

Comprehensive Review of Nanomaterials Synthesis Methods, Characterization and Multifaceted Applications in Medical Field

Malvika Chaudhary^{1*}, Sobinder Singh², Sachin Dhull³, Rekha Tripathi⁴,
Rashmi Gupta⁵, Sarita Pundhir⁶, Alka Srivastava⁷

Abstract

Nanomaterials associated by special qualities derived from their nanoscale size nanomaterials have tremendous potential in a variety of industries like, medicine & healthcare. Due to today busy life & unhealthy life schedule many abnormal cell growth take place in our body & affect the other organ. Sometimes it may leads to cancer & others dangerous diseases, nanomaterials such as nanotubes, liposomes & polymeric micelles are help for designing the drugs which is used in cancer treatment. In order to use nanomaterials & their application in various field, the most important process is the synthesis & development of nanomaterials. In this chapter a thorough discussion has been done including various methods used in the synthesis of nanomaterials, their characterization techniques & applications in various field. It begins with an exploration of different synthesis approaches employed to fabricate nanomaterials, including top-down and bottom-up methods, chemical vapor deposition, and sol-gel techniques. Atomic force microscopy is a characterization techniques its able to developed not only the image of conductor & semiconductor surface but also develop a high resolution image of any type of surface like glass, polymer & composite etc. Transmission electron microscopy (TEM), one lakh times magnified image of the parent materials, in the same way scanning electron microscopy (SEM), develop 3 lakh times high resolution & magnified image of the samples. These characterization technique enable researchers to see and examine nanomaterials structures with high resolution. The chapter then discusses the application of nanoparticles in catalysis, where their distinct chemical characteristics and high surface area-to-volume ratio provide substantial benefits. Furthermore, it examines the use of nanomaterials for drug delivery, highlighting their potential for targeted therapy and controlled release of pharmaceuticals. Finally, the chapter addresses the environmental and health implications of nanomaterials, emphasizing the need for responsible development and use of these materials to mitigate potential risks.

*Author for Correspondence

Malvika Chaudhary

^{1,3,5}Assistant Professor, Department of Applied Science, Maharaja Surajmal Institute of Technology/ Guru Gobind Singh Indraprastha University, Delhi, India.

^{2,4}Associate Professor, Department of Applied Science, Maharaja Surajmal Institute of Technology/ Guru Gobind Singh Indraprastha University, Delhi, India.

⁶Associate Professor, Department of Applied Science, Delhi Technical campus, Greater Noida, Uttar Pradesh, India.

⁷Professor, Department of Applied Science, Delhi Technical campus, Greater Noida, Uttar Pradesh, India.

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INTRODUCTION

Nanotechnology, situated at the crossroads of chemistry and nanoscience, represents a complete & important change in our methods to work with a matter at the atomic and molecular levels. In this chapter, we embark on an exploration of the transformative potential of nanotechnology, where the manipulation of materials at the nanoscale opens doors to a plethora of innovative applications. Nanotechnology is also used for the detection of

cancer, Worldwide; cancer is one of the main causes of death and low life quality [1]. Despite the development of several ways to lower mortality, alleviate chronic pain, and enhance quality of life, there is still a lack of effectiveness in these cancer treatments. Nanotechnology doing excellent in every field including electronics, biopolymer, biochemistry, defense, medical & drug delivery [2][3] But still there are lots of different view to understand that how we perfectly define the nanotechnology & their extended field. There are diversity in the definition of Nanotechnology which indicates that its cover a broad area of research, it is not a hyperbole if it is define as multidisciplinary in nature. Generally speaking, nanotechnology is the design, manufacturing, and application of nanostructures and Nanomaterials. Understanding physical attributes fundamentally is another aspect of nanotechnology and the properties of nanostructures and Nanomaterials [4]. Research on the basic connections between material dimensions and physical characteristic at the nanoscale is also known as nanotechnology. A family of Nanomaterials known as nanocomposites, they are Nanocomposites can be prepares by enclosed it closely with the metal or polymer materials with one or more nanoscale phases imbedded in them (zero, one, and two dimensions). When a matrix is form by organic and inorganic component at their molecular level, they show quite different properties than the parent materials [5][6]. These nanocomposites have excellent mechanical strength, electrical & thermal properties. This paper navigates through the captivating world of nanotechnology, uncovering its vast implications for catalysis, materials synthesis, drug delivery, and environmental remediation.

NANOMATERIAL SYNTHESIS METHODS

Nanomaterials have sparked immense interest in the world of engineering chemistry, captivating researchers and engineers with their extraordinary properties at the nanoscale. These materials boast unique electronic, optical, magnetic, and catalytic characteristics, making them invaluable across various industries. From electronics and medical devices to environmental cleanup and energy storage, nanomaterials offer versatile solutions to complex problems.

