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A Comparative Study of Nanoparticles: Properties and Applications in the Textile Industry

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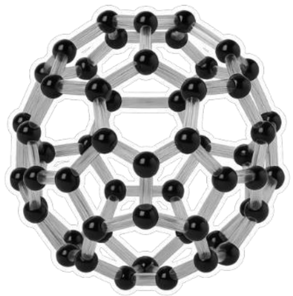
Abstract**—** *This review explores the multidisciplinary realm of nanotechnology, highlighting its principles, historical evolution, and wide-ranging applications. Beginning with an overview of nanoscience and its foundational concepts, the paper delves into nanomaterials' classification and synthesis methods, including both top-down and bottom-up approaches. A comparative insight into green synthesis and conventional chemical synthesis of nanoparticles is also discussed, where green synthesis is emphasized as an eco-friendly, sustainable, and less toxic alternative, in contrast to chemical synthesis, which often involves hazardous reagents and generates harmful by-products. The paper further emphasizes the unique properties of nanomaterials that differ significantly from their bulk counterparts, making them suitable for diverse applications. Key areas of focus include the role of nanotechnology in electronics, medicine, environmental protection, and agriculture. Additionally, the paper addresses potential risks, toxicity concerns, and the prospects of nanotechnology, stressing the importance of responsible development and application. This comprehensive review aims to provide a foundational understanding of nanotechnology and its transformative potential across various sectors.*

Keywords**— *Nanotechnology, sustainability, synthesis, application***

Introduction

A nanoparticle is an ultra-fine particle, invisible to the unaided human eye, typically measuring between 1 and 100 nanometers in diameter. Owing to their minuscule scale, these particles often possess unique and remarkable physical and chemical properties that distinguish them from their larger counterparts. This classification also extends to slightly larger particulate matter, including nanoscale fibres and nanotubes measuring less than 100 nanometers in at least one dimension. (Aruna *et al.,*2023; Wiesenthal *et al.,*2011; Mishra *et al.,*2014). When a bulk material is broken down into minuscule particles with one or more dimensions, such as length, width, or thickness, within the nanometre scale, these individual nanoparticles begin to demonstrate extraordinary and often unpredictable properties that diverge significantly from those of the original bulk substance. This nanometre scale marks a pivotal threshold where the material's characteristics shift from the predictable, continuous behaviour typical of bulk matter to the intriguing, quantum-like behaviour observed at the atomic and molecular level. (Purushotham, 2012; Jeevani, 2011).



For more than thirty years, the textile industry has actively harnessed the potential of nanotechnology, integrating nanoparticles either by embedding them directly into fabric structures or by meticulously engineering their distribution within the fibres themselves. This innovative approach has revolutionised textile functionality, paving the way for advanced materials with enhanced performance and novel properties.(Yang and Westerhoff, 2014Nano-textiles provide a wide array of advanced functional advantages, including superior chemical resistance, increased mechanical durability, water repellency, extended lifespan through anti-ageing properties, antimicrobial effectiveness, self-cleaning abilities, and robust protection against ultraviolet (UV) radiation. These enhanced features position nano-textiles at the forefront of high-performance and smart fabric innovations. (Thomas *et al.,*2006; Singh *et al.,*2023) Currently, the textile industry is placing significant emphasis on investigating the application of metallic nanoparticles (MNPs) to advance fibre manufacturing processes and develop fabrics with innovative or significantly improved properties. This cutting-edge exploration aims to unlock new functionalities and elevate the performance of textile materials to unprecedented levels. (McArthur *et al.,*2012) The incorporation of nanoparticles into textile materials has been the focus of extensive research to create finished fabrics that exhibit a variety of enhanced functionalities. For instance, silver nanoparticles (nano-Ag) have been widely utilised to endow textiles with potent antibacterial properties, significantly improving their hygiene and durability.(Lee *et al.,*2003; Durán *et al.,*2007), nano-TiO_2 for UV-blocking and self-cleaning properties (Xin *et al.,*2004; Fei *et al.,*2006; Qi *et al.,*2007) and ZnO nanoparticles for antibacterial and UV-blocking properties (Wang *et al.,*2004; Baglioni *et al.,*2003; Wang *et al.,*2005; Vigneshwaran *et al.,*2006).

Metal nanoparticles (MNPs) have been widely explored for textile functionalization owing to their unique physicochemical and biological characteristics. Their remarkable properties make them ideal candidates for enhancing textile performance across various applications. (Mehravani *et al.,*2021; Ribeiro *et al.,*2020). Metal nanoparticles (MNPs) serve as pivotal contributors to this technological advancement, owing to their exceptional surface characteristics that deliver significantly greater efficacy compared to traditional bulk additives. Their high surface-area-to-volume ratio amplifies their functionality, enabling enhanced performance in textile applications. (Rivero *et al.,*2015; Ribeiro *et al.,*2018Metal nanoparticles are composed entirely of metallic elements and are renowned for their unique electrical properties, primarily attributed to the phenomenon of localised surface plasmon resonance (LSPR). Notably, copper (Cu), silver (Ag), and gold (Au) nanoparticles display a broad absorption band within the visible region of the solar electromagnetic spectrum. These nanoparticles are extensively utilised across various scientific disciplines due to their exceptional attributes, including controlled synthesis based on facets, size, and shape, which significantly enhance their functional capabilities. (Khan *et al.,*2019).

