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DIVING INTO NANOSCIENCE: THE SYNTHESIS, CHARACTERIZATION, AND DIVERSE BIOLOGICAL APPLICATIONS OF SILVER NANOPARTICLES

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ABSTRACT

Nanoscience and nanobiotechnology have revolutionized the exploration of bactericidal and fungicidal properties, particularly through the utilization of silver nanoparticles (AgNPs) known for their ancient antibacterial efficacy. This review paper delves into the synthesis methods of AgNPs, emphasizing physical, chemical, and biological approaches. Physical methods like evaporation-condensation and laser ablation are highlighted alongside chemical processes such as chemical reduction and micro-emulsion. Biological methods leveraging biological organisms like bacteria and plants are also discussed. The review elucidates the importance and applications of AgNPs in various industries, including their pivotal role in antibacterial treatments, water purification, and medical devices. The synthesis methods discussed are not only cost-effective and energy-efficient but also environmentally friendly, making them conducive to medicinal applications. Additionally, AgNPs' applications in biosensors for pathogen detection, anticancer agents, and wound healing are explored.Furthermore, the paper delves into characterization techniques crucial for understanding AgNPs' properties and their applications. Various methods such as UV-Visible spectrophotometry, scanning electron microscopy (SEM), and dynamic light scattering (DLS) are discussed for characterizing AgNPs' morphology, size, stability, and surface charge.The biological applications of AgNPs are also covered comprehensively, including their antifungal, antibacterial, antiviral, anti-inflammatory, anti-cancer, and anti-angiogenic properties. The mechanisms underlying AgNPs' action against pathogens and their potential in medical treatments are elucidated, offering insights into their diverse applications in healthcare, environmental protection, and material science. Overall, this review provides a comprehensive overview of AgNPs synthesis, characterization, and biological applications, highlighting their immense potential in various industries and medical fields.

Keywords: Silver nanoparticles, Nanoscience, Antiviral properties, Anti-angiogenic properties, Nanotoxicity.

I. INTRODUCTION

Nanoscience and nanobiotechnology provided numerous chances for investigating bactericidal and fungicidal properties. Silver has been known for its antibacterial properties since antiquity, and it has been used for millennia to prevent and control a wide range of illnesses. Silver nanoparticles that have been produced and described serve an important role in current science. Recently, there has been a lot of scientific and technological interest in the synthesis and characterisation of nano-sized materials in various ranges for a variety of applications [1].Nanotechnology is the study, control, and manipulation of nanoscale materials, which typically have dimensions of less than 100 nm in at least one dimension [2].

Nanoparticles are characterized as particulate dispersions or solid particles with diameters ranging from 10 to 1000 nm. In nanotechnology, the basic unit of measurement is one billionth of a meter. AgNPs outperform silver in bulk forms principally because of their size, shape, composition, crystallinity, and structure. Physical, chemical, and environmentally friendly approaches can be used to synthesize silver nanoparticles. The physical production of silver nanoparticles is carried out using evaporation-condensation and laser ablation. Many metal nanoparticles have been created using evaporation-condensation, including fullerene, lead sulfide, cadmium sulfide, gold, and silver [3].

Some of the chemical processes used to make nanoparticles include chemical reduction, photo-induced reduction, micro-emulsion, microwave-assisted synthesis, UV-initiated photo-reduction, electrochemical synthetic techniques, and irradiation procedures. Temperature, pH, concentration, precursor type, reducing and stabilising agents, and surfactant/precursor molar ratio are some of the reaction parameters that influence how NPs form and grow in the chemical process. The use of biological organisms such as bacteria, mold, algae, and plants allows for one-step synthesis. Proteins and enzymes found in plants and bacteria are employed in the reduction process to produce nanoparticles. Silver nanoparticles act as nanoscale antennas at the plasmon resonant frequency, enhancing the strength of a nearby electromagnetic field. The plasmonic Au/Ag hollow-shelled NIR SERS probes were stacked atop silica nanospheres, causing a redshift in the plasmonic extinction band in the NIR optical window region (700-900 nm). NIR-SERS nanoprobe signals for single particle identification revealed a detectable signal in animal tissues 8 mm deep. Size-tunable absorption spectra of silver nanoparticles can be employed in point-of-care diagnostics to measure multiplex optical properties. Nanoparticles made of silver Antimicrobial, anti-neoplastic, antioxidant, and anti-diabetic properties. Silver nanoparticles are also hazardous in several ways, such as orally, immunologically, neurologically, environmentally, and reproductively [4].