The process of creating nanomaterials entails carefully creating structures that range in size from 1 to 100 nanometers. Through the rational design of Nanomaterials a superior high surface area can be achieved [7]. This process requires precise control over composition, dimension, shape, and crystallinity to modify the characteristic of the final materials to specific applications. In this chapter, we'll explore the diverse methods used for synthesizing nanomaterials, uncovering their underlying principles, benefits, and real-world applications in engineering chemistry

BOTTOM-UP SYNTHESIS METHODS

There are many bottom-up synthesis methods to form nanomaterials; some of them are discuss here.

Sol-Gel Method

The sol-gel method is like a delicate dance, transforming a colloidal solution (sol) into a solid (gel) phase through chemical reactions or physical processes. This technique allows researchers to fine-tune the composition, size, and shape of nanomaterials by adjusting parameters such as precursor concentration, solvent composition, pH, and temperature [7]. Widely used for crafting metal oxides, silica nanoparticles, and hybrid organic-inorganic materials, sol-gel synthesis offers precise control over material properties. Chaudhary S. [8] used this Sol gel technique to make nanomatirals. One important bottom-up approach is the Sol-Gel method. Making a colloidal solution of the precursors is the first step. It then changes into a gel composed of distinct polymer particles. Colloids are created by hydrolyzing and poly-condensing precursors. "Figure 1" displays a schematic diagram. Products made from sol-gel are widely employed in thin-film technology. Compared to previous methods, this thin filmmaking is significantly simpler and less expensive. Materials generated from sol-gel are widely used in many industries, including sensors, electronics, space, energy, medical (primarily medication therapy), the glass industry, etc. The mechanism of sol-gel will be covered in this review, along with the various domains in which materials derived from sol-gel are used.

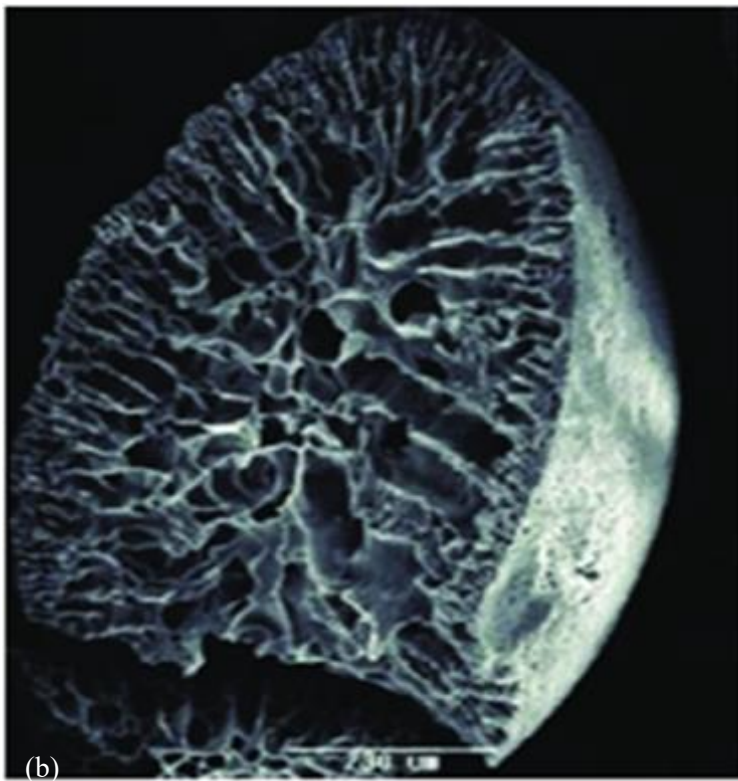
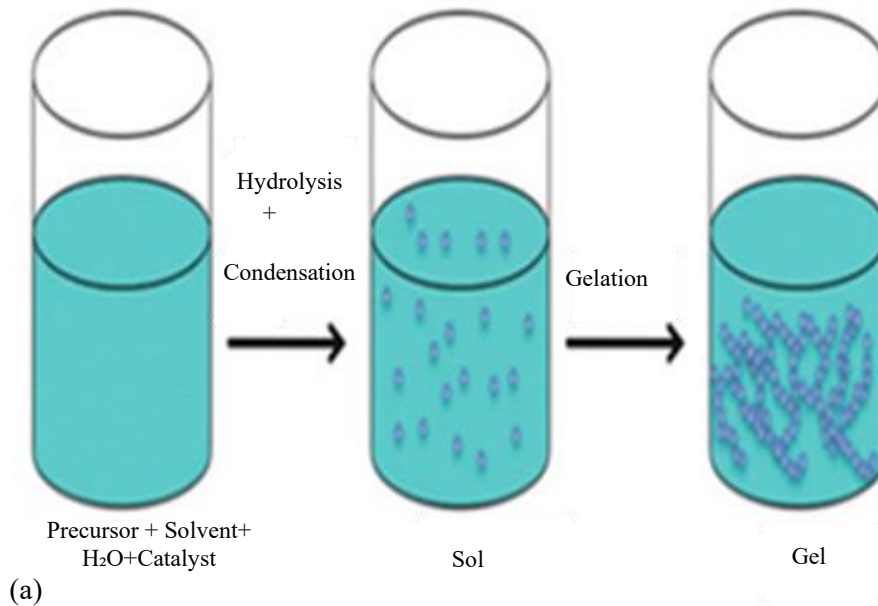


Figure 1 (a) A Sol Gel Process. **(b)** Show A Scanning Electron Microscopy Image of a Dried Gel Formed by Sol-Gel Process. The Presence of Nanoscale Porosity with a Very High Specific Surface Area Is Confirmed by This Image [8].