Nanotechnology plays a vital role in tackling contemporary challenges within the textile industry, particularly the growing demand for sustainable, environmentally friendly materials and manufacturing processes. By integrating nanomaterials, the industry is empowered to create cutting-edge textile solutions that align with shifting consumer preferences, ranging from intelligent fabrics for wearable technology to high-performance protective textiles and eco-conscious materials that support a greener planet. The true significance of nanotechnology lies in its transformative potential to push the frontiers of textile science, drive innovation, and elevate market competitiveness across diverse sectors. (Prasad *et al.,*2023).

Types of metallic nanomaterials used in textile

To understand the practical use of nanoparticles in textiles, it is essential to explore the specific types of metallic nanomaterials that have demonstrated effectiveness in this domain

Silver nanoparticles (AgNPs)

Silver nanoparticles are nanoscale particles of silver typically ranging in size from 1 to 100 nanometers. Although often referred to simply as "silver," many of these nanoparticles consist largely of silver oxide, owing to their exceptionally high surface-area-to-volume ratio, which increases surface reactivity. Depending on the intended application, silver nanoparticles can be synthesized in a variety of shapes. Among the most commonly utilised forms are spherical particles, octagonal structures, and ultra-thin sheets, each offering distinct properties suited to specific functional requirements (Graf *et al.,*2003).

Green synthesis of silver nanoparticles was achieved using *Azadirachta indica* (Neem) leaf extract. This eco-friendly process involved mixing silver nitrate with the extract, 1 mm $AgNO_3$ solution. 10 ml of extract was added to 90 ml of $Agno_3$. UV-Vis peak at 450 nm confirmed synthesis. leading to nanoparticle formation indicated by a colour change. Characterisation confirmed size and shape. This method is cost-effective, sustainable, and avoids harmful chemicals (Ahmed *et al.,* 2016).

Silver nanoparticles (AgNPs) were synthesised through the chemical reduction of a 12 mm aqueous solution of $AgNO_3$. The reaction was conducted under an argon atmosphere using 70 ml of the silver nitrate solution combined with polyvinylpyrrolidone (PVP), maintaining a molar ratio of 34:1 between PVP repeating units and silver ions. Additionally, 21 ml of Aloe Vera extract was added to the mixture. This solution was subjected to ultrasonic agitation for 45 minutes at room temperature, followed by a controlled heating process at a rate of 2°C per minute until reaching 80°C. The reaction was sustained for two hours, resulting in a clear solution containing finely dispersed nanoparticles, which were then isolated by simple filtration (Shenashen *et al.,*2014; Gloria *et al.,*2017).

Zinc oxide nanoparticles (ZnO)

Zinc oxide nanoparticles are ultra-fine particles of zinc oxide (ZnO) with diameters typically under 100 nanometers. Due to their nanoscale dimensions, they exhibit an exceptionally high surface area-to-volume ratio, which significantly enhances their catalytic efficiency and reactivity, making them valuable in a wide range of applications (Shamhari *et al.,*2018). The most common use of ZnO nanoparticles is in sunscreen (Smijs and Pavel, 2011). They are employed for their excellent UV light absorption capabilities, while their wide bandgap ensures full transparency to visible light, making them ideal for applications needing invisible UV shielding (Smijs and Pavel, 2011; Osmond and Mccall, 2010). They are also being explored for their antimicrobial properties in packaging and use in UV-protective materials like textiles, enhancing both safety and functionality (Singha *et al.,*2020; Mousa and Khairy, 2020).

Zinc oxide nanoparticles were green synthesised using *Syzygium aromaticum* (clove) extract and zinc nitrate, followed by calcination at 400°C. UV–Vis showed a peak at 376 nm; TEM revealed 10–30 nm spherical particles. The nanoparticles exhibited strong antibacterial activity, making this eco-friendly method effective, sustainable, and suitable for biomedical applications (Naiel *et al.,* 2022)

Copper nanoparticle (CuO)

A copper nanoparticle is a nanoscale particle composed of copper, typically ranging in size from 1 to 100 nanometers. (Din, *and* Rehan, 2017Copper nanoparticles can be chemically synthesised, with one approach involving the reduction of copper hydrazine carboxylate in an aqueous solution under reflux or ultrasonic conditions within an argon environment, resulting in the formation of copper oxide or metallic copper clusters. (Dhas *et al.,*1998; Rani, 2015).

Copper oxide nanoparticles were green synthesised using *Calotropis gigantea* leaf extract and copper sulfate solution. The mixture was stirred and heated at 80°C for 2 hours, forming CuO NPs. UV–Vis showed absorption at 285 nm; XRD confirmed crystalline nature with ~18 nm size. The nanoparticles exhibited strong antimicrobial activity, proving this eco-friendly method effective and sustainable (Alhalili, 2022).

