

TIN NANOPARTICLES: A REVIEW OF RECENT ADVANCES IN SYNTHESIS STRATEGIES, CHARACTERIZATION TECHNIQUES AND FUNCTIONAL APPLICATIONS

**Savita Verma¹, Deepika Rani^{2*}, Shameena³, Arun Sharma⁴, Anupama Kumari⁵,
Bhartendu Sharma⁶, Ravinesh Mishra⁷**

¹M.Pharm Final Year-Department of Industrial Pharmacy, School of Pharmacy and Emerging Sciences, Baddi University of Emerging Sciences & Technology, Makhnumajra, Distt Solan, Tehsil Baddi, Himachal Pradesh 173205.

^{2*}Professor-Department of Pharmaceutics, School of Pharmacy and Emerging Sciences, Baddi University of Emerging Sciences & Technology, Makhnumajra, Distt Solan, Tehsil Baddi, Himachal Pradesh 173205.

³M.Pharm Final Year-Department of Pharmaceutics, School of Pharmacy and Emerging Sciences, Baddi University of Emerging Sciences & Technology, Makhnumajra, Distt Solan, Tehsil Baddi, Himachal Pradesh 173205.

⁴M. Pharm Final Year-Department of Pharmaceutics, Sardar Bhagwan Singh University, Balawala, Dehradun, Uttarakhand, 248019.

⁵Assistant Professor-Department of Pharmaceutics, Himachal Pharmacy College, Majhauri, Nalagarh, Distt Solan, Tehsil Baddi, Himachal Pradesh 173205.

^{6,7}Professor-Department of Pharmaceutical Chemistry, School of Pharmacy and Emerging Sciences, Baddi University of Emerging Sciences & Technology, Makhnumajra, Distt Solan, Tehsil Baddi, Himachal Pradesh 173205.

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***Corresponding Author**

Deepika Rani

Professor-Department of Pharmaceutics,
School of Pharmacy and Emerging
Sciences, Baddi University of Emerging
Sciences & Technology, Makhnumajra,
Distt Solan, Tehsil Baddi, Himachal
Pradesh 173205.



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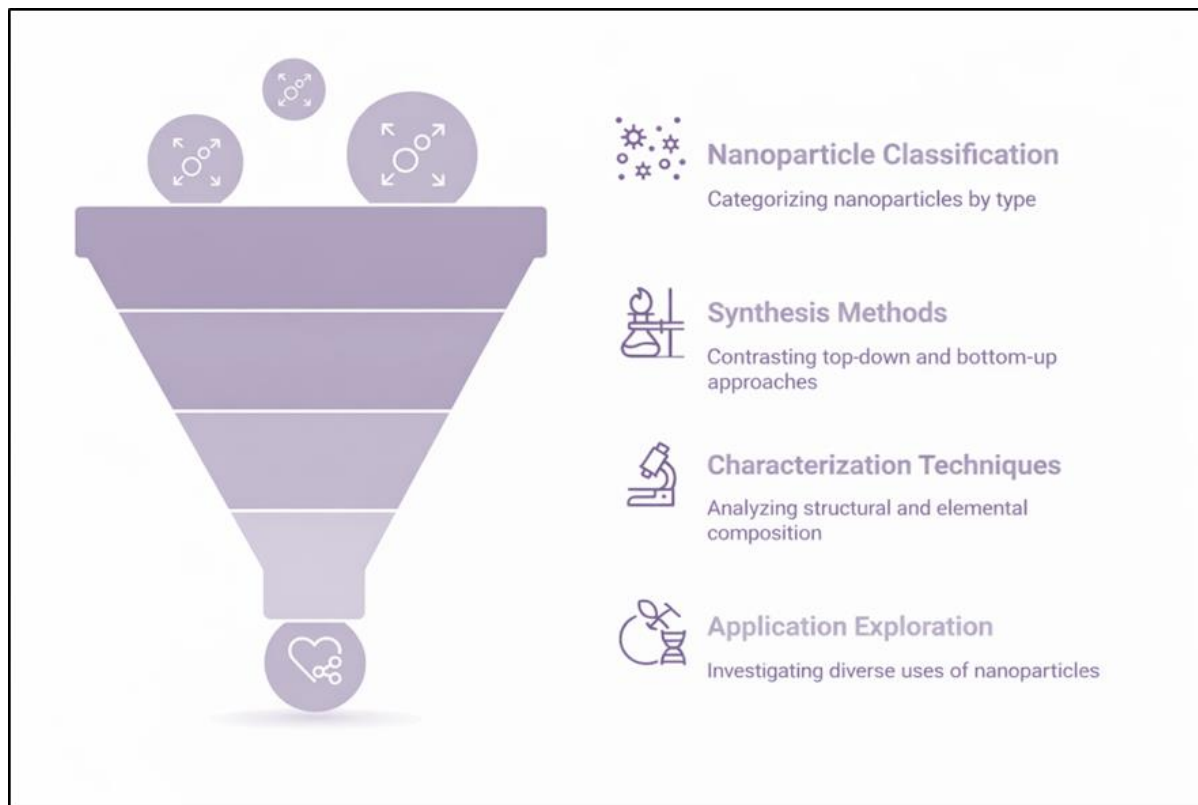
ABSTRACT