Hydrothermal and Solvothermal Synthesis:

Hydrothermal and solvothermal synthesis dive into the depths of high-temperature and high-pressure conditions to nurture the growth of nanomaterials from precursor solutions or suspensions. These methods empower researchers to produce crystalline nanomaterials with exact control over size, shape, and purity. While hydrothermal synthesis excels in producing metal oxides, hydroxides, and sulphides, solvothermal synthesis is ideal for crafting metal nanoparticles and carbon-based materials [9].

Chemical Vapor Deposition (CVD)

Chemical vapor deposition is like a painter's brush, delicately laying down thin films, nanowires, and nanostructures onto solid substrates. By decomposing or reacting precursor gases on a heated surface, With CVD, nanomaterials can be deposited with exact control over the composition, thickness, and crystallinity of the film [10]. Widely applied in creating semiconductor devices, carbon nanotubes, and graphene, CVD offers unparalleled precision in material synthesis.

TOP-DOWN SYNTHESIS METHODS: -

In this process the breakdown of a large material into smaller nanoscale particles take place. There are various process involved in this process like mechanical milling, lithography etc.

Mechanical Milling

Mechanical milling is akin to sculpting, grinding or chiseling bulk materials into nanoscale powders or particles. Using high-energy ball milling or attrition milling, this method breaks down larger particles into tiny fragments [11]. Figure 2 show the blend of nano composite in different phase.Mechanical milling is a versatile approach for crafting metallic nanoparticles, alloy powders, and ceramic nanoparticles with controlled size distribution and crystallinity.

Lithography

Lithography is like a precision tool, etching nanoscale features onto substrates or surfaces. By selectively removing or modifying material layers using techniques such as photolithography, electron beam lithography, and nanoimprint lithography, lithography enables precise control over feature size, shape, and arrangement.[12] Widely embraced in the semiconductor industry for creating integrated circuits, sensors, and microelectromechanical systems (MEMS), lithography drives innovation in nanotechnology. Figure 3 represent how nanosphere lithography used to creat uniform , regular alloy of nano particles of different size.

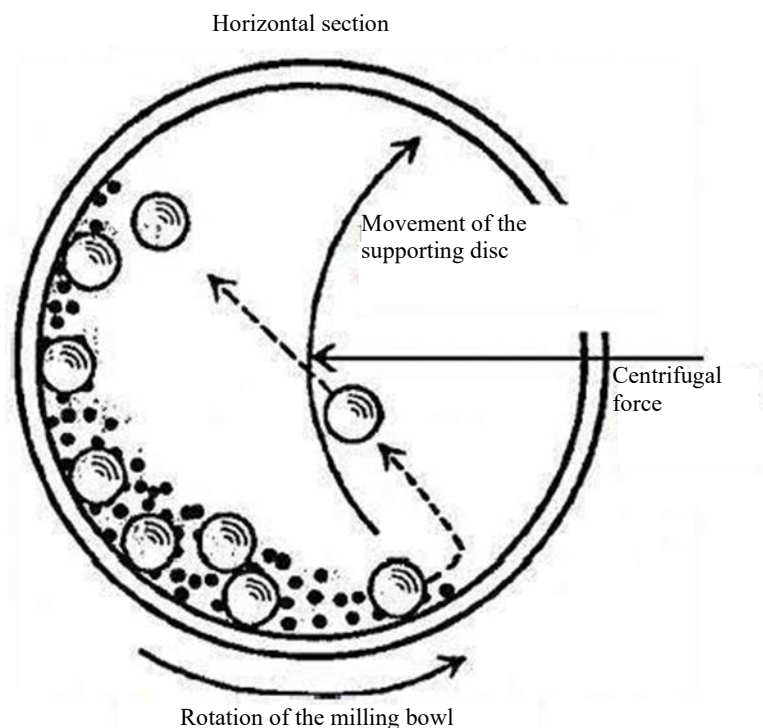


Figure 2. Mechanically Milling image for producing blend of different phases, it is used in the production of nanocomposites [11].