Gold Nanoparticles (AuNPs)

Gold nanoparticles (AuNPs) are nanoscale particles composed of gold, known for their distinctive physical and chemical characteristics. They possess the ability to absorb and scatter light across the visible and near-infrared spectrum. (Rad *et al.,*2011; Compostella *et al.,*2017).

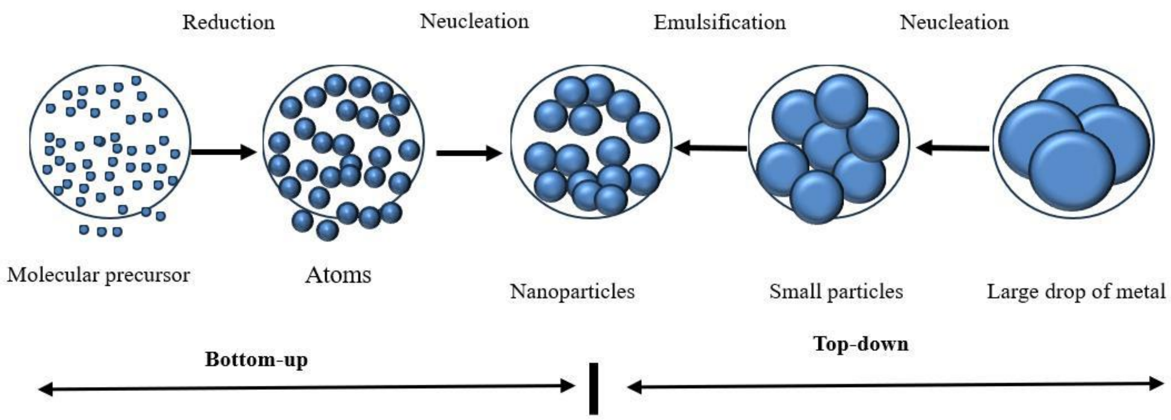
The synthesis of gold nanoparticles began in 1951, when Turkevich employed sodium citrate as a reducing agent to produce them. Since that time, various other reducing agents—such as gallic acid, hydrogen peroxide, and hydrazine—have been utilised by researchers. Subsequently, Brust Schiffrin introduced a two-phase synthesis method in 1994, further advancing the field. However, the use of agents such as citric acid, sodium borohydride ($NaBH_4$), polyethene glycol (PEG), hexadecyltrimethylammonium bromide (CTAB), trioctylphosphine (TOPO), and oleylamine (OAm) poses concerns due to their toxic, irritating, flammable, or environmentally hazardous nature. As a result, greener synthesis approaches have recently emerged, utilising eco-friendly alternatives like plant extracts, bacteria, yeasts, fungi, and enzymes in place of conventional chemical reducing agents. (Kalimuthu *et al.,*2020; Fan *et al.,*2020)

Synthesis of nanoparticles

The functionality of nanoparticles is strongly influenced by their synthesis methods. Therefore, a discussion of the synthesis approaches is imperative for a comprehensive understanding.

The nanoparticles are synthesised by various methods that are categorised into bottom-up or top-down methods.

Top-Down and Bottom-Up Approaches



1. Top-down synthesis

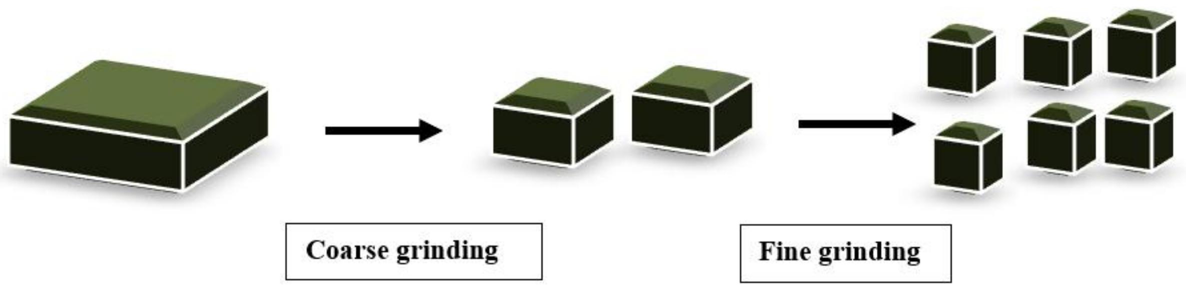
In top-down synthesis, a larger bulk material is broken down into smaller molecular units, which subsequently convert into nanoparticles. Techniques such as grinding, milling, and physical vapour deposition are commonly used in this approach, as they involve the disintegration of larger structures into nanoscale particles (Iravani, 2011)

A. Mechanical milling

Among the diverse top-down techniques, mechanical milling stands out as the most widely utilised method for producing a range of nanoparticles. This process involves the milling and subsequent annealing of nanoparticles, where various elements are ground together under an inert atmosphere to prevent unwanted reactions during synthesis (Yadav *et al.,*2012)

Mechanical milling involves the use of balls enclosed within containers and is typically performed using high-energy systems such as planetary or shaker mills. This impact-driven process delivers intense energy, facilitating the breakdown of materials into nanoscale particles (Gorrasi and Sorrentino, 2015). Ball-milled carbon nanomaterials represent a distinctive category of nanoparticles with promising potential to address critical demands in energy storage, energy conversion, and environmental remediation. Their unique structural and functional properties make them highly versatile for advanced technological applications (Yadav *et al.,*2012; Lyu *et al.,*2017).