II. IMPORTANCE AND APPLICATIONS OF AGNPS IN VARIOUS INDUSTRIES

Ag-NPs are among the most exciting and appealing nanomaterials for commercial applications. They have been utilized in a variety of applications, most commonly as antibacterial and disinfection agents for biological water treatment. Nanoparticle-based biosensors are utilized to detect both abiotic and biotic pollutants in the textile sector, food storage, electronic products, cosmetics, antifungals, medication applications, medical equipment, and a variety of other industries [5]. In addition, Ag-NPs are used in a variety of applications, including antibacterial treatments for water treatment, bacteria eradication, and medical devices [6-8].

So, these methods have contributed to the cost-effective and energy-efficient preparation of Ag-NPs. These methods are environmentally friendly. Because of their non-hazardous qualities, these methods are mostly advantageous for using Ag-NPs in medicinal applications. Furthermore, Ag-NPs are now exploited for biosensor and antibacterial applications; in biosensors, Ag-NPs are used to detect pathogen microorganisms in water and food [9–14]. Figure 1 illustrates some of their applications. For thousands of years, silver has been employed in a variety of antibacterial applications. Because the little Ag-NPs have a high surface area, learning about nano-silver materials is surely one of their exceptional properties. It is proposed for the interaction that provides a greater bactericidal effect than big Ag-NPs [15,16].

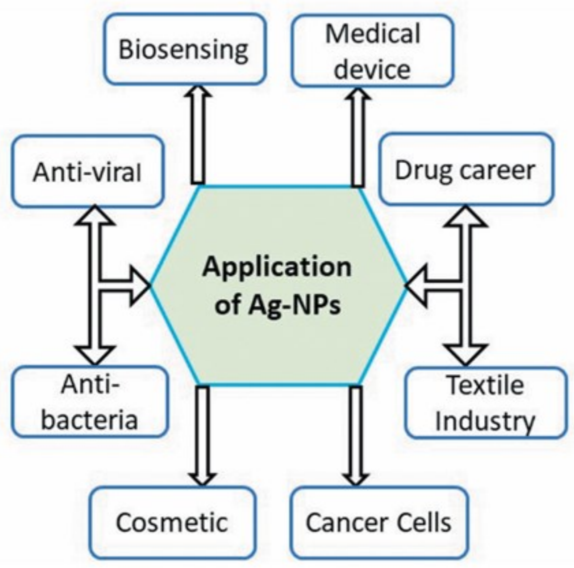

Fig.1 Schematic Scheme of application study of Ag-NPs

A few reports have been provided on the effects of Ag-NPs on viruses [17]. The Ag-NPs are also used in the rapidly growing coating and paint industries. It is utilized not just for aesthetic purposes, but also to safeguard important structures from corrosion. Cotton fibers containing Ag-NPs demonstrated excellent antibacterial activity against Escherichia coli [18,19]. Several recent investigations have claimed that inkjet technology can be manufactured in low-cost flexible electronic circuits. Because of their electrical conductivity, metal nanoparticles such as gold and silver are appropriate for the production of electronic circuits [20].

As a result of these advantages, the existing methods are practically adequate for possibly applying in big industries manufacturing with stable colloidal Ag-NPs, which are relevant in numerous sectors, particularly for medical and digital fabrication of electronic circuit applications [21,22]. Ag-NPs-rooted magnetic nanoparticles were made up of an 18 nm magnetic core and a 16 nm thick silica shell adorned on the surface of the Ag-NPs. The Ag-NPs-rooted magnetic nanoparticles were very sensitive to surface enhanced Raman spectroscopy (SERS) signals, allowing them to be used for cancer cell targeting, isolation, and imaging [23].