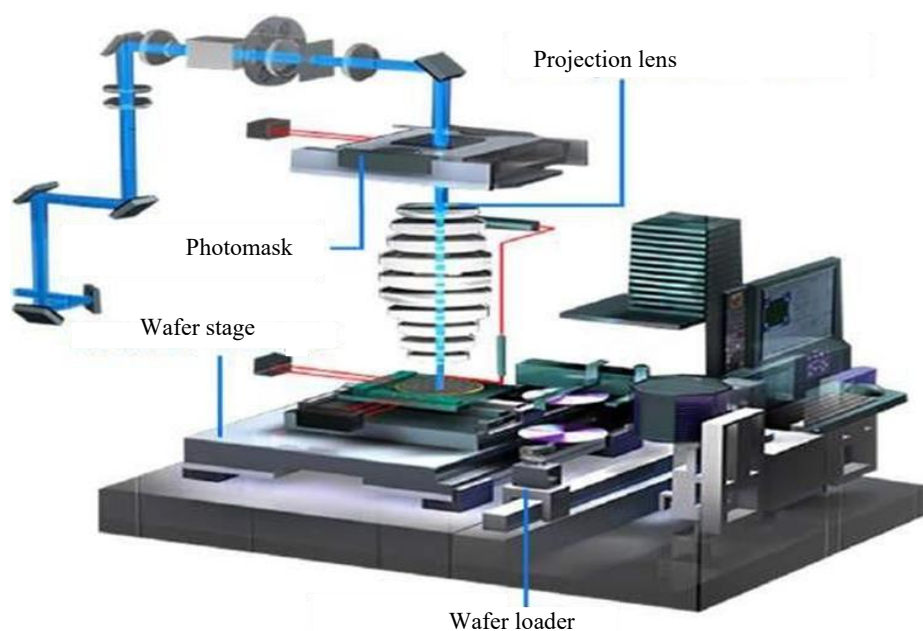


Figure 3. A Proposed low-cost production technique for creating uniform, regular arrays of nanoparticles of various sizes in Nanosphere Lithography (NSL).

Nanomaterial synthesis is at the heart of engineering chemistry, driving progress and innovation across diverse fields. By harnessing bottom-up and top-down synthesis methods, researchers and engineers can craft nanomaterials with tailored properties to tackle pressing challenges. As we journey through this chapter, we'll unravel the intricacies of nanomaterial synthesis and explore its profound impact on advancing engineering chemistry.

CHARACTERIZATION TECHNIQUES (TEM, SEM, AFM)

Characterization techniques are essential in the fields of engineering chemistry and nanotechnology, allowing researchers to explore and comprehend the structural, morphological, and chemical attributes of materials at the nanoscale. Among the plethora of methods available, transmission electron microscopy (TEM), scanning electron microscopy (SEM), and atomic force microscopy (AFM) emerge as indispensable tools for visualizing and analyzing nanomaterials with remarkable precision and details.

Transmission Electron Microscopy (TEM):-

TEM stands out as a formidable imaging technique, providing intricate insights into the internal structure of nanomaterials at the nanometer scale. Figure 4 represent TEM, it is used to get high resolution image of nano particles, By transmitting a focused electron beam through an ultra-thin specimen, TEM generates high-resolution images that unveil the morphology, crystal structure, and defects within the sample [13]. A beam of electrons is passed through an incredibly thin specimen using the transmission electron microscope (TEM) technology, interacting with the object as it does so. The interaction of the electrons passing through the specimen creates an image, which is then focused and enlarged and projected onto a layer of photographic film, a fluorescent screen, or a sensor for detection [14]. TEM can achieve resolutions down to sub-nanometre levels, allowing researchers to discern individual atoms and atomic arrangements in nanomaterials. Coupling energy-dispersive X-ray spectroscopy (EDS) with TEM enables elemental analysis and mapping of chemical composition across nanomaterials.

Characterization of Nanoparticles

TEM is instrumental in investigating the size, shape, and distribution of nanoparticles and nanostructures, aiding in synthesis optimization and understanding structure-property relationships.