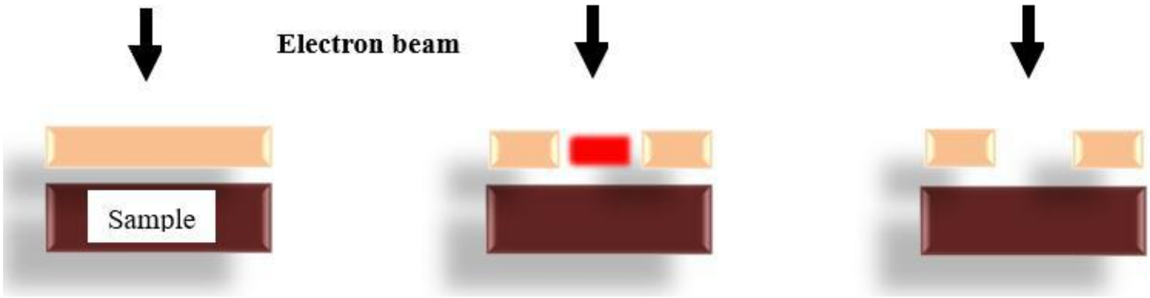
Basic material



B. Lithography

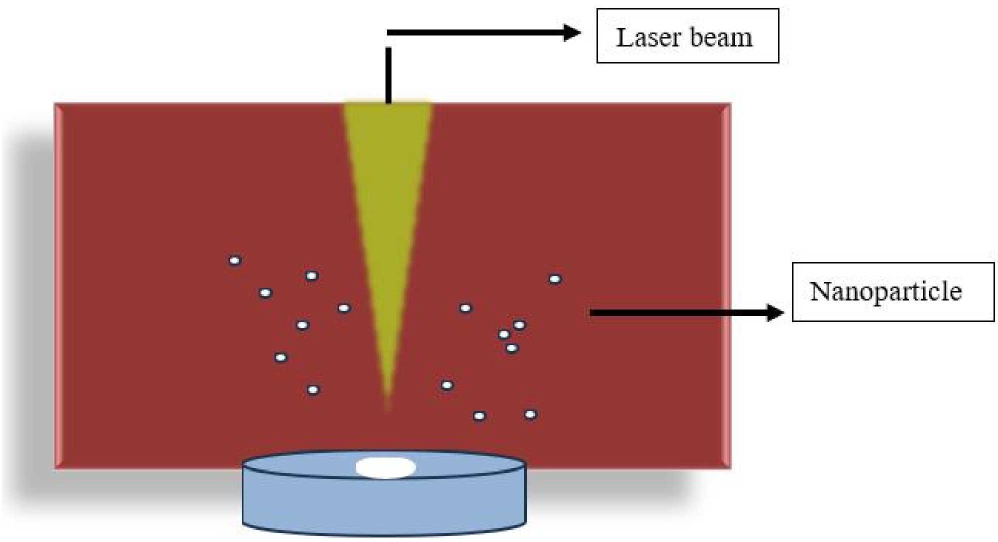
Lithography is a technique used to pattern specific shapes or structures onto a light-sensitive material by selectively removing portions to form the desired design. One of the key advantages of nanolithography is its precision in fabricating anything from a single nanoparticle to organised clusters with controlled shape and size. However, its limitations include the need for sophisticated, complex equipment and the high costs involved in the process (Hulteen *et al.,*1999)

Lithography commonly employs a focused beam of light or electrons to fabricate nanoparticles, making it a valuable and precise technique in nanoscale manufacturing (Pimpin and Srituravanich, 2012). Lithography is primarily divided into two main types: masked and maskless. In maskless lithography, nano-patterns can be directly printed without the use of a physical mask, allowing for greater design flexibility. This method is also cost-effective and relatively simple to implement (Brady *et al.,*2019).



C. Laser ablation

Laser ablation synthesis in solution is an efficient and straightforward method for producing nanoparticles using various solvents. When a laser beam irradiates metal targets submerged in a liquid medium, it generates a plasma plume that condenses to form nanoparticles (Amendola and Meneghetti, 2009)