Similarly, easy-to-use Ag-NPs have been widely used in the healthcare business as anticancer and antibacterial agents. Surface charges of Ag-NPs have been used to test their toxicity in anti-cells [24]. However, because Ag-NPs had a positive surface charge, they could be left on the tissue surface of a blood artery for an extended period of time, which was an important avenue for managing anticancer drugs [25]. The inherent cytotoxic characteristics of Ag-NPs have been utilized to several types of cancer cells, including hepatocellular carcinoma [26], lung [27], and the worrisome cervical carcinoma and breast cancer [28]. Another study found that a specific hazardous microbe prompted the use of silver in a variety of items, including packaging materials, wound dressings, and antifouling surface coatings [29].

Another promising technique was Ag-NP-coated binding, which killed microorganisms and improved tissue repair. In addition, silver ions have been employed as antibacterial agents in dental resin composites and medical instrument coatings. The produced Ag-NPs have also been used in food packaging to help it survive longer without contamination [30].

III. SYNTHESIS METHODS

The nanoparticle production method might be "bottom-up" or "top-down" [31]. Various strategies (physical, chemical, and biological) can be used to produce particles of varying sizes during nanoparticle production. The shape and content of nanoparticles have a significant impact on their physical and chemical properties. The new "Green Synthesis" method for biocompatible nanomaterials has had a significant impact on advancements in nanotechnology and materials science. Nanomaterials can be made from natural components like cellulose and plant biomolecules [32].

Physical Method of Nanoparticle Synthesis

UV irradiation, sonochemistry, and laser ablation are all physical approaches for synthesis of nanoparticles. During the physical synthesis process, metal atoms evaporate before condensation on various supports, causing the metal atoms to congregate into tiny clusters of metallic nanoparticles. This approach allows us to produce high-quality nanoparticles with specific shapes. A typical laser necessitates unusually sophisticated equipment, materials, and significant power consumption, which adds to high manufacturing costs [33]. Physical approaches for synthesis of nanoparticles have the advantage of creating large quantities of nanoparticles; nevertheless, they have limitations in terms of form and size control.

The physical synthesis techniques are known as evaporation-condensation, physical vapour phase, laser ablation, and arc discharge. These operations can be performed in an atmospheric pressure tube furnace. The materials inside the boat are focused in the furnace, where they are quickly evaporated in a carrier gas. The evaporation/condensation process is used to make nanoparticles of various materials such as silver and gold, as well as fullerenes [34–35]. However, there are many drawbacks to generating Ag-NPs with a tube furnace, such as the fact that the tube furnace is located in a large space and the consumers require a lot of energy, whereas raising the environmental temperature near the source of material takes a long time to achieve thermal stability. Furthermore, Ag-NPs have been produced in metallic solution materials using laser ablation [36-38]. Laser ablation has an advantage over traditional approaches for producing metal colloids in the absence of a chemical reagent solution. As a result, pure colloids are ideal for advanced applications [39]. The physical energy necessary to generate Ag-NPs with a restricted size distribution are often added together throughout the Ag-NPs synthesis. The physical synthesis method enables for the production of vast quantities of Ag-NP samples in a single step. This technique is most effective for manufacturing Ag-NPs in powder form. Consequently, the fundamental cost of dealing with the equipment might be considered [40-43].

Laser ablation and evaporation/condensation are the most important physical procedures. Ag-NPs were produced using a somewhat ceramic heater with a small heating surface [44]. It was demonstrated that the laser ablation productivity for femtosecond and second ablation was lower in water than in air; however, in the case of nanosecond pulsations, the laser ablation efficiency was similar in both water and air [45]. The arc discharge procedure for producing Ag-NPs in deionized water without the need of surfactants. Silver wires (Gredmann 99.99%, 1 mm diameter) were utilized as electrodes in this synthesis after being immersed in deionized water. The silver rod consumed 100 mg/min, producing 10 nm metallic Ag-NPs and ionic silver at concentrations of around 11 and 19 mg/L, respectively [46-47]. This confirmed the production of Ag-NPs via direct metal spitting into a liquid media. The mechanism of physical deposition of metal reported by 1, 2, 3 triol (Glycerol) provides an intriguing alternative to the time-consuming wet-made chemical synthesis process. Ag-NPs have a diameter of around 3.5 nm and a standard variation of 2.4 nm, maintaining their round form. It was determined that the nanoparticle size distribution and uniform particle dispersion were uncharged when diluted in aqueous solution at a glycerol-to-water ratio of 1:20 [48].