In nanotechnology, materials with enhanced chemical, structural, and morphological properties are produced by carefully manipulating matter at the nanoscale (1–100 nm). This topic revolves around Tin (IV) Oxide (SnO₂), a versatile semiconductor of the n type with a large bandgap (3.6 to 3.8 eV) and a rigid tetragonal crystalline structure. The top-down, or physical method, and bottom-up, or chemical method, synthesis approaches are contrasted in this study. Additionally, it highlights the biological (green) synthesis process as an affordable, safe, and sustainable substitute. To comprehend the structural and elemental composition of these nanomaterials, characterization techniques like XRD, scanning electron microscopy, TEM, FT-IR, and UV-visible Spectroscopy are investigated. Finally, the study explores the diverse applications of SnO₂ nanoparticles, ranging from biological (anti-cancer, anti-microbial, and anti-inflammatory therapy) to

ecological and electronic (photo catalysis and solar cell technology).

KEYWORDS: Nanotechnology, SnO₂ Nanoparticles, Green Synthesis, Semiconductor, Photo catalysis, Biomedical Applications.

GRAPHICAL ABSTRACT



1. INTRODUCTION

The creation and modification of particles on a nanoscale, typically between 1 to 100 nanometers, is the subject of the scientific discipline known as nanotechnology.^[1,2] Because of their incredibly small size, nanomaterials are widely used in biological and biomedical disciplines, among other scientific domains. They are special and innovative option for biomedical applications due to the alteration in their morphological, structural, and chemical characteristics.^[3,4] Common types of nanoparticles, categorized by origin, size, properties and morphology^[5,6,7] are carbon-based nanoparticles which are fullerenes and carbon nanotubes and used in many scientific and technological domains.^[8,9] These are typically employed because of their great strength, electron affinity and electrical conductivity^[10]; Ceramic nanoparticles seem to be stable throughout a wide pH and temperature range^[11]; polymeric nanoparticles, semiconductor nanoparticles, lipid-based nanoparticles, metal nanoparticles, which can be nanosized metals, metal oxides, metal sulphides, metal phosphates etc., are

made from metallic precursors. The size, shape and dimensions of the nanoparticles are significantly influenced by temperature, pH, and substrate concentration.^[12] The fields of biology, physics, electronics, optics, catalysis and biomedicine all benefit greatly from these metallic nanoparticles.^[13,14] These metallic nanoparticles are mostly prepared by adding a stabilizing and reducing agent. The introduction of biocompatible stabilizing agents, such as enzymes and biodegradable polymers, improved the stability and surface functionalization of the nanoparticles.^[15] Most metal nanoparticles are made by reducing solutions of metal salts.^[16]

1.1 TYPES OF METAL NANOPARTICLES

1.1.1. Silver Nanoparticles: Silver is the most profitable precious metal utilized in the production of nanoparticles and nanomaterials and it also acts as a medicinal agent for a variety of illnesses.^[17] Cancer treatment makes extensive use of silver nanoparticles.^[18,19] They are useful in the medical profession because of their anti-bacterial, anti-microbial, anti-viral, anti-fungal and anti-oxidant properties. They are renowned for having strong anti-oxidant and catalytic activities.^[20-22]