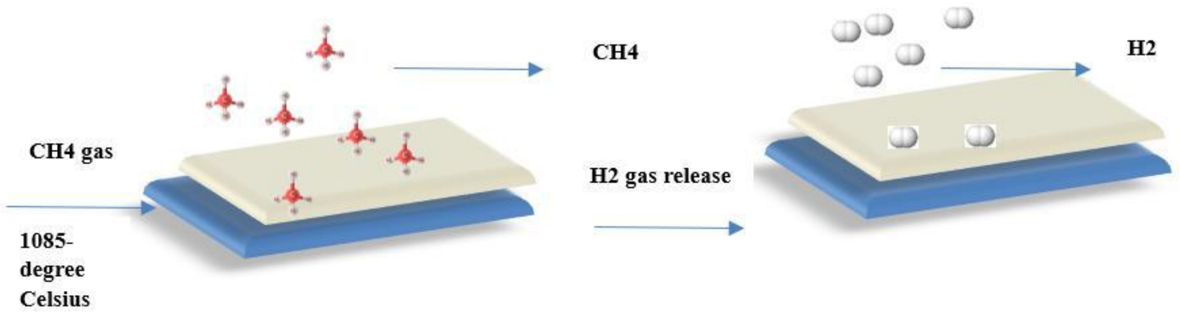


2. Bottom-up approach

The bottom-up approach is generally preferred for synthesizing nanoparticles in food-related applications, as it offers superior control over particle size and surface structure compared to other methods (Khan *et al.,*2019). The bottom-up approach enhances particle size uniformity and distribution stability by utilizing self-assembly processes of the constituent materials (Sinha *et al.,*2013)

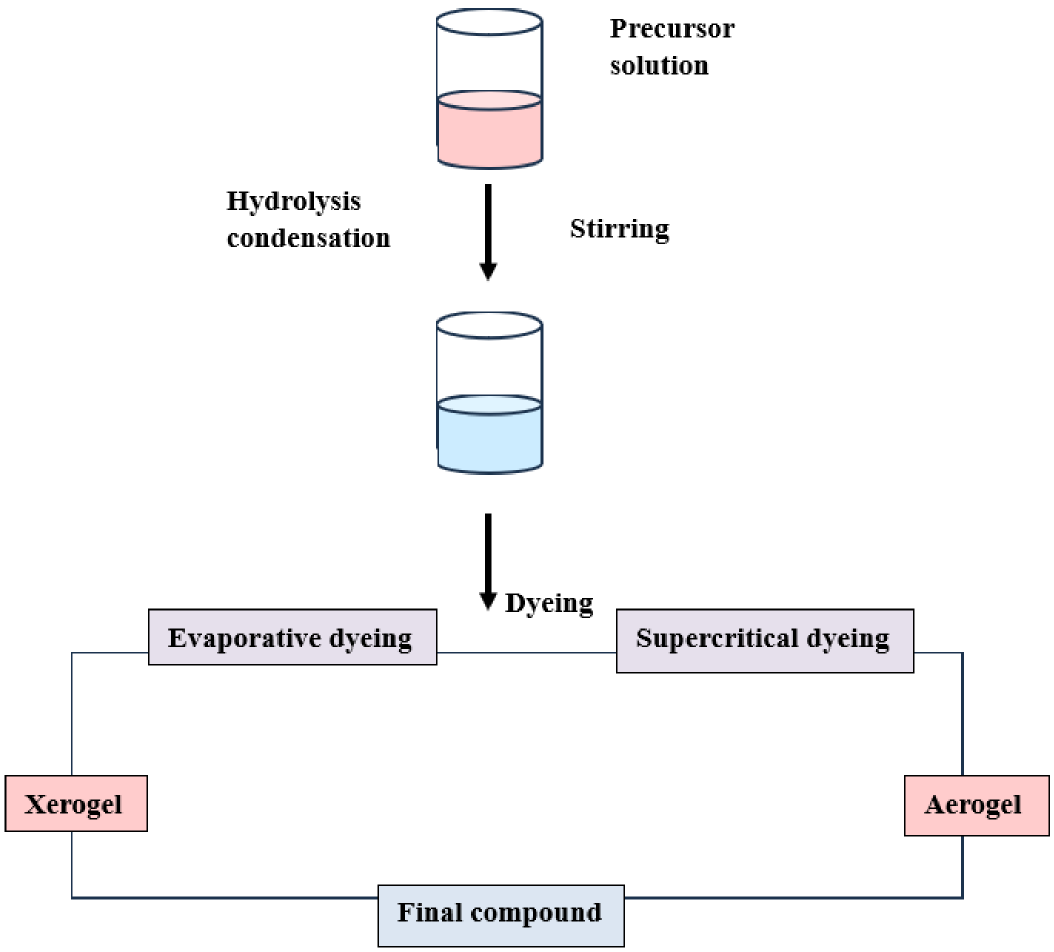
1. Chemical vapor deposition (CVD).

Chemical Vapor Deposition (CVD) forms a thin film on the surface of a substrate through a chemical reaction involving vapor-phase precursors (Dikusar *et al.,*2009). Precursors are considered suitable for Chemical Vapor Deposition (CVD) if they possess high volatility, exceptional chemical purity, stable evaporation properties, low cost, non-toxic nature, and an extended shelf life. Moreover, their decomposition should not result in any residual contaminants. Variants of CVD include vapor phase epitaxy, metal-organic CVD, atomic layer epitaxy, and plasma-enhanced CVD. One of the key advantages of this technique is its ability to produce nanoparticles that are highly pure, uniform, robust, and structurally consistent. (Ago, 2015). Chemical Vapor Deposition (CVD) is a highly effective method for producing nanomaterials of exceptional quality (Machac *et al.,*2020). It is also widely recognized for its capability to fabricate two-dimensional nanoparticles with precision and consistency (Baig *et al.,*2021).