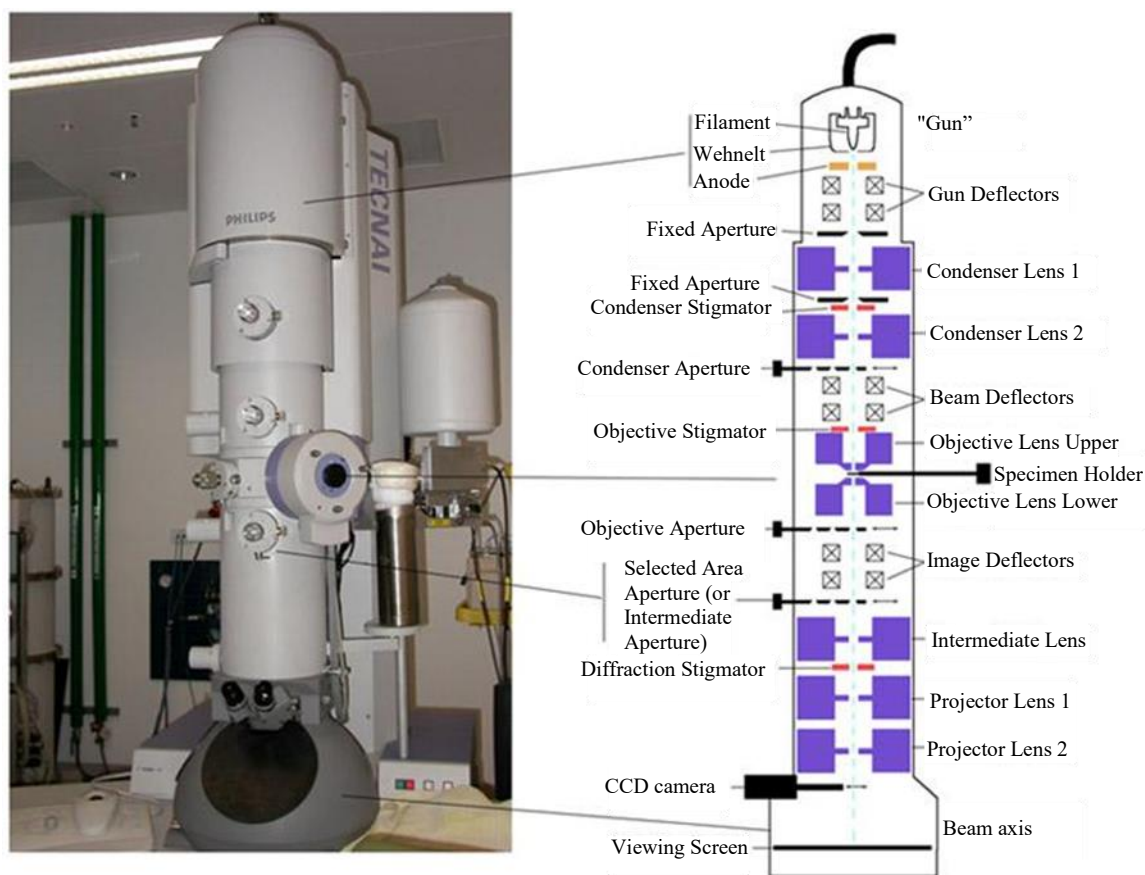


Figure 4. Original & Basic Layout Of TEM. (<https://trustrade.ae/comparison-of-tem-and-hr-tem-analysis>).

Scanning Electron Microscopy (SEM):

SEM offers versatility in visualizing surface morphology and topography of nanomaterials. Unlike TEM, SEM scans the sample's surface using a focused electron beam and detects emitted secondary electrons to generate high-resolution images. In Figure 5 SEM provides detailed views of surface features, roughness, and defects in nanomaterials. Integrated with EDS, SEM enables qualitative and quantitative analysis of elemental composition across nanomaterial surfaces. SEM facilitates the investigation of microstructure and surface properties of nanocomposites, coatings, and biomaterials, supporting materials design and optimization.

Atomic Force Microscopy (AFM):

AFM offers non-destructive imaging with high-resolution surface topography and mechanical property mapping of nanomaterials. Using a sharp probe tip mounted on a cantilever, AFM scans the sample surface, detecting interactions to generate detailed images [16]. AFM achieves sub-nanometer resolution, enabling precise visualization of surface morphology, roughness, and nanoscale features. AFM techniques such as force spectroscopy provide insights into mechanical properties like stiffness, adhesion, and elasticity of nanomaterials. AFM is pivotal in studying biomolecular interactions, polymer dynamics, and thin film morphology, supporting research in biomedicine, materials science, and nanotechnology.

In Figure 6, AFM can characterize particles that are 0.5 meters in diameter very uniquely. Naoyuki Ishida work defines that AFM has made a name for itself as a powerful tool for examining nanoparticles having different geometries, directly visualization of hydrated nanoparticles, many physical properties, surface behaviors and structures in a variety of scientific and technological research fields [18]. In addition to surface imaging, AFM may be used to measure the forces that interact between surfaces, which is significant in many fields.

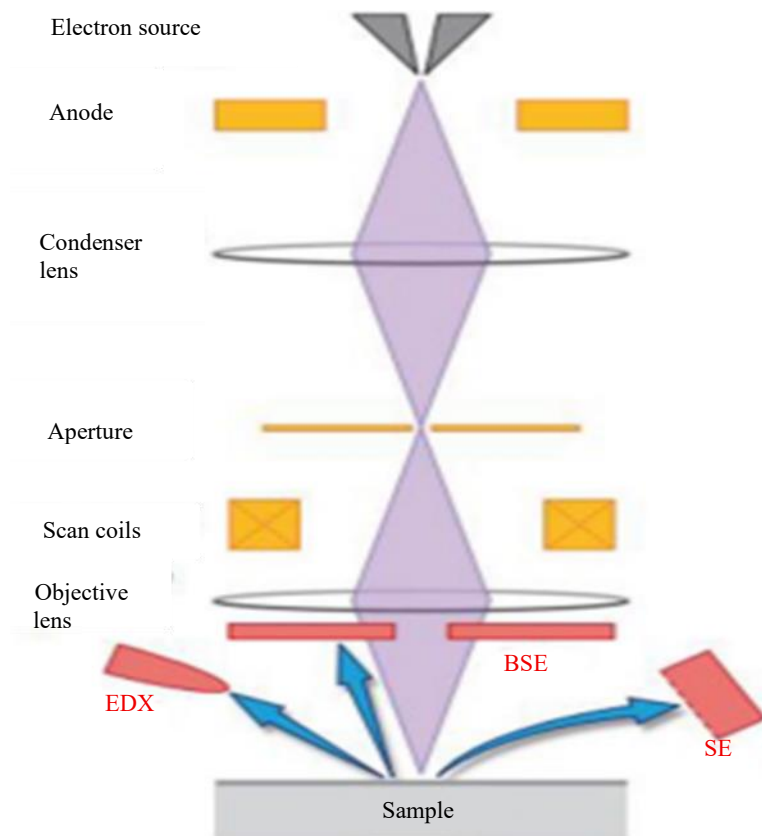


Figure 5. Parts of Scanning Electron Microscopy by AZIZ A, Shaikh S, Abbas (2025) [15]. After Cropping, The Scanning Electron Microscope Is Chosen from the Original Image.