Chemical method of Nanoparticle Synthesis

Nanotechnology appears to be a combination of chemical, biological, physical, and engineering sciences. As a result, new technologies for examining and operating single atoms and molecules are being developed for a variety of applications in material science. One of the most sought-after and rapidly expanding aspects of nanotechnology is nanoengineering and science technology [49]. Several researchers have synthesized Ag-NPs using various approaches, including physical, biological, chemical, and photochemical techniques [50]. However, each technique has advantages and disadvantages when compared to how precursor concentrations and temperature affect nanoparticle size, cost, dispersion, form, and stability. Chemical approaches have been employed as a fruitful strategy in addition to the most synthetic approach. Chemical approaches provide a straightforward and easy way to produce Ag-NPs in solution [51]. Ag-NPs are prepared via a chemical reduction methodology, an electrochemical procedure, a solution-based route, a sol gel synthesis method, a microwave process, and irradiation procedures [52].

Several reducing agents, including sodium borohydride (NaBH 4), ascorbic acid, hydrazine dehydrates, Tollens reagent, elemental hydrogen, sodium citrate, and polyethylene glycol copolymers, are used in the chemical synthesis of Ag-NPs. These decrease silver (Ag) ions in aqueous and non-aqueous solutions [53]. These agents reduce Ag + (Ag o), resulting in the synthesis of Ag with reduced ion, which agglomerates into oligomeric clusters. Finally, the clusters produce colloidal Ag metallic nanoparticles [54,55]. The chemical process for creating Ag-NPs in solution consists of three stages: a metal precursor, reducing agents, and capping/stabilizing agents. The reduction of Ag salt occurs in two stages for the development of the colloidal solution: following and nucleation growth. These procedures have a significant impact on the shape and size of synthesized Ag-NPs [56]. Furthermore, synthesizing monodispersed Ag-NPs with consistent size distribution and nuclei is critical for formulation. All nuclei have the same size and development pattern. The specified reaction parameters, such as precursors, temperature, pH, and reducing agents, can be used to determine the future growth and first nucleation of preliminary nuclei [57,58]. The simplest and most used bulk solution synthetic approach for metal nanoparticle synthesis is salt reduction [59,60]. The previous study demonstrated the synthesis of nano-scale metal Ag-NPs with variable morphology and size [61].

Because of surface plasmon resonance absorption, Ag-NP dispersions exhibit rich hues. The metal surface is identical to a plasmon with free electrons, ions in positively charged nuclei in conductive incorrect, but there was collective excitement around the surface of nanoparticles in the surface plasmon resonance with conduction band and electrons. The electrons are restricted to vibration modes appropriate for the particle size and form. As a result, the metallic nanoparticles were identified by their optical absorption spectra in the UV-visible domain. The nanoparticles were created from two-part alloys of bimetallic silver and copper (Cu) nanoparticles, with Chitosan and Starch serving as a capping agent through microwave heating. Chitosan has antibacterial properties, is suitable for human applications, and has a low toxicity. To avoid particle aggregation, the production and reduction of ions with stabilising agents are used [62].

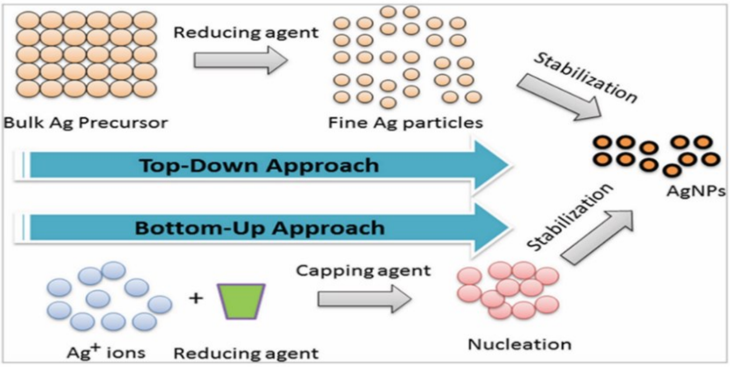

Fig .2(Schematic diagram of the synthesis process of nanoparticles.)