2. Sol-gel process

The sol-gel method, a wet-chemical technique, is extensively employed for the synthesis of nanomaterials (Das and Srivasatava, 2016; Baig *et al.,*2021). In the sol-gel process, metal alkoxides or metal-based precursors in solution undergo hydrolysis, condensation, and thermal decomposition, forming a stable sol or colloidal solution. As hydrolysis and condensation progress, the gel's viscosity increases. Particle size can be precisely controlled by adjusting factors such as precursor concentration, pH, and temperature. During the maturation phase, which may take several days, the solvent is gradually removed, Ostwald ripening occurs, and phase transformations facilitate the formation of a solid structure. Unstable chemical components are separated in the process, and the resulting nanomaterial is eco-friendly, offering numerous advantages through this sustainable synthesis method (Patil *et al.,*2021). The sol-gel technique offers numerous advantages, including the ability to produce materials with uniform quality, operate at relatively low processing temperatures, and the simplicity of fabricating composites and intricate nanostructures with precision and efficiency (Parashar *et al.,*2020).



3. Biosynthesis

Biosynthesis is an eco-conscious and sustainable method for producing nanoparticles that are both non-toxic and biodegradable, making it a highly environmentally friendly alternative to conventional synthesis techniques (Bhardwaj *et al.,*2020). Eco-friendly green synthesis of nanoparticles involves using natural precursors in place of traditional chemicals for both bioreduction and capping processes. The nanoparticles produced through this biosynthetic route possess distinctive and improved properties, making them highly suitable for a range of biomedical applications (Hasan, 2015).

(Oves *et al.,*2022) Employed a bottom-up synthesis strategy and demonstrated that silver nanoparticles (AgNPs) produced using *Conocarpus lancifolius* fruit extract present a sustainable, environmentally friendly substitute for traditional chemical synthesis methods. Characterisation through UV-Vis spectroscopy, XRD, TEM, and FT-IR revealed that the AgNPs were spherical with an average particle size of 26.28 nm.

Approach	**Method**	**Nanoparticles**
Top-down synthesis	Mechanical milling	Metal, oxide and polymer-based
	Lithography	Metal based
	Laser ablation	Carbon and metal oxide-based
Bottom-up synthesis	Chemical vapor deposition (CVD).	Carbon and metal-based
	Sol-gel process	Carbon, metal and metal oxide based
	Biosynthesis	Organic polymers and metal-based

Different analytical techniques and their purposes in studying nanoparticles

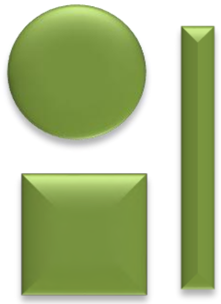
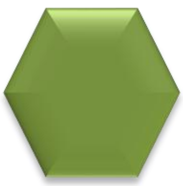
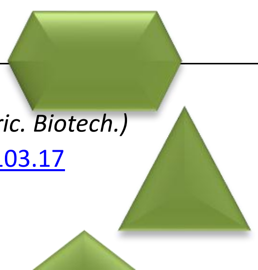
Characterization of nanoparticles is crucial for evaluating their structure, size, and other properties. The following analytical techniques provide insight into these attributes.

Name of test	**Objective**	**References**
Particle size analyser (PSA)	Utilized to assess the particle size distribution within a given sample.	(Gee *and* Bauder, 1986).
X-ray diffraction XRD	Employed for the characterisation of nanopowders of various sizes, it offers valuable insights and aids in linking microscopic observations with the properties of the bulk material.	(Holder *and* Schaak 2019).
Transmission electron microscopy (TEM)	Captures high-resolution images using a light microscope and is commonly used to examine the structure and detect the presence of nanoparticles.	(Liu, 2005).
Scanning electron microscope (SEM)	Provides a three-dimensional view based on how the electron beam interacts with the surface of the specimen.	(Goldstein *et al.,*2017).
Scanning tunnelling microscopy (STM)	Used to investigate the local electronic structure of metal nanoparticles, along with analysing their presence and overall structural characteristics.	(Kano *et al.,*2015).
Ultraviolet-visible spectroscopy (UV-Vis)	Employed for the optical analysis of materials and to confirm the successful synthesis of nanoparticles.	(Rathod *and* Waghuley, 2015).
Fourier transform infrared spectroscopy (FTIR)	Used to analyse the surface chemistry of metal nanoparticles. It helps identify organic, inorganic, and polymer-based materials by scanning samples with infrared light and is also effective in detecting functional groups within the material.	(Dutta, A. 2017).
Zeta potential instruments/zeta potential	Measures the electrical charge on the surface of particles suspended in a liquid and is used to assess the stability of metal nanoparticles in solution.	(Doane *et al.,*2012).

Field emission scanning electron microscope (FESEM)	Employed to obtain detailed images of the microstructure of materials.	(Cik *et al.*,2015).
Nanoparticle tracking analysis (NTA)	Utilised to determine the size distribution of nanoparticles in liquid suspensions, analysing numerous particles individually and simultaneously on a particle-by-particle basis.	(Gross *et al.*,2016)
Centrifugation	Used to isolate the synthesised nanoparticles from the reaction mixture.	(Kahnouji *et al.*,2019)

Characteristics of metal-based nanoparticles

A deeper understanding of the behavior and effectiveness of nanoparticles requires an analysis of their physical and chemical characteristics.

