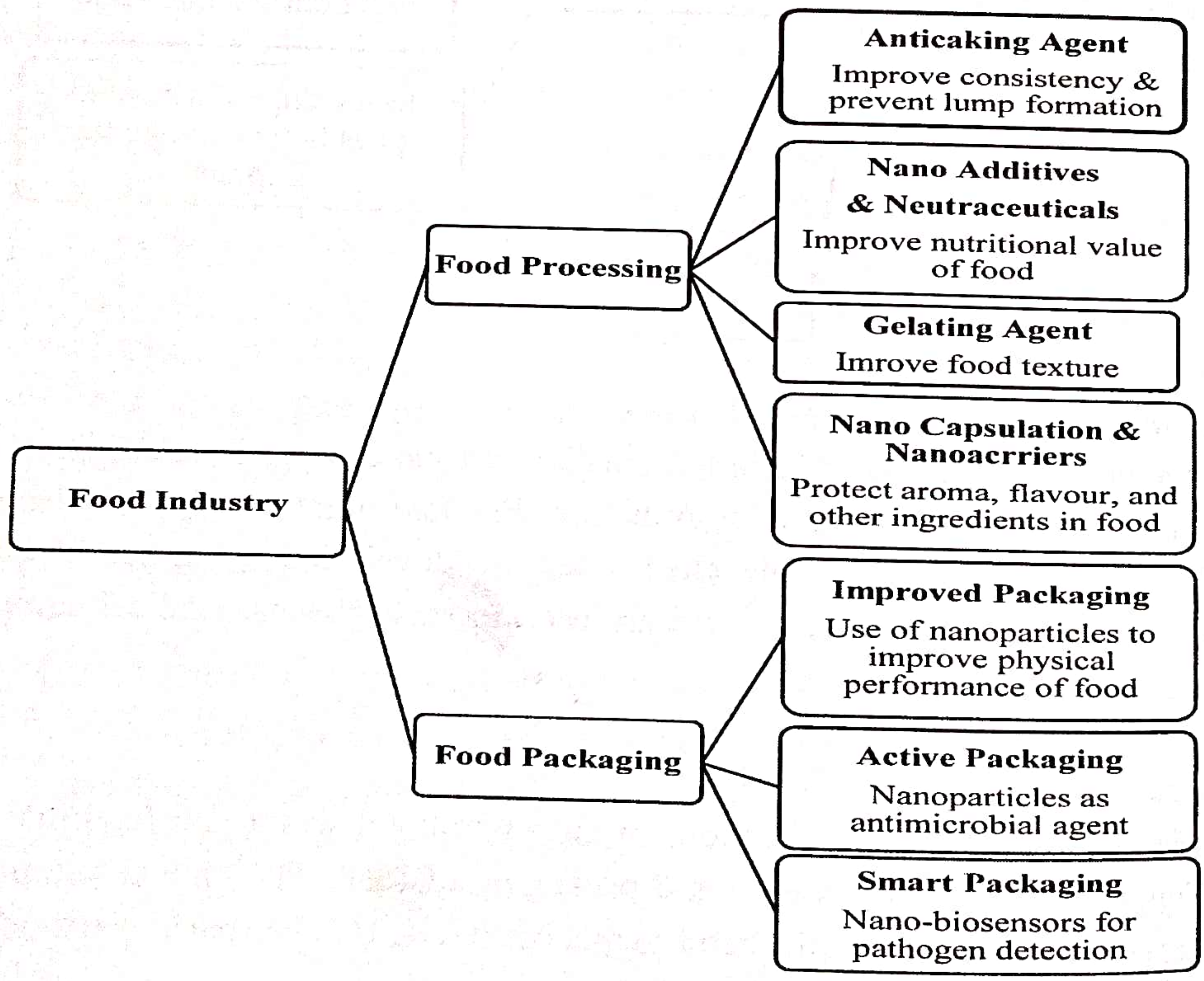
2. Electronics and IT Applications

Nanomaterials are used in faster, smaller and more portable computer systems which can store larger amounts of information. Flexible, light weight, flat, bendable, foldable, rollable, and stretchable electronics are developed using semiconductor nanomaterials. These electronic devices are used in smartphones, medical equipment, aerospace, etc.

3. Food and Agriculture

Nanotechnology has applications in the agricultural sector and food industry in production, processing, preservation and packaging of food. The known antimicrobial properties of materials such as silver and copper can be used to keep packaged foods fresh.


