# Impact of Nanoparticle Shape, Size, and Properties of Silver Nanocomposites and Their Applications

**Arpita Hazra Chowdhury, Rinku Debnath, Sk. Manirul Islam and Tanima Saha**

## 1 Introduction

The genesis of nanotechnology can be traced back to 1959 when in a meeting of the American Physical Society, Richard Feynman first introduced the branch of science [1]. One can define nanotechnology as the production and modification of structures which have at least one dimension less than 100 nm. The birth of nanoscience could be attributed to Michael Faraday as he had reported the intense red colour of stained glass, which originated from small particles of goldin 1857. He also reported that different size of gold particles gave rise to different resultant colours [2]. Recently, nanomaterials have emerged as very important materials in the scientific world as these act as a bridge between bulk materials and isolated atoms and molecules. They increase fractions of atoms at the surface due to their large surface to volume ratio. Nanomaterials have superior properties than the bulk substances due to the following attributes, like mechanical strength, thermal stability, catalytic activity, electrical conductivity, magnetic properties and optical properties etc. The applications of nanomaterials are continuously expanding and their applications in different fields are shown below (Fig. 1).

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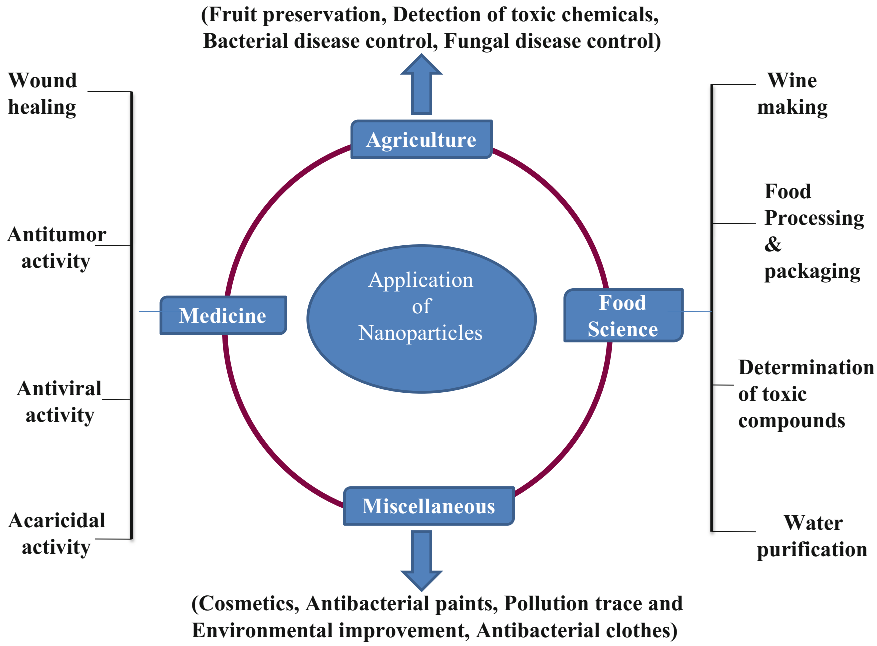



**Fig. 1** Schematic illustration of different applications of nanoparticles

Researchers have growing interest in silver nanoparticles (AgNPs) as they have remarkable localized surface plasmon resonance and antimicrobial properties, which render them with unique properties for applications in broad-spectrum surface-enhanced Raman spectroscopy (SERS) [3, 4], as antimicrobial agents [5–7], biological/chemical sensors and biomedicine materials [8–10], biomarkers [11–13] and so on. Size of AgNPs usually varies within 1–100 nm. They are incorporated into industrial applications of catalysis, electronics, and photonics as they have unique electrical, optical and thermal properties. Recently, many synthetic methods and approaches for preparing AgNPs have been reported through physical, chemical, photochemical and biological routes. Every method has its own advantages and disadvantages like costs, scalability, particle sizes and size distribution and so on [14–18].

In recent years, nanocomposite (NC) materials have drawn much attention and interest at industrial and academic level due to their improved properties than single metal nanoparticles. Nanocomposite can be defined as the combination of materials to develop new properties of the materials where one of the materials has a size in the range of 1–100 nm. So, there are two parts to nanocomposite i.e. continuous phase and discontinuous reinforcing phase. Hence, nanocomposites can have a combined or have completely different electrochemical, mechanical, electrical, thermal, optical and catalytic properties of the component materials [19–23].

There can be different phases of nanocomposites such as zero-dimensional (0D) (core-shell), 1D (nanowires and nanotubes), 2D (lamellar) and 3D (metal matrix composites) [9]. Nanocomposite materials have developed as an appropriate replacement to overcome the limitations of microcomposites and monolithic while having synthetic challenges like the control of elemental composition and stoichiometry in the nanocluster phase. Nanocomposite materials have uniqueness in design and property combinations that are not observed in conventional composites and these properties establish the nanocomposites materials as the materials of the 21st century. Even though the first speculation on these properties was reported as early as 1992 [24], the general understanding of them is yet to be established.

The focus of this chapter is on silver nanocomposite systems. These NC materials have promising properties which make them suitable for wide range of structural and functional applications in various fields.

## 2 Different Synthesis Methods of Silver Nanoparticles

Different synthesis methods and approaches for AgNPs production have been reported by using chemical, physical, photochemical and biological routes. Each method has its own advantages and disadvantages involving costs, scalability, particle sizes and size distribution and so on [14–17, 25].

### *2.1 Physical Methods*

In physical methods, metal nanoparticles are generally synthesized by evaporation-condensation, which is carried out at atmospheric pressure using a tube furnace. The source material is vaporized into a carrier gas, within a boat centred at the furnace. Different kinds of nanoparticles such as Ag, Au, PbS, and fullerene, have been produced using the evaporation/condensation technique [26–28]. Silver nanoparticles have been synthesized by laser ablation of the solution of metallic bulk materials [29, 30]. The most important advantage of laser ablation technique over another conventional method for synthesizing metal colloids is the absence of toxic chemical reagents in solutions. In summary, the physical synthesis utilizes the physical energies for preparing AgNPs with nearly narrow size distribution. The physical approach can produce large quantities of AgNPs in a single process as well as this is also the most effective method to produce AgNPs. On the other hand, primary costs for the investment of equipment have to be kept in mind before implementing such methods.

## 2.2 Photochemical Methods

This method is based on the light-assisted the reduction of the metal cation $M^{n+}$ to $M^0$. The mechanism of this method is based on the addition of one or more electrons to a photoexcited species. The aqueous and alcoholic solution of silver perchlorate ($AgClO_4$) was subjected to photoreduction by UV-light irradiation at 254 nm. This photochemical reaction involved electron transfer from a solvent molecule to the electronically excited state of $Ag^+$ to form $Ag^0$. In most of the cases, UV excitation is usually required as the metal cations and/or the metal salts absorb only in this region. This method is advantageous in harsh conditions like increased temperatures can be avoidable resulting in effective control of shape and size of Silver nanoparticle (AgNP) [31].

$$Ag^+ + H_2O \xrightarrow{hv} Ag^0 + H^+ + HO^\bullet$$
$$Ag^+ + RCH_2OH \xrightarrow{hv} Ag^0 + H^+ + R\dot{C}HOH$$
$$Ag^+ + R\dot{C}HOH \xrightarrow{hv} Ag^0 + H^+ + RCHO$$
$$nAg^0 \rightarrow AgNP$$

Various photo-induced synthetic processes have been developed recently. Huang and Yang [32] synthesized AgNPs by photoreduction of $AgNO_3$ in layered inorganic clay suspensions. This suspension acts as a stabilizing agent which prevents aggregation of nanoparticles. Light irradiation leads to the disintegration of the AgNPs into a smaller size with a single mode distribution until a relatively stable size and diameter distribution were achieved [32]. However, this method requires high-end equipment and experimental environment.

## 2.3 Biological Methods

Lately, biosynthetic methods have emerged as a facile and simple alternative to more complex chemical synthetic methods to prepare AgNPs. In biosynthetic methods, natural reducing agents like polysaccharides, biological microorganisms like bacteria, and fungi or plant extracts, i.e. green chemistry are used. This method includes a broad range of natural resources for the synthesis of AgNPs. This method has several advantages over conventional chemical routes of synthesis and it is also an environment-friendly approach as well as a low-cost technique for nanoparticle synthesis. However, the drawback of this method is that it is not easy to synthesize a large quantity of AgNPs by using biological synthesis.

### 2.3.1 Microbe-Assisted Synthesis

There are two types of microbe-assisted synthesis of AgNPs:

(a) Bacterial Synthesis: Bacteria can produce inorganic materials either intra- or extracellularly. Thus, they act as potential biofactories for the synthesis of nanoparticles such as gold and silver. Specifically, silver is widely known for its biological properties. AgNPs with different shapes and sizes can be effectively synthesized by varying different parameters using different bacteria such as *Klebsiella pneumonia*, *Lactobacillusfermentum*, *Bacillus flexus*, *Escherichiacoli*, and *Enterobacter cloacae* at different pH, temperatures and concentrations of $AgNO_3$ solutions [33–36].

(b) Fungal Synthesis: Researchers have been interested in patenting their research work on the microbial synthesis of nanoparticles. One of these significant works is the synthesis of AgNPs with particle size 5–50 nm, harnessing wet biomass of *Trichoderma reesei* fungus after 120 h of continuous shaking at 28 °C [37]. When antimicrobial properties of AgNPs were tested on *Escherichia Coli* and *Staphylococcus aureus*, it was found that *E. coli* was more susceptible to silver nanoparticles than *S. aureus* [38]. Extracellular nanoparticles were formed by using thermophilic fungus *Humicola* sp. which reacted with Ag(+) ions and reduced the precursor solution [39].

### 2.3.2 Plant-Mediated Synthesis

Microbe-mediated synthesis requires highly aseptic conditions and their maintenance which lowers the industrial feasibility of this method. Therefore, the plant extract mediated synthesis (Fig. 2) of nanoparticles is potentially advantageous

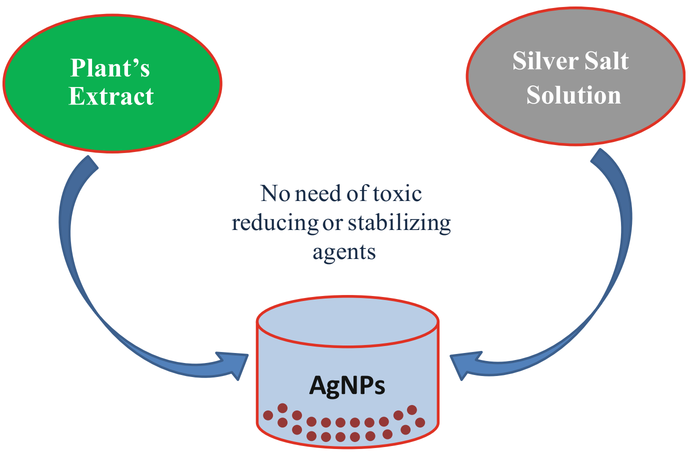



**Fig. 2** Schematic diagram showing the one pot plant-mediated synthesis of silver nanoparticles

**Table 1** Synthesis of silver nanoparticles using different plant extracts

| Plants | Plant's part | Particle size (nm) | Particle shape | References |
|---|---|---|---|---|
| *Averrhoa carambola* | Fruit | 12–16 | Spherical | [41] |
| *Abutilon indicum* | Leaf | 7–17 | Spherical | [42] |
| *Withania somnifera* | Leaf | 5–30 | Spherical | [43] |
| *Eclipta prostrate* | Leaf | 35–60 | Triangles, pentagons, hexagons | [44] |
| *Nelumbo nucifera* | Leaf | 25–80 | Spherical, triangular | [45] |
| *Citrus sinensis* | Peel | 10–35 | Spherical | [46] |
| *Pelargonium graveolens* | Leaf | 16–20 | Spherical | [47] |
| *Tanaetum vulgare* | Fruit | 10–40 | Spherical | [48] |
| Tea extract | Leaf | 20–90 | Spherical | [49] |
| *Tribulus terrestris* | Fruit | 16–28 | Spherical | [50] |

over microbe assisted synthesis due to the ease of improvement, the less biohazard and elaborate process of maintaining cell cultures [40]. It is the best way to synthesize nanoparticles without using any toxic chemical reducing and stabilizing agents as it provides natural capping agents for the stabilization of silver nanoparticles. A list of silver nanoparticles synthesis using different plant extracts is given in Table 1.

## 2.4 *Chemical Methods*

Besides all the methods described earlier, the most common method is the chemical reduction method for nanoparticle synthesis because of its convenience and simple equipment. It is required to control the growth of metal nanoparticles to prepare nanoparticles with a spherical shape and small size with a narrow particle size distribution. It is widely known that chemical reduction method can produce silver nanoparticles at low cost with high yield.

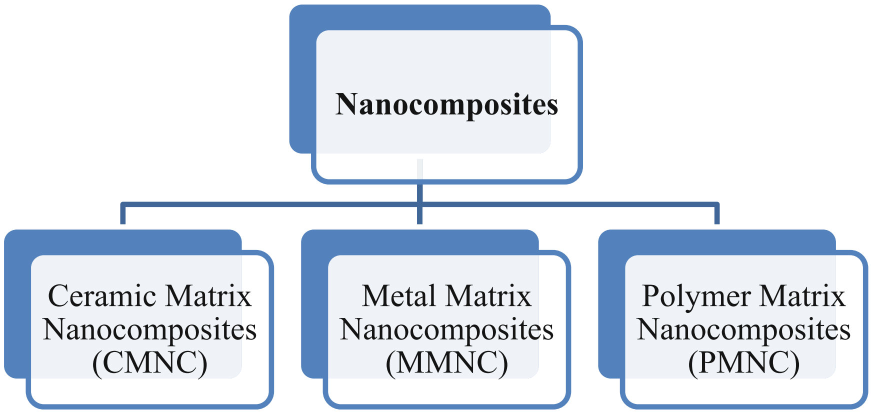
Usually, the chemical synthesis process of AgNPs in solution requires the following three main components: (1) metal precursors, (2) reducing agents and (3) stabilizing/capping agents. Generally, silver nitrate [51–54], silver acetate [55, 56], silver citrate [56–58], and silver chlorate [56, 57, 59] are the most frequently used precursors for the chemical synthesis of silver nanoparticles. Among various reducing agents, borohydride, citrate, ascorbate, and compounds with hydroxyl or carboxyl groups like aldehydes, alcohol, carbohydrates, and their derivatives

[60–63] are the most commonly used reductants. The colloidal solution formation from the reduction of silver salts involves two stages (i) nucleation and (ii) subsequent growth. It is also observed that the size and the shape of synthesized AgNPs are strongly dependent on these two stages. The two phenomenon i.e., nucleation and growth of initial nuclei can be controlled by adjusting different reaction parameters like reaction temperature, pH, precursors, reducing agents (i.e. NaBH4, ethylene glycol, glucose) and stabilizing agents (i.e. PVA, PVP, sodium oleate) [64–66] (Fig. 3).

## 3 Nanocomposite Systems

Nanocomposite systems have been extensively studied since the 1990s and, it is observed that a steady and continuous increase has taken place in the number of publications on the subject, including time to time reviews. Nanocomposites can be defined as multiphase solid materials in which one of the phases has dimensions of less than 100 nm. There are two parts of NC: (i) continuous phase and (ii) discontinuous reinforcing phase. Nanocomposite materials can be classified into three different categories according to their matrix materials.


**Fig. 3** Schematic diagram showing the one-pot chemical synthesis of AgNPs




Hence, nanocomposites can have a combined or have markedly different electrical, mechanical, electrochemical, thermal, catalytic and optical properties of the component materials [20–23].

## *3.1 Silver-Ceramic Matrix Nanocomposites*

The synthesis of nanocomposites composed of noble metals (Au, Ag, Pt and Pd, as well as AuAg alloy) and ceramic matrixes such as metal oxides (ZnO, $TiO_2$, $Cu_2O$, $MnO_2$, $Fe_2O_3$, $WO_3$, $CeO_2$ etc) has received considerable attention in recent years for their applications in heterogeneous catalysis, photocatalysis, drug delivery, solar cells, surface enhanced Raman spectroscopy and many other important areas. Now-a-days, among the many nano-catalysts developed, controllable integration of different noble metals (e.g., Au, Ag, Pt, and Pd) and metal oxides (e.g., $TiO_2$, $CeO_2$, and $ZrO_2$) into single nanostructures has become one of the hottest research topics as they not only merge the functions of individual nanoparticles (NPs) but also show a unique combined and synergetic catalytic properties compared to the single-component materials. Generally, these composites are easily prepared by different methods like impregnation [67], co-precipitation [68], deposition-precipitation [69] and many more.

Liu et al. [70] synthesized plasmonic silver nanoparticle incorporated mesoporous metal–oxide (MMO) semiconductors to get increased photocatalysis. Different typical MMO such as $TiO_2$, ZnO, and $CeO_2$ semiconductors were synthesized by integrating evaporation-induced self-assembly and in situ pyrolysis of metal salts. Then Ag nanoparticles of different amounts were then loaded in these MMO semiconductors through an efficient photo-deposition process. The Ag nanocrystals were synthesized with sizes of 50–100 nm and then they were embedded in MMO semiconductors (Fig. 4) [70].

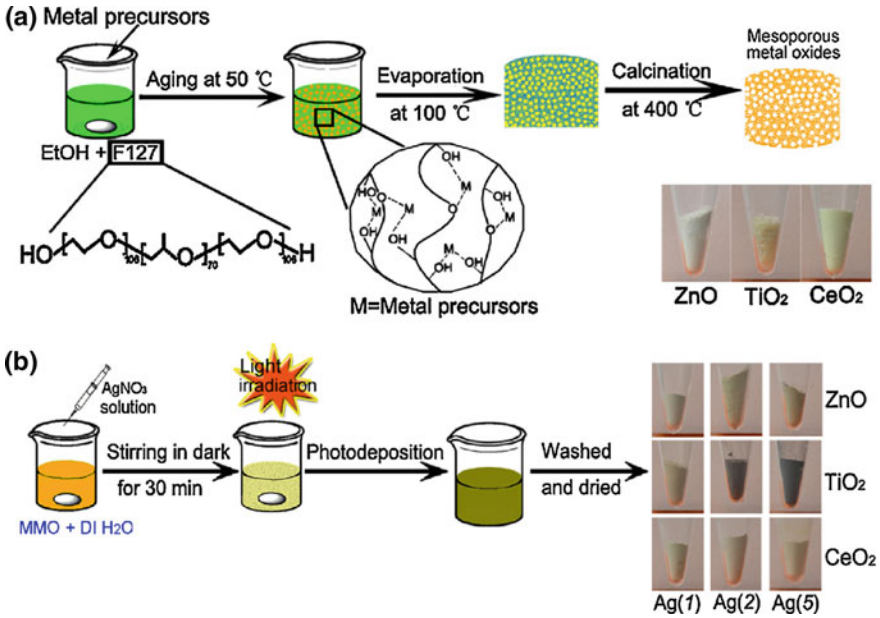



**Fig. 4** Schematic diagram showing the synthesis of **a** mesoporous metal oxides (MMO) and **b** Ag/MMO nanocomposites [70]

## 3.2 *Silver-Metal Matrix Nanocomposites*

Metal matrix nanocomposites (MMNC) can be described as the materials where nanosized rein-forcement material is implanted in a ductile metal or alloy matrix. Most common metal matrix nanocomposite for silver is gold-silver nanocomposite. Choudhury et al. [71, 72] synthesized Ag—Aunanocomposite substrates by a one-step galvanic replacement reaction from thin films of silver, coated on glass slides. Then there was deposition of metallic layers on the cleaned slides using a vacuum evaporation chamber under high vacuum ($<5 \times 10^{-7}$ Torr). At first, there was an adhesion layer of chromium deposited on the slides, then gold ($\sim$5 nm) and silver ($\sim$600 nm) films were deposited, without breaking vacuum [72].

## 3.3 *Silver-Polymer Matrix Nanocomposites*

Recently, researchers in various fields incorporated silver nanoparticles into the polymer matrix to enhance its performance. Polymer materials act not only as an excellent host for incorporating nanoparticles but also terminate the growth of the particles by controlling their nucleation [73]. Silver-polymer nanocomposites can be prepared by using two main approaches.

(a) Insitu Polymerization

In the in situ method, the silver nanoparticles are prepared inside a polymer by dissolving metallic precursor salt in the polymer, followed by chemical reduction of the precursor salt. The reduction of $Ag^+$ to $Ag^0$ takes place. Several reducing agents like sodium borohydride, hydrazine etc. are used in the reduction process. Curcumin-loaded chitosan-PVA silver nanoparticles film (CCPSNP) was prepared by adding $AgNO_3$ to chitosan solution. AgNP solution was formed, to which, poly (vinyl alcohol), glutaraldehyde (a crosslinker) and curcumin solution were added [74]. Ag-PVA film was prepared by Porel and his group by mixing an aqueous solution of $AgNO_3$ and poly(vinyl alcohol) (PVA) wherein the silver precursor $AgNO_3$ was reduced by the hydroxyl groups of the PVA macromolecule [75]. Further, Ag-polyaniline nanocomposite was prepared from a mixture of aniline and silver nitrate as precursor after well rinsing with nitric acid [76].

(b) Exsitu Polymerization

In the ex situ method, silver nanoparticles are formed first and then dispersed into a polymer matrix. The prepared nanoparticles show higher dispersibility in the polymer and get long-term stability against aggregation. Sonication provided the dispersion of nanoparticles in the polymer matrix [77]. Thin nanocomposite films of silver nanocrystal in polystyrene matrix were prepared by sonicating polystyrene and silver nanoparticles with toluene for even dispersion of the nanoparticles [78]. Silver embedded mesoporous polyaniline nanocomposite [79] and mesoporous cross-linked polymer (polyacrylic acid) (MCP-1) supported silver nanoparticles [80] were prepared by dispersing mesoporous polymers in TRIS stabilized AgNPs and then stirring it at room temperature for 1 h. At the end of the reaction, black coloured Ag-NPs containing mesoporous polymer mPANI/Ag and mesoporous polyacrylic acid/Ag nanocomposites were obtained (Fig. 5).

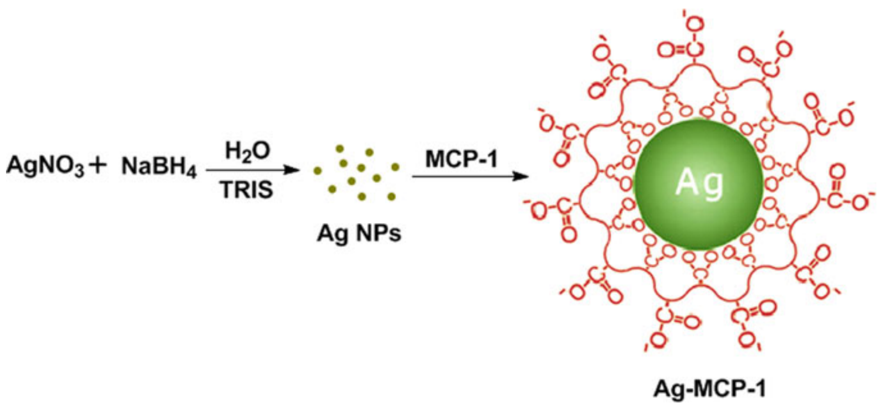



**Fig. 5** Schematic diagram showing the synthesis of mesoporouspolyacrylic acid/Ag nanocomposite [80]

## 4 Applications of Silver Nanocomposites

Recently silver nanocomposites are used extensively as anti-microbial agents in the health industry, food packaging, water treatment, agriculture, winemaking, and textile coatings. They are used as absorbents, photocatalysts, and sensors for detection and removal of environmental pollutants. Silver nanoparticles are also used in cosmetics, personal care products, and electronic devices.

### *4.1 Medical Field*

Silver nanocomposites represent the most important polymer based functionalizing agent among the numerous nanocomposites due to their antimicrobial properties [81, 82]. Two different mechanisms are responsible for antimicrobial activity of silver nanoparticles, (a) adhesion to the cell surface, degradation of lipopolysaccharides, increasing permeability [83] and (b) penetration inside the bacterial cell, DNA damaging [84]. The silver nanoparticles release silver ions, which bind to electron donor groups in biological molecules containing sulfur, oxygen or nitrogen.

Liu et al. [85] demonstrated the doping of $TiO_2$ with silver that greatly improved photocatalytic bacterial inactivation. Polyethyleneglycol-polyurethane-$TiO_2$ silver nanocomposites showed antimicrobial activity against *E. coli* and *Bacillus subtilis* [86]. Silver nanoparticle encapsulated porous PMMA (poly methyl methacrylate) spheres have also shown good antimicrobial activity [87, 88]. Silver nanocomposites of POA (porous aluminium oxide) are effective against both Gram-negative and Gram-positive bacteria, *E. coli* and *Staphylococcus epidermidis*. Nadagouda and Varma [89] studied the applications of Ag nanocomposites with biodegradable carboxymethylcellulose in antimicrobial and antifungal coatings and biomedical devices. Zeolite is a porous crystalline material of hydrated sodium aluminosilicate. Silver can electrostatically bind to zeolite with high affinity and form silver-zeolite (SZ). Human saliva contains several kinds of cations which help in the release of silver ions from SZ and under anaerobic conditions they inhibit the growth of several oral bacteria [90]. SZ incorporated mouth rinses, acrylic resins, and tissue conditioners are used in the dental field [91]. Matsuura et al. [92] showed that tissue conditioners containing SZ exhibit the antimicrobial effect against *Candida albicans*, *Pseudomonas aeruginosa* and *Staphylococcus aureus* for a week and the use of SZ incorporated mouth rinse for 5 days showed a reduced plaque score [93].

Recently, synthesis of graphene oxide (GO) metal nanocomposites has gained attention due to excellent biocompatibility and high antibacterial activity of GO. They have possibilities to be used as an antibacterial reinforcement in biomaterials, exploration of the antiseptic properties and cytotoxic activity of GO-containing nanocomposites. Silver nanoparticles functionalized magnetic graphene oxide nanocomposites (GO/$Fe_3O_4$/PEI/Ag) were synthesized via in situ generate silver nanoparticles on magnetic graphene oxide