Nanoparticles and its Size	**Shape of Nps**		**Aspect ratio**	**Surface area**	**Solubility**	**Optical property**
AgNp 1–100 nm (Graf *et al.*,2003) (Sriram *et al.*,2012).	Spheres (diameter 40–80 and 120–180 nm; two different samples), platelets (20–60 nm), cubes (140–180 nm), and rods (diameter 80–120 nm, length > 1000 nm (Helmlinger *et al.*,2016)		AgNPs synthesized with 40, 80, and 120 mM Fe3+ have aspect ratios 490, 1156, and 236, respectively (Saw *et al.*,2019).	23.81 m2/g (Zhou *et al.*,2009).	Excellent water solubility and long-term colloidal stability. (Jana *et al.*, 2007; Rahmati-Abkenar and Manteghian, 2020.)	Highly reflective, can be made transparent (Stepanov *et al.*,2011).
ZnO 1–100 nm (Khan *et al.*,2019).	Hexagonal pyramid-shaped (Thirugnanasambandan *et al.*,2021)		For rod-shaped ZnO nanoparticles is approximay 6 (Wang *et al.*,2018).	64.4 m 2 g (Bai *et al.*,2011)	0.3–3.6 mg/L in aqueous medium (Siddiqi and Husen, 2016).	high optical transparency and Luminescence (Swati *and* Mahendra, 2015). E_g=3.14 eV. (Katiyar *et al.*,2018)
CuONp 1–100 nm (Khan *et al.*,2019).	spheres, rods and spindles (Thit *et al.*,2015)		For copper nanowires (CuNWs), range from 500 to 1666 (Saw *et al.*,2019)	5–10 m2 /g (Ndolomingo and Meijboom, 2016)	Minimal Cu solubility is found at pH 9–11, although above pH 11, CuO solubility increases slightly due to complexing with hydroxide ions (Hortin *et al.*,2020).	have maximum absorption in the ultraviolet range E_g = 2.74 eV. (AI *et al.*,2023)
AuNp	triangular, pentagonal,		For gold nanorods	5.8–107 m2 /g	AuNPs have great solubility in	Highly reflective

1–100 nm (Khan *et al.,*2014)	hexagonal, and spherical (Hammami *and* Alabdallah, N. M. 2021).		ranged from 1.83 to 5.04 (Feng *et al.,*2015)	(Ahmad *et al.,*2014)	organic solvents such as toluene, while the hydrophilic (1-mercaptoundec-11-yl) tetraethyleneglycol functionalized gold nanoparticles dissolve in water and alcohols (Guo *et al.,*2015).	(Stepanov *et al.,*2011).

Types of nanoparticles	**Green synthesis**	**Chemical Synthesis**
AgNp	Silver nanoparticles synthesized using $AgNO_3$, $NaBH_4$, and chitosan showed strong stability. Low molecular weight chitosan produced ~4–6 nm uniform particles. TEM, UV-vis, and zeta potential confirmed excellent dispersion, size control, and long-term colloidal stability, highlighting their potential in biomedical and environmental applications (Kulikouskaya et al., 2022)	Silver nanoparticles (9–30 nm) were synthesized and characterized using UV-Vis, TEM, EDX, and HEED. Smaller particles (9, 11 nm) showed strong antibacterial activity against MRSA, S. aureus, E. coli, and P. aeruginosa, proving size-dependent antimicrobial effectiveness at low concentrations (Guzmán et al., 2009)
ZnONp	Aloe vera-mediated ZnO nanoparticle synthesis achieved ~100% yield in 6 h with 25% extract. Particles (25–55 nm) showed strong UV absorption (358–375 nm), PL emission shift, wurtzite structure, bio-organic capping, and antimicrobial potential, confirming suitability for biomedical and optoelectronic applications (Sangeetha et al., 2011)	This study compares green and chemical synthesis of ZnO nanoparticles. Green synthesis using *Coriandrum sativum* produced purer, smaller (66 nm) particles with better crystallinity, while the chemical method yielded larger (81 nm), flower-like structures. The green method proved eco-friendly, cost-effective, and scalable (Gnanasangeetha and Sarala Thambavani, 2013)
CuNp	This study demonstrates a green, eco-friendly synthesis of stable, cubical copper nanoparticles (CuNPs) using *Azadirachta indica* leaf broth. Optimal conditions included 20% broth, 7.5×10^3 M $CuCl_2$, 85 °C, and ph 6.6, yielding 48 nm, crystalline, monodispersed CuNPs (Nagar and Devra, 2018)	Copper nanoparticles were synthesised using ascorbic acid. Optimal results appeared at 60 min (red colour, stable), ph 10 (plasmon peak at 573 nm), and PEG: Cu^{2+} ratio 18:1 (smallest, uniform particles, ~10–20 nm, minimal aggregation by TEM) (Dang et al., 2011)
AuONp	This study synthesized gold nanoparticles (GNPs) using four plant extracts. UV-vis peaks appeared at 535–538 nm (SO, LC, PeG) and 568 nm (PuG). DLS showed PuG had larger particles (30–70 nm), others had 1–8 nm. GNPs were stable, biocompatible, and gold-confirmed by EDS(Elia et al., 2014)	This study reports the chemical synthesis of gold nanoparticles from copper anode slime using sodium citrate and VenMet solution. Results showed particle size reduced from 700 nm (cubic) to 10–35 nm (spherical) at 45 °C and 1200 rpm, confirmed by SEM, DLS, TEM, EDS, and XRD (Abkenar and Naderi, 2016).