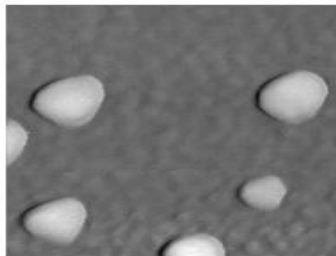


Fig.6.1 Sample of 1 nm cobalt Nanoparticles

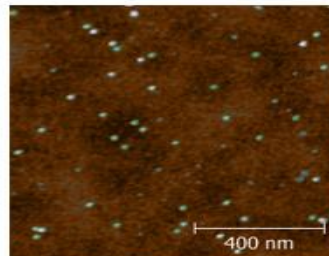


Fig 6.2 CdSe quantum dot sample deposited on a polymer film.

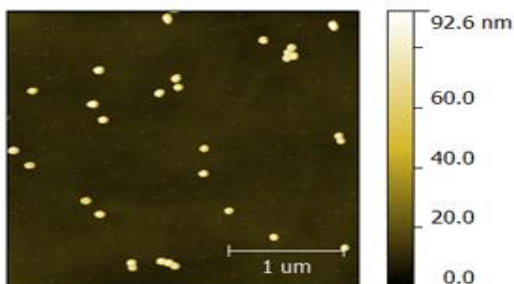


Fig 6.3 Sample of 100 nm gold Nanoparticles.

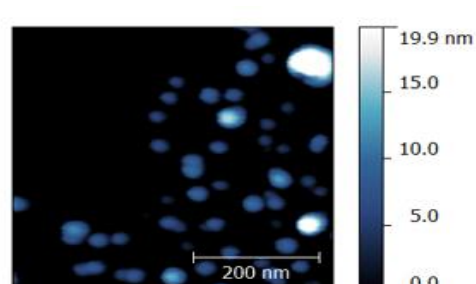


Fig 6.4 Sample of 20 nm gold Nanoparticles.

Figure 6. AFM Is Used for Nanaoparticles 3 D Characterization. The Ability of the Atomic Force Microscope to Immediately Produce Images of Nanoparticles with Sizes Ranging from 0.5 Nm To 50+ Nm is One of Its Best Features [17].

NANOMATERIALS FOR DRUG DELIVERY SYSTEMS IN THE MEDICINE FIELD

Today, nanotechnology has become very important in the field of medicine. Nanotechnology evaluates its work by understanding the atomic & molecular structure of the materials [19]. Allen S. Hoffman's Research work on Control Drug Delivery (CCD) field. This field originated in 1960 when many Implants and macroscopic "controlled drug" delivery (DD) systems were created [20]. Systems that were first postulated in the 1970s, employed in the clinic for the first time in the 1980s, matured in the 1990s, and are currently developing into many fascinating and therapeutically successful products in the 2000s marked the beginning of the nanoscopic era. Presently, these nanoscopic materials are used as a drug delivery system [21]. Nanomaterials have emerged as promising candidates for drug delivery systems in the field of engineering chemistry, offering unique advantages such as improved drug solubility, targeted delivery, controlled release, and reduced side effects.

Nanosize materials, can encapsulate medicinal substances, shield them from deterioration & effectively deliver them to particular bodily locations. The scientific scenery regarding disease management, prevention, and diagnosis is starting to shift as a result of the development of a broad range of nanoscale technologies. Figure 7 Nanoparticles Used In Drug Delivery System For Targeting The Effective Cells.

The Design & formation of nanoparticles play an important role in the drug delivery system. [22] Some nanostructures, like micelles, dendrimers and liposomes can wrap the therapeutic molecule to the targeted cell. Targeting ligands, like peptides or antibodies, can be modified into these nanocarriers to enable particular delivery to diseased tissues or cells, reducing off-target effects and improving therapeutic efficacy. Nanocarriers are microscopic drug delivery system (size 1-100 nanometer) that are intended to carry drugs to a particular human region of cell. Nanocarriers are made through nanoparticles, like lipids and polymers. Nanocarrier also reduce the toxicity of drug because they improve the therapeutic efficacy of drugs [23]. Targeted distribution is made possible by nanocarriers, which reduce exposure to healthy tissues while releasing the medication precisely where it is needed, such as in malignant areas. This focused strategy significantly lessens the adverse effects that are often connected to many powerful medications.