IV. CHARACTERIZATION TECHNIQUES

Characterization approaches for Ag-NPs are critical for understanding nanoparticle control throughout the synthesis process and their applications in a variety of industries. Several parameters were determined using various characterization methods, including UV-Visible spectrophotometer, Fourier transform infrared (FT-IR), (UV-Vis), dynamic light scattering (DLS), scanning electron microscopy (SEM), high-resolution transmission electron microscopy (TEM), atomic force microscopy (AFM), x-ray diffractometry (XRD), zeta potential analyzer, dynamic light scattering (DLS), zeta potential analyzer, energy-dispersive spectroscopy . Figure 4 depicts the schematic characterization procedures for Ag-NPs. All of these characterization methods are utilized for a variety of parameters, including determining particle morphology, crystallisation, surface charge, particle size and shape, surface roughness, surface area, and pore size. Similarly, the dispersion and orientation of nanotubes and nanoparticles in nanocomposite materials are employed to determine similar characterisation procedures. First, UV-Visible validated Ag-NP structure formation in the surface plasmon resonance band and colloidal solution [63-65]. AFM, SEM, and TEM can be used to determine the size, shape, and dispersion uniformity of the particles as well as their entire morphology and crystal structure [66,67]. The AFM deals with ultra-high resolution in particle size measurement, and it has an advantage over traditional microscopy techniques SEM and TEM in that it studied the three-dimensional images of the particles and calculated the particle's height, width, and volume to well explain the morphology [68–72]. The SEM technique is used to characterize nanoparticles by directly measuring shape and size [73]. The crystalline structure and phase purity of particles are determined using X-ray diffraction [74]. FT-IR analysis was utilized to categorize the principal functional groups as the molecular fingerprint for organic material characterization, as well as to demonstrate promising involvement in Ag-NP synthesis and stabilization [75,76]. Furthermore, EDS validated the purity of materials and chemical composition, as well as the presence of elemental silver at the nanoscale [77].

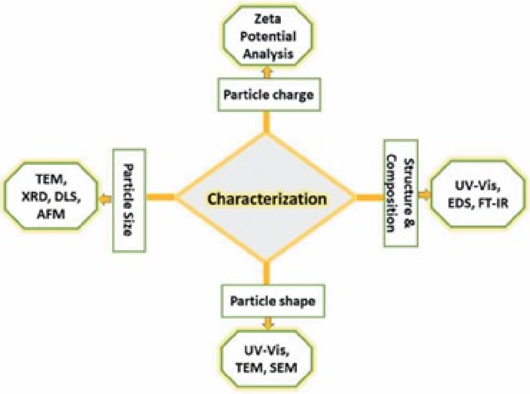

Fig.3 (Scheme techniques of the characterisation of silver nanoparticles.)

The zeta potential and DLS determine particle size, tell about the surface potential charge, and confirm particle stability, while the zeta sizer investigates mean particle size distributions. The zeta potential is important because nanoparticles interact outside the medium. Electrostatic repulsion is thought to stabilize particles with zeta potentials greater than +30 mv or less than −30 mv [78-81].

V. BIOLOGICAL APPLICATIONS OF AGNPS

Because of their unique features, AgNPs are widely used in a range of applications, including health care, home products, food storage, the environment, and biology. In biological and therapeutic applications, we are particularly interested in their antifungal, antibacterial, antiviral, anti-inflammatory, anti-cancer, and anti-angiogenic characteristics. We concentrated on seminal studies that had already been published, and we concluded with some current updates on our research. Figure 4 depicts a schematic design of various AgNP uses.