1.1.2. Gold Nanoparticles: Gold is a remarkable metal having strong scattering, absorption, minimal toxicity and compatibility.^[23] Gold nanoparticles have the ability to transport many pharmacological molecules, recombinant proteins, vaccinations or nucleotides to their targets.^[24] They can also regulate drug release through light activation or biological stimulation. Due of silver nanoparticles based medication delivery's notable performance; it has drawn a lot of interest.^[25] Here, the reduction and creation of stable gold nanoparticles is caused by a variety of reducing agents in addition to the gold metal ion.^[26] The production of gold nanoparticles is aided by certain biomolecules found in the plant extract such as proteins, phenols and flavonoids. Interestingly decahedral, icosahedral, spherical and triangular gold nanoparticles were produced.^[27,28]

1.1.3. Copper Nanoparticles: They also have high anti-bacterial qualities because of their huge surface area, which facilitates easy interaction with bacteria. They have nematocidal qualities as well.^[29-31] Copper nanoparticle's primary benefit over gold and silver nanoparticles is their low cost and availability, which leads to sample synthesis and a variety of copper nanoparticle applications.^[32,33]

1.1.4. Palladium Nanoparticles: Palladium nano-based materials with demonstrated cytotoxic and anti-bacterial pharmacological action have been developed as self-therapeutics.^[34,35] The brilliant feature for loading anti-cancer medications was palladium nanoparticle's high porosity. A connecting molecule can be used to indirectly conjugate the therapeutic medication to the palladium nanoparticles.^[36]

1.1.5. Platinum Nanoparticles: Because they are utilized in the development of several chemotherapy medications such as cisplatin and carboplatin, they are useful in the treatment of cancer. They are also employed as anti-oxidants and anti-microbials, and they have been used in sensors.^[37,38] However, platinum nanoparticle's toxicity has been shown in recent research which restricts their application in medicine and healthcare.^[39]

1.1.6. Zinc Oxide Nanoparticles: ZnO nanoparticles are utilized extensively in the biomedical area and have properties including wound healing, anti-inflammatory and high catalytic activity.^[40,41] These nanoparticles aid in controlling diabetes and cholesterol in addition to treating infectious infections.^[1,6]

1.1.7. Titanium Oxide Nanoparticle: Titanium oxides are two crystalline forms: rutile and the more chemically active anatase. Rutile titanium dioxide is thought to be chemically inert.^[42] Gambogic acid, cisplatin, valproic acid, doxorubicin, temozolomide and daunorubicin are among the anti-cancer medications for which various titanium oxide nanostructures are being used as drug delivery vehicles.^[43-45]

1.1.8. Iron Oxide Nanoparticles: The sizes of iron oxide nanoparticles range from 1 to 100 nm. Magnetite and its oxidized version, maghemite are the two primary forms of iron oxide nanoparticles.^[46] Iron nanoparticles are extensively utilized in waste and waste water treatment as well as environmental remediation.^[47,48]

1.1.9. Tin Oxide Nanoparticles: Semiconductor oxides called tin oxide nanoparticles serve as photocatalyst for the breakdown of specific organic molecules. They are one of the most significant nanomaterials because of their many characteristics, which include biocompatibility, antibacterial, antimicrobial, anticandidal and cytotoxic qualities. The sol-gel procedure, hydrothermal method, coprecipitation etc., can be used to create tin oxide nanoparticles. These nanoparticles are used extensively in sensors and in magnetic resonance imaging.^[49]