Varied applications of metallic nanoparticles

The distinctive properties of nanoparticles translate into a wide array of applications, particularly in the textile sector. The following section outlines these applications in detail.

Silver Nanoparticles (AgNPs)

Antimicrobial Properties: Prevent bacterial and fungal growth, making fabrics ideal for medical textiles, sportswear, and undergarments.

Odour Control: Reduce unpleasant odours caused by microbial activity.

(Zhang *et al.,*2009) state that nano-silver colloidal solutions, synthesised using $AgNO_3$ and $HBP-NH_2$ at room temperature, exhibit excellent stability and antimicrobial properties. The silver nanoparticles, averaging 18 nm, were effectively fixed onto cotton fabric, as confirmed by SEM and XPS analysis. The treated fabric demonstrated over 98.77% bacterial reduction against *S. aureus* and *E. coli* even after 20 washes. $HBP-NH_2$ played a crucial role as a reducing, stabilising, and binding agent. This study confirms the durability and effectiveness of AgNPs in textile applications. Nano-silver-treated fabrics hold great potential for medical and functional textile industries.

(Velmurugan *et al.,*2014) revealed that green-synthesized silver nanoparticles (AgNPs) provide strong antibacterial properties for textile and leather applications. These nanoparticles prevent bacterial adhesion, reducing odor and infection risks in shoes and socks. AgNPs penetrate bacterial membranes, disrupting cellular functions and ensuring prolonged antimicrobial activity. Their high surface area enhances effectiveness compared to bulk silver. A simple coating method allows easy integration into fabrics and leather. Further research is needed to optimize long-term performance for commercial applications.

2. Zinc Nanoparticles (ZnO NPs)

UV Protection: Absorb harmful UV rays, enhancing sun protection in outdoor and sportswear.

Self-Cleaning Textiles: Used in smart and functional clothing to reduce washing frequency.

(Fouda *et al.,*2018) revealed that biosynthesized ZnO nanoparticles (ZnO-NPs) offer effective antibacterial and UV-protective properties for medical textiles. Using *Aspergillus terreus* AF-1, ZnO-NPs were successfully synthesized without toxic chemicals, ensuring eco-friendliness. The nanoparticles exhibited strong antibacterial action, inhibiting *Staphylococcus aureus*, *Bacillus subtilis*, *Pseudomonas aeruginosa*, and *E. coli*. Cotton fabrics treated with ZnO-NPs showed over 82% bacterial inhibition and enhanced UV protection. These findings highlight ZnO-NPs' potential for safe and multifunctional textile applications. Further research is needed to refine their biocompatibility and long-term stability.

(Dejene *and* Geletaw 2024) state that green-synthesized ZnO nanoparticles (ZnO-NPs) offer eco-friendly self-cleaning properties for textiles. These nanoparticles enable physical, chemical, and biological self-cleaning, mimicking lotus leaf surfaces, degrading stains via photocatalysis, and exhibiting antibacterial effects against *S. aureus* and *E. coli*. ZnO-NPs effectively remove dirt, dyes, and liquids while maintaining environmental sustainability. Such textiles align with market demand for sustainable products with vast application potential. However, further research is needed to enhance their durability and comfort for long-term use.

3. Copper Nanoparticles (CuNPs)

Antiviral and Antimicrobial Effects: Effective against bacteria, fungi, and viruses, making them suitable for hospital textiles and PPE.

Conductivity: Used in smart textiles for wearable electronics and sensors.

(Sharaf *et al.,*2016) revealed that CuO-PANI-treated cotton fabric enhances conductivity and antibacterial properties. CuO ensures uniform PANI distribution, with CuO-pretreated samples showing the highest conductivity and superior antibacterial activity.

4. Gold Nanoparticles (AuNPs)

Biomedical Textiles: Incorporated into wound dressings for enhanced healing and biocompatibility.

Smart Textiles: Enable sensing and diagnostic applications due to their excellent conductivity.

(Silva *et al.,*2019) revealed that AuNPs-chitosan-coated soybean fibres exhibit strong antimicrobial properties, UV protection, and washing durability. XPS confirmed AuNPs binding to chitosan, suggesting antimicrobial action through oxidized Au species and reactive oxygen generation.

(Chan *et al.,*2016) revealed that AuNP-treated fabrics obey Ohm's law and hold potential for wearable sensors. Silk fabric showed promise as a chemical sensor for ethanol vapor detection. Further research is needed on fabric durability and broader chemical sensitivity. Future work aims to develop specialized sensing devices.

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