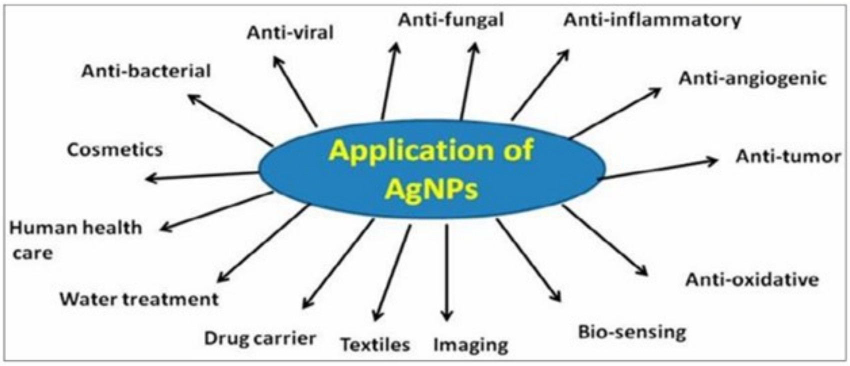

Fig 4: Representing various applications of AgNPs

Four distinct types of saccharides were employed to make AgNPs with an average particle size of 25 nm, which demonstrated to be efficient against Gram-positive and Gram-negative bacteria, as well as multi-resistant illnesses. Because AgNPs interact in a form-dependent manner with the Gram-negative bacteria E. coli, their shape and size are crucial for determining efficiency [82]. AgNPs appear to be an effective alternative to antibiotics in terms of antibacterial activity and the potential to overcome antibiotic resistance in bacteria. As a result, antibacterial agents based on AgNPs will be needed. In addition to other promising nanomaterials, AgNPs have high surface-to-volume ratios and a crystalline surface structure, making them a potential antibacterial agent [83]. The data suggest that at low dosages of AgNPs, yeast and E. coli growth is totally suppressed, but S. aureus growth is only somewhat decreased [84]. Silver nanoparticles may discharge silver ions indefinitely, perhaps killing germs. The exact process is unknown, although it is comparable to how silver (Ag) ions accumulate in the aqueous solution of Acton bacterial strains like as trypanosomes and yeasts, causing enzyme and protein saturation in the cell [85]. In a published publication, the scientists proposed a mechanism in which modifications caused by AgNPs in the cell's Wallan nucleus, as well as DNA and RNA, are the major cause of bacterial cell growth retardation. Meanwhile, Li et al. proposed three potential mechanisms for AgNP particle-induced bacterial cell death [86]. The first hypothesis is that AgNPs' adherence to the bacterial cell wall (due to their small particle size) limits bacterial cell development and proliferation, causing modifications in the cell wall such that the membrane is unable to shield the internal section of the cell. According to the scientists, the diffusion of AgNPs into the bacterial cell alters the DNA, slowing the cell's normal activity and eventually leading to death. Silver nanoparticles enter bacteria's cell walls and destroy DNA. The third hypothesis is that Ag+ ions interact with sulphur-containing proteins in the bacterial cell wall, causing the cell wall to collapse. This is assumed to be the major mode of antibacterial action [87].

Antifungal activity of AgNPs

Antiviral medications are crucial since viral-mediated diseases are widespread and becoming more common around the world. Understanding the mechanisms underlying AgNPs' antiviral action is critical for antiviral treatment. Because of various size ranges and shapes, AgNPs interact with bacteria and viruses in a unique way. Nano-Ag integrated into polysulfone ultrafiltration membranes (nAg PSf) demonstrated considerable antiviral activity against the MS2 bacteriophage, owing to improved membrane hydrophilicity [91]. The first mechanistic analysis revealed anti-human immunodeficiency virus (Anti-HIV) action at an early stage of viral replication. When AgNPs were coated with polyvinylpyrrolidone (PVP), both cell-free and cell-associated HIV-1 isolates were not transmitted. AgNPs have been demonstrated to be effective HIV and hepatitis B virus (HBV) inhibitors [92]. AgNPs have antiviral properties and have been shown to reduce the spread of the severe acute respiratory syndrome coronavirus (SARS-CoV-2) [93], It is still spreading due to a lack of effective antiviral treatments. Due to the 2019 coronavirus sickness (COVID-19), medical research, notably AgNP-related research, has increased, with daily total global cases rising. AgNPs' inhibition activity was demonstrated in a Gram-positive bacterium, S. aureus, by inhibiting the respiratory chain dehydrogenase into dihydroxyacetone through the metamorphosis of a number of enzymes, including glycerol 3-phosphated ehydrogenase, resulting in the bacteria's normal growth and metabolic activity being obstructed [94].