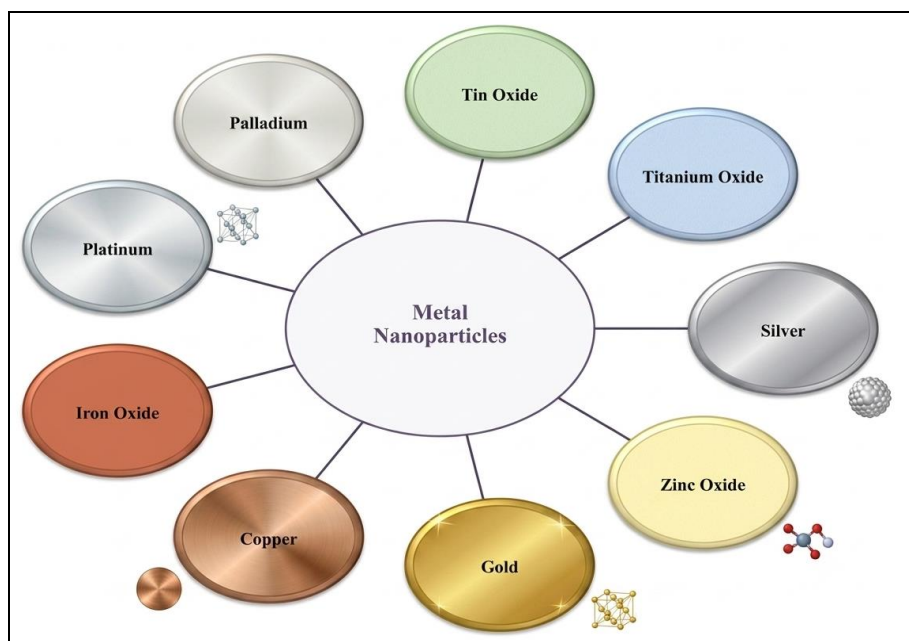


Fig.1: Types of Metal Nanoparticles.

2. TIN-NANOPARTICLES

A well-known group 14 metal oxide nanoparticle with notable optical, chemical, physical and therapeutic capabilities is tin (IV) oxide (SnO_2) also called stannic oxide,^[51,52] having molecular mass of $150.69 \text{ g mol}^{-1}$. The crystallites of SnO_2 nanoparticles have spherical and quasispheroidal morphologies and a rutile tetragonal phase.^[53-55] Because of their adjustable band energy gap, which range from 3.6 to 3.8 eV, and their appropriately constructed shape, nanostructured SnO_2 particles have enormous potential in environmental remediation.^[50] Semiconductor oxides called tin oxide nanoparticles serve as photocatalyst for the breakdown of specific organic molecules. The high photocatalytic activity of tin oxide is due to its octahedral structure.^[56-60] They are one of the most significant nanomaterials because of their many characteristics, which include biocompatibility, antibacterial, antimicrobial, anticandidal and cytotoxic qualities. The sol-gel procedure, hydrothermal method, coprecipitation etc., can be used to create tin oxide nanoparticles. These nanoparticles are used extensively in sensors and in magnetic resonance imaging.

2.1 PROPERTIES OF SnO_2 NANOPARTICLES

In the field of infrared radiation, SnO_2 is an amphoteric white or gray solid with good optical transparency and reflectance. It is a semiconductor material of the n-type (oxygen-deficient) type with a large bandgap (3.6eV). Because of its substantial excitation binding energy (130 meV) and n-type behavior which correlates to photo activation in the UV region of 350nm,

this material is an excellent photocatalyst for the destruction of a variety of organic contaminants.^[61,62] SnO₂ nanoparticles can be found as faceted diamagnetic oxide nanostructures with a large surface area. Typically measuring 20-40nm, nanoscale SnO₂ has a specific surface area of 10-80m²g⁻¹. It can be found in rutile, ultra high purity, transparent, coated and dispersed forms.^[63]

The physical and crystallographic properties of SnO₂ nanoparticles are tabulated below.

Table 1: Physical and crystallographic properties of SnO₂ nanoparticles.^[64]

Element (wt%)	Sn: 78.76 and O: 21.21
Molecular weight (g/mol)	150.69
Density (g/cm ³)	6.90
Melting point (°C)	1500-1630
Boiling point (°C)	1800-1900
Crystal system	Tetragonal
Electronic configuration	Sn: [Kr] 4d ¹⁰ 5s ² 5p ² O: [He] 2s ² 2p ⁴

3. METHOD OF SYNTHESIS OF TIN NANOPARTICLES

Research indicates that SnO₂ nanoparticles are synthesized using a variety of chemical and physical processes. Sol-Gel, chemical breakdown, flame synthesis, vapour deposition are some of these.^[65-67]

3.1. Bottom-up/ Chemical Method: The production of bulk material from atoms to clusters to SnO₂ nanoparticles is known as the bottom-up or constructive technique, which involves two steps i.e. nucleation and growth. Sol-gel, spinning, chemical vapor deposition, flame spraying, pyrolysis and biosynthesis are among its methods. Because it is simple and effective to adjust the particle size as needed, this approach is widely used.^[68,69]