To overcome the biological barriers is the great ability of nanomaterials-based drug delivery system. Some time the traditionally drug delivery system isn't able to cross barriers like blood blood-brain and cellular membranes.

Nanoparticles can penetrate these barriers more efficiently, allowing drugs to reach their intended targets within the body, including the brain, tumors, inflamed tissues, and intracellular compartments.

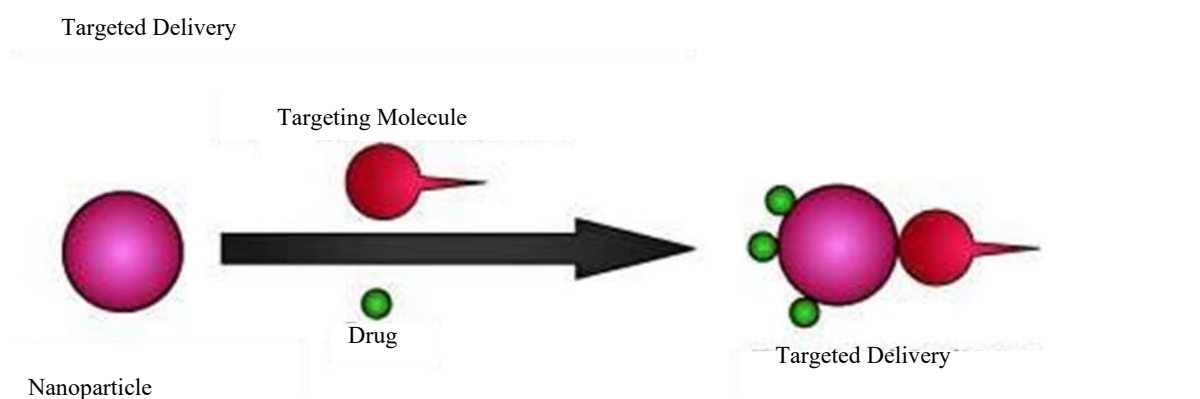


Figure 7. Nanoparticles Used in Drug Delivery System for Targeting the Effective Cells.

VARIOUS NANOMATERIALS ARE UTILIZED FOR DRUG DELIVERY, EACH OFFERING UNIQUE PROPERTIES AND ADVANTAGES:

Lipid-Based Nanocarriers:

Liposomes and lipid nanoparticles are composed of lipid bilayers or lipid cores capable of encapsulating both hydrophobic and hydrophilic drugs [24]. Lipid-based nanocarriers are biocompatible, biodegradable, and easily modifiable, making them suitable for the delivery of a wide range of therapeutics.

Polymeric Nanoparticles

Polymeric nanoparticles are fabricated from biocompatible polymers such as poly (lactic-co-glycolic acid) (PLGA), polyethylene glycol (PEG), and chitosan [25]. These nanoparticles offer controlled drug release kinetics, tunable particle size, and surface modification capabilities for targeted drug delivery applications.

Dendrimers

Dendrimers are highly branched macromolecules with a defined structure and size, offering precise control over drug loading and release kinetics. Dendrimers can encapsulate drugs within their interior void spaces or conjugate them to their surface functional groups, enabling controlled and sustained drug delivery [26].

Inorganic Nanoparticles

Inorganic nanoparticles, including gold nanoparticles, silica nanoparticles, and magnetic nanoparticles, possess unique physicochemical properties suitable for drug delivery applications. These nanoparticles can be functionalized with drug molecules or targeting ligands and offer advantages such as high drug loading capacity and stimuli-responsive drug release.

Nanomaterials for drug delivery have numerous applications in the treatment of various diseases, including cancer, infectious diseases, inflammatory disorders, and neurological disorders [27]. By improving drug bioavailability, reducing systemic toxicity, and enhancing therapeutic efficacy, nanomaterials-based drug delivery systems have the potential to revolutionize the field of medicine and pave the way for personalized and precision medicine approaches.

Above “Table 1” represents the use of nanomaterials & their application area, it also explains how nanoparticles enhance the properties of their respective field.

SUPPORTING STUDIES

Nanotechnology covers a wide area in almost every field. Apart from our research paper topic, we also done some supporting studies of nanomaterials like area to volume ratio in medical nanomaterials [38], nanocarriers in reducing drug toxicity & variation in the characteristic according to their bulk counterpart [38].

Nanomaterials show different physical, chemical & biological properties comparatively to their bulk counterpart. Due to high surface area to volume ratio a significantly higher percentage of atoms are on the surface of the substance rather than inside it when particle size drops to the nanoscale. This increases the reactivity of catalyst & surface energy.

An object's surface area in relation to its volume is expressed mathematically by the surface area-to-volume ratio (SA:V). It is computed by dividing a particle's volume by its total surface area. In terms of mathematics, given a sphere:

- **Surface area-to-volume ratio** $SA:V =$

Where r is the radius of the sphere. SA:V ratio increases as the size of the nanoscale decreases.

Nanomaterials generally have minor structural defects & tiny grain sizes which can improve mechanical strength [39], thermal & electrical characteristics.