AgNPs preferentially attack viral surface proteins containing sulfhydryl groups, cleaving disulfide bonds and destabilizing the protein, hence affecting viral infectivity [95]. According to HIV research, AgNPs form disulfide bonds near the CD4 interaction area of the gp120 surface protein. According to Hati and Bhattacharyya, disulfide bonds play a key role in the binding of the SARS-CoV-2 spike protein to the angiotensin converting enzyme-2 (ACE2) receptor, and their elimination hampers viral attachment. Other authors discovered that AgNPs disrupt disulfide linkages on the spike protein and ACE2 receptors, resulting in antiviral action against SARS-CoV-2.Additional research is being conducted to determine AgNPs' antiviral mechanism on SARS-CoV 2 and to fully understand it later [96].

Anti-inflammatory activity of AgNPs

Tissue's early immunological reaction to foreign particles is characterized by an increase in the production of pro-inflammatory cytokines, immune system activation, and the release of prostaglandins and chemotactic chemicals such as complement factors, interleukin-1 (IL-1), TNF-, and TGF- [97]. AgNPs have lately become relevant in the realm of anti-inflammatory medications. Although AgNPs have been found to be antibacterial, their anti-inflammatory activities remain unknown. Bhol and Schechter [98] observed that it has an anti-inflammatory effect in rats, significantly reducing colonic inflammation. In mice, AgNP therapy resulted in rapid therapeutic and cosmetic improvements, which were dose-dependent. AgNPs also shown antibacterial action, reduction in wound inflammation, and cytokine modulation [99].

Anti-angiogenic activity of AgNPs

Pathological angiogenesis is a feature of cancer, as well as a number of ischemic and inflammatory illnesses.Several research organizations are working to produce new anti- and pro-angiogenic compounds for the treatment of angiogenic illnesses. Although certain synthetic drugs with anti-angiogenic properties have been identified, a more physiological approach to treating angiogenesis-dependent disorders may become available in the near future. AgNPs have recently been proven to have anti-angiogenic and anti-cancer properties in multiple studies using both in vivo and in vitro models [100].

VI. CONCLUSION

In conclusion, the field of nanoscience and nanobiotechnology has opened up numerous opportunities for exploring the bactericidal and fungicidal properties, especially with the focus on silver nanoparticles (AgNPs). Silver, known for its antibacterial properties since ancient times, has been extensively used for disease prevention and control. The synthesis and characterization of AgNPs have become crucial in modern science, attracting significant scientific and technological interest.

Various synthesis methods, including physical, chemical, and biological approaches, have been employed to produce AgNPs with desirable properties such as size, shape, composition, and crystallinity. These methods are not only cost-effective and energy-efficient but also environmentally friendly, making them advantageous for medicinal applications. Additionally, AgNPs have demonstrated diverse applications across industries, including antibacterial treatments, biosensors, healthcare, electronics, textiles, and food packaging, among others.

Characterization techniques play a vital role in understanding and controlling the properties of AgNPs, including particle morphology, size distribution, crystalline structure, surface charge, and stability. These techniques, such as UV-Visible spectrophotometry, SEM, TEM, XRD, FT-IR, and zeta potential analysis, provide valuable insights into AgNP structure and behavior.

In biological applications, AgNPs have shown promise as antibacterial, antifungal, antiviral, anti-inflammatory, anti-cancer, and anti-angiogenic agents. Their unique properties, including high surface area and crystalline structure, make them effective alternatives to traditional antibiotics and antiviral medications. AgNPs' mechanisms of action involve interactions with bacterial cell walls, disruption of viral proteins, and modulation of inflammatory and angiogenic processes.

Overall, the synthesis, characterization, and biological applications of AgNPs represent a significant advancement in nanoscience and nanobiotechnology, with potential implications for various industries and medical fields. Continued research and development in this area hold promise for addressing global challenges related to microbial infections, healthcare, environmental sustainability, and advanced materials.

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