3.2. Top-down/ Physical Method: The manufacture of SnO₂ nanoparticles by reducing a bulk material to nanometric scale particles is known as the top-down or destructive technique. It includes thermal degradation, sputtering, laser ablation, mechanical milling and nanolithography. This method's inability to regulate particle size is one of its main disadvantages. As a result, this method is less common in the advancement of matter nanotechnology.^[68,69]

3.3. Biological Method: It has been discovered that the biological approach, which uses plant phytochemicals or microbial enzymes for synthesis, is more environmentally friendly. This approach has proven to be the most effective, safe and biocompatible method for creating

nanoparticles. Numerous research have documented the synthesis of SnO₂ nanoparticles using aqueous or alcoholic extract from plant and tree leaves, flowers, fruits, fruit peels, roots, waste plant material and agricultural waste. The primary benefit of employing biological synthesis is its affordability and non-toxicity, which guarantees its use in many applications across numerous industries.^[70]

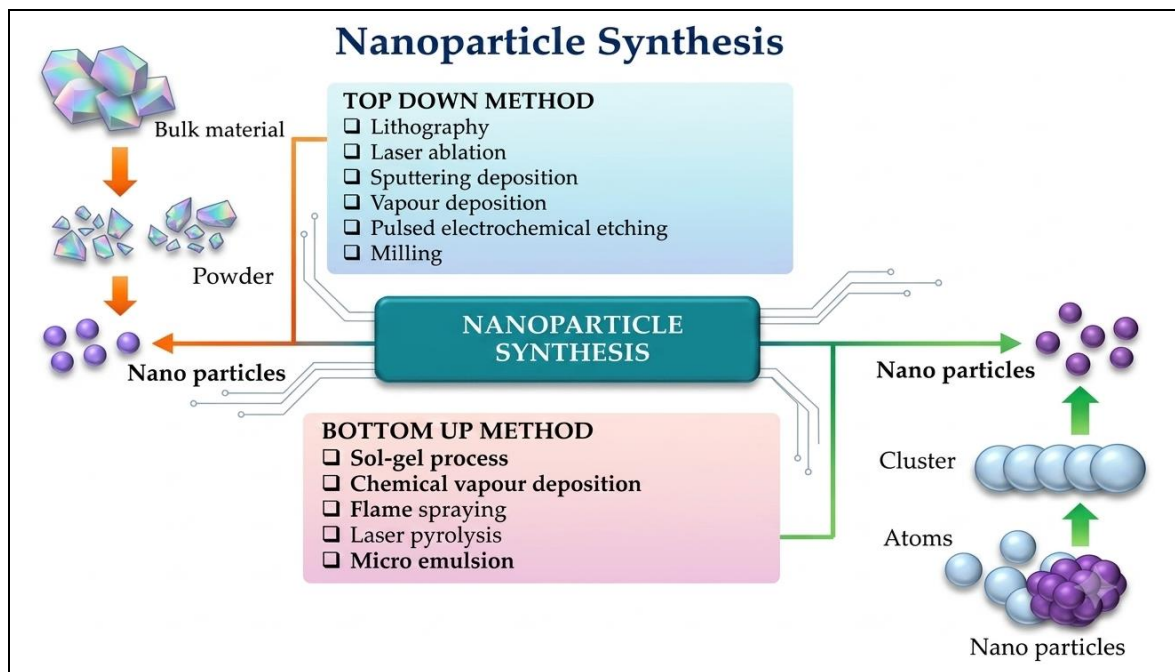


Fig.3 Methods for Synthesis of SnO₂ Nanoparticles.^[17]

4. CHARACTERIZATION OF TIN NANOPERTICLES

Using various spectroscopic techniques, the nanoparticles can be described. These consist of TEM & SEM, X-ray Diffraction, FT-IR, DLS, AFM and UV-Visible Spectroscopy. These spectroscopic methods provide information about concentration, structural details, and elemental makeup.^[71]

4.1. Particle Size & Zeta Potential: The mean particle size and zeta potential of the nanoparticles were measured using photon correlation spectroscopy (PCS) at room temperature. The samples were sufficiently diluted with deionized water before being put in an electrophoretic cell.^[72]