Nanofertilizers
Sustainable Agriculture
Nanopesticides
Agricultural Applications
Pollution Monitoring
Precision Farming
Remediation of Soil and Water
Agricultural Diagnostics

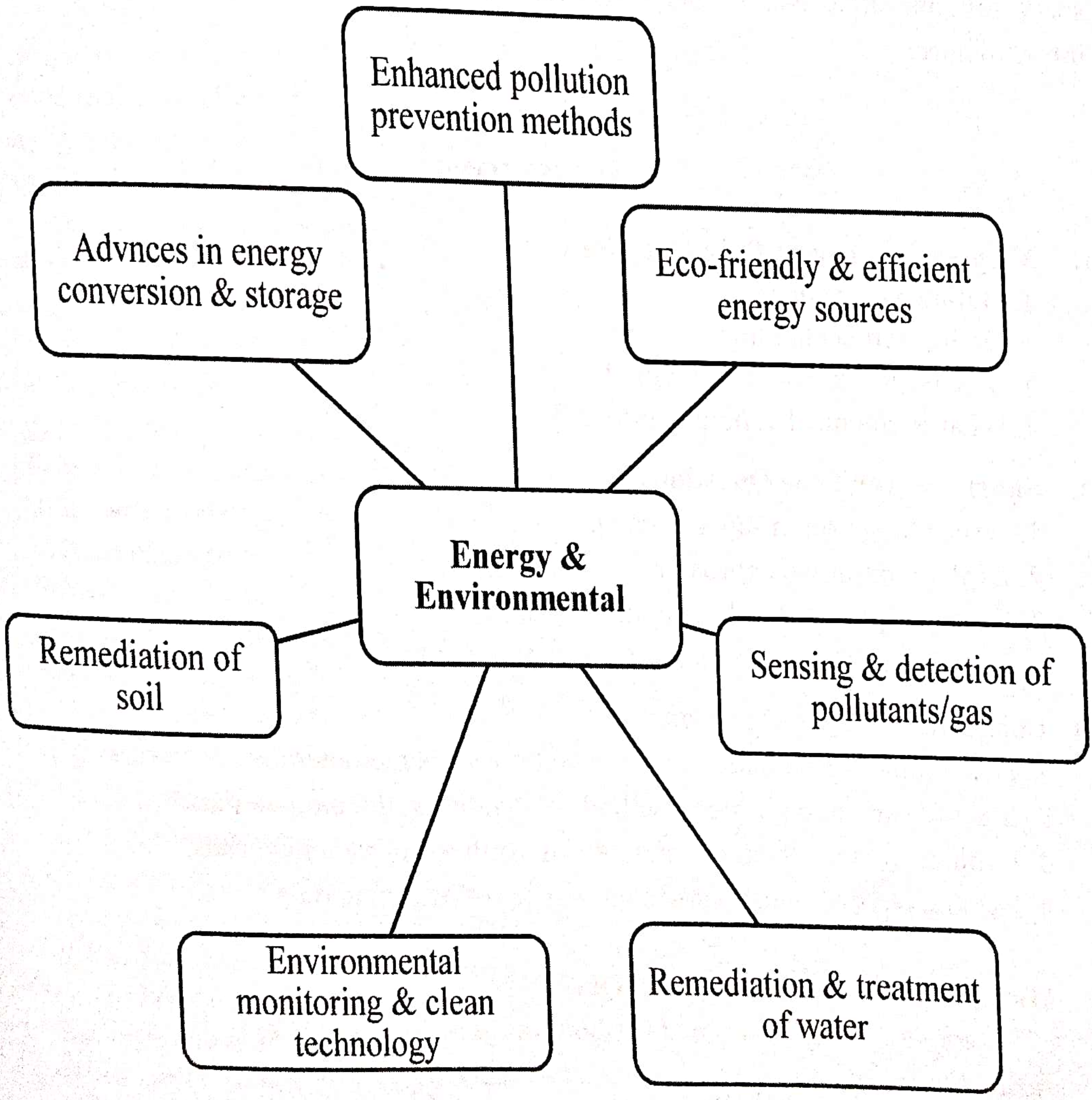

Food Industry
Food Processing
Food Packaging
Anticaking Agent
Improve consistency & prevent lump formation
Nano Additives & Neutraceuticals
Improve nutritional value of food
Gelating Agent
Imrove food texture
Nano Capsulation & Nanoacrriers
Protect aroma, flavour, and other ingredients in food
Improved Packaging
Use of nanoparticles to improve physical performance of food
Active Packaging
Nanoparticles as antimicrobial agent
Smart Packaging
Nano-biosensors for pathogen detection

4. Sensors of gases

The gases like nitrogen dioxide and ammonia can be detected based on change in electrical conductivity of nanomaterials which is due to charge transfer from nanomaterials to adsorbed gas molecules.

5. Energy and Environment

Nanomaterials are being used in many applications to improve the environment and to produce more efficient and cost-effective energy, such as generating less pollution, producing solar cells, removal of organic pollutants, heavy metals, inorganic pollutants, and microorganisms from water and soil. In recent years, contaminants are degraded by photocatalytic activity of metal oxide nanoparticles such as TiO_2.



6. Catalysis

In general, nanoparticles have large surface to volume ratio, and hence nanoparticles serve as efficient catalysts for some chemical reactions. In recent years, nanomaterials are used as catalysts due to its high activity, selectivity and productivity. The small metal nanoparticles (1–10 nm) show unexpected catalytic activity. The high catalytic activity of nanomaterials may be due to high surface-to-volume ratio, the electronic effect, and quantum size effect.

7. Transportation

Nanomaterials are used in lighter, safer, smarter, and more efficient vehicles, aircraft, spacecraft, and ships. Nanotechnology offers various means to improve the transportation infrastructure.

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