Table 1. Use of nanomaterials in different medical fields.

Application Area	Nanoparticles Used	Applications	Properties Enhance	References
food packaging	Silver nanoparticles (AgNPs),	antimicrobial, anti-fungi, anti-yeasts, and anti-viral activities	can be combined with both non-degradable and edible polymers for active food packaging.	[28]
Agricultural & Food Industry	Silver nanoparticles (nanosilver) and copper nanoparticles (nanocopper)	antimicrobial activity	To stop the migration of nanoparticle exposure to humans.	[29]
Biomedical	lipid-based Nanoparticles	Multifunctional lipid-based nanoparticles for wound healing	Used in medicine and cosmetic practices.	[30]
Cancer Treatment	Nano structured Lipids (NSD)	chemotherapeutic agents for cancer Treatment	high toxicity and lack of specificity, which may result in severe side effects, noncompliance and patient inconvenience	[31]
Medical Field	Iron oxide nanoparticles based magnetic luminescent quantum dots (MQDs)	Nanoparticles improve contrast in imaging techniques like MRI and fluorescence microscopy, aiding in early disease detection.	Enhanced imaging contrast, site-specific targeting, improved sensitivity.	[32]
Gene Therapy	Nanoparticle-based delivery vector, like siRNS nanomedicine	Nanoparticles facilitate the delivery of genetic material into cells, offering potential treatments for genetic disorders.	Efficient gene delivery, protection of genetic material from degradation, potential to treat a variety of genetic diseases.	[33]
Tissue Engineering	Nano fibers	Nanofibers serve as scaffolds to support the growth and regeneration of tissues, including bone and cartilage.	Biocompatible scaffolds, promotion of cell growth and differentiation, potential to repair or replace damaged tissues.	[34]
Dental Health	Microrobots with nanoparticles, nanodentistry	Researchers are developing microrobots using nanoparticles to effectively remove plaque and improve dental hygiene.	Precise plaque removal, potential to automate dental cleaning procedures, improved oral health.	[35]
Neurological Disorders	Lipid nanoparticles carrying mRNA	Lipid nanoparticles have shown success in delivering treatment instructions past the brain's blood-brain barrier, which could lead to breakthroughs in treating neurological disorders.	Non-invasive delivery method, potential to treat a variety of neurological disorders, bypasses the blood-brain barrier.	[36]
Space Medicine	Nanocrystalline materials, polymer composite & nanofillers	Nanoparticles are being developed to address medical problems astronauts face on long-term deep-space missions, such as cancer-causing radiation and immune system issues.	Potential to protect astronauts from radiation-induced cancer, enhancement of immune system function, critical for long-duration space missions.	[37]

Currently, the main area of scientific research is waste management. Organic waste that is recyclable and reusable ends up in landfills, where it might be transformed into material that reinforces polymers for specific applications [40]. The polymeric system that makes up nanocomposites hydrogels is filled

with effective nanoparticles or nanostructures, which enhances their mechanical properties and adds bioactivities that regulate cell behavior [41].

Composites made of polymers based on glass and natural fibers have drawn a lot of interest because of their superior mechanical performance and combined sustainability benefits [42]. Although natural fibers like hemp, flax, and jute are lightweight and biodegradable, they frequently lack the mechanical strength of synthetic fibers.

The semiconducting characteristic of CdS nanoparticles results in improved electrical properties for polyurethane cadmium sulfide nanocomposites. Spread throughout the PU matrix, CdS adds carriers of charge that enhance dielectric property and electric conductivity [43]. The addition of CdS nanoparticles raises the composite's dielectric constant by increasing polarization in an electric field.

CONCLUSION

Nanoparticles have emerged as crucial components in revolutionizing the field of polymers, engineering, chemistry, healthcare & medicine by offering enhanced selectivity, and efficiency

compared to conventional particles. These tiny structures, typically ranging from 1 to 100 nanometers in size, exhibit unique properties due to their high surface area-to-volume ratio, surface reactivity, and quantum confinement effects. Nanoparticles serve as active sites for chemical reactions, facilitating the conversion of reactants into desired products with greater efficacy.

The utilization of nanoparticles in various applications, including environmental remediation, energy conversion, chemical synthesis, and pollution control. One of the key advantages of nanoparticles is their tunable properties, which can be tailored through precise control over size, shape, composition, and surface structure. This customization allows researchers to optimized performance for specific reactions and applications.

Several synthesis methods are employed to fabricate nanoparticles for various applications, including chemical reduction, sol-gel processes, hydrothermal synthesis, and atomic layer deposition. These techniques enable the production of nanoparticles with uniform size distribution and controlled morphology, ensuring consistent catalytic performance.

In catalytic reactions, nanoparticles exhibit unique catalytic behaviors attributed to their size-dependent electronic and chemical properties. The high surface area of nanoparticles provides ample active sites for catalytic reactions, while their small size enhances mass transport and diffusion of reactant molecules to the catalytic surface. Additionally, quantum confinement effects in nanoparticles lead to changes in electronic structure and reactivity, further influencing catalytic activity.

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