4.2. Drug loading capacity: The amount of drug loaded in the produced nanoparticles and their entrapment ability were determined by analyzing their drug loading capacity. After dispersing the necessary quantity of drug-loaded nanoparticles in an appropriate solvent, the

mixture was centrifuged for 30 minutes. Following additional dilution and absorbance measurement of the removed supernatant using a UV spectrophotometer, the amount of medication that was not entrapped in the nanoparticles was assessed.^[73]

% DL= Amount of total drug entrapped/ weight of total nanoparticles × 100

4.3. TEM & SEM: The size, internal structure and shape of the nanoparticles can be determined by TEM. Excellent image clarity and great resolution for nanoscale samples are the technique's key benefits. Conversely, SEM's inherent subnanometer scale resolution facilitates efficient nanoparticle characterization. Resolution with SEM is between 1 and 3 nm. By using a concentrated electron beam to scan the sample, SEM creates surface pictures of the material and aids in the identification of various signals generated by the sample's electrons interacting with the electron beam.^[71]

4.4. X-ray Diffraction: Particle size, lattice dimensions and crystal characterization can all be determined with the help of the X-ray technique.^[74] The primary purpose of this technique is to assess the crystallinity and three-dimensional architectures of nanoparticles.^[75] The XRD pattern was used for this, Bragg's equation was used to obtain the lattice parameters from the XRD pattern:

$$N \lambda = 2d \sin (\theta)$$

Where; N is order of reflection

λ is wavelength of the incident radiation

d is distance between the crystal planes

θ is the angle of incidence^[76]

4.5. FT-IR: This provides information on how infrared light impacts molecular rotation and vibration and is used to identify organic compounds. Both liquid and solid materials can be subjected to FT-IR analysis.^[77] FT-IR makes it simple to identify the characteristics of the metabolites and functional groups that are present on the surface of the nanoparticles.

4.6. Atomic Force Microscopy: The scanning probe microscopic method known as atomic force microscopy (AFM) provides data on surface area, volume distribution, surface texture, roughness, size, and morphology. The height of the nanoparticles may be ascertained since the AFM image is three-dimensional. Compared to SEM & TEM techniques, AFM is more advantageous since it takes significantly less laboratory space, is more affordable, and is much easier to use.^[71]

4.7. UV-Visible Spectroscopy: This can be used to analyze the scattering and absorption of light that passes through the material. A sample is positioned between the light source and the photodetector, and the light's intensity is measured both before and after it passes through the sample. This method aids in the stability assessment of the nanoparticles as well as the identification and characterization of nanoparticles.^[78,79]

Other helpful techniques for characterizing nanoparticles include thermal gravimetric analysis, dynamic light scattering and energy dispersive X-ray spectroscopy (EDX).^[80] The elemental composition of nanomaterials and the metal content of metal nanoparticles are often determined using EDX. Nanoparticles smaller than one nanometer (0.1-10nm) are analyzed using dynamic light scattering (DLS) or Photon Correlation Spectroscopy (PCS). It can be used to measure the hydrodynamic diameter and aggregation condition of the nanoparticles in solution. This technique typically aids in assessing the nanoparticle's thermal stability.^[81-84] TGA aids in identifying the amount of coating, moisture and volatile components on the surface of nanoparticles as well as their thermal stability.^[85]

5. APPLICATIONS OF TIN NANOPARTICLES

5.1. Biomedical Applications: MRI, medication administration and heat are just a few of the biomedical applications for doped and undoped SnO₂ nanoparticles.^[86-89]

5.2. Anti-cancer Therapy: Nanoparticles are employed as vectors in hydrophobic medicine, therapies, diagnostic and particularly in the administration of anti-neoplastic medicines to malignant tissues, where they can enter and deliver the medications to a precise targeted spot.^[90,91]

5.3. Anti-microbial Activity: Because of their surface-to-volume ratios and various mechanisms for bacterial inhibition and bactericidal effect, which reduces bacterial resistance, metal nanoparticles seem to be potential antibacterial agents.^[92,93]

5.4. Anti-Viral Activity: Nanoparticles have become a promising class of anti-viral medicines because of their special physiochemical characteristics, which include tiny size, large surface area and catalytic activity. Because of these traits, they can interact with viral components and alter their structure or function, which stops the virus from replicating and spreading.^[94]

5.5. Anti-inflammatory Activity: Numerous studies have shown that nanomaterials can reduce inflammation by inhibiting the synthesis of chemokines, ROS and pro-inflammatory cytokines. These qualities make them attractive therapeutic options for the management of numerous inflammatory conditions.^[95-98]

5.6. Photo-catalytic Application: Because of their wonderful qualities- transparency, affordability, environmental friendliness, good chemical and biological inertness, non-toxicity, ease of production, high photosensitivity, photostability and thermodynamic stability- SnO₂ nanomaterials are anticipated to be a strong photocatalyst for the degradation of organic pollutants in solution.^[99-101]

5.7. Electronic Application: Because of its optical and electrical qualities, SnO₂ is widely utilized in electronic devices such as thin films, solar cells, light-emitting diodes etc. Tin oxide's outstanding transparency, superb shape and appropriate energy levels make it an emerging possibility for usage in perovskite light-emitting diodes.^[102,103]

5.8. Anti-Fungal Activity: While investigating the anti-fungal potential of doped and undoped nanoparticles against specimens of *aspergillus nigr*a, *aspergillus flavus* and *C. albicans* fungus. However, in subsequent attempts, the green synthesized SnO₂ nanoparticle's anti-fungal and anti-bacterial properties were used. According to the Potato Dextrose Broth Anti-fungal Assay which was used to measure the anti-fungal activity of SnO₂ nanoparticles, *Aspergillus nigr*a exhibiting significantly more activity than *Trichoderma Viride*fungi.^[104,105]

5.9. Anti-oxidant Property: In order to ensure its usage in biomedical applications, the free radical equivalent of DPPH per milligram of the sample was determined to be 0.8026. Alkaloids, cyclopeptides, flavonoids, phenols, tannins and minerals including Cu, Fe, Mg, Zn and Se are present in the plant extracts which contributes to the medicinal and anti-oxidant qualities of the resulting nanoparticles.^[105]

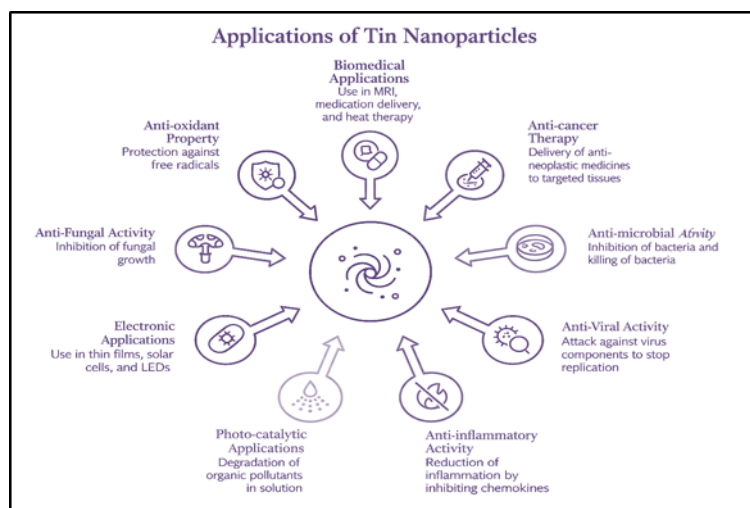


Fig. 4: Applications of Tin Nanoparticles.

6. CONCLUSION

SnO₂ exhibits exceptional physicochemical characteristics that position it as a versatile material for advanced technological and biomedical applications. Nevertheless, its practical implementation is constrained by intrinsic challenges, notably the high surface energy of nanostructures leading to agglomeration and reduced active surface area. Moreover, while biologically derived green synthesis routes enhance sustainability, their compositional variability complicates reproducibility and scalability. Future research should prioritize the rational design of hierarchical 3D nanostructures (e.g., nanoflowers, hollow architectures) to improve stability and charge transport properties. Concurrently, the development of surface-functionalized SnO₂ systems for stimuli-responsive drug delivery must be supported by rigorous nanotoxicological evaluation to ensure biosafety. Overcoming these limitations through advanced surface and interface engineering will be critical for bridging laboratory-scale innovation with industrial and clinical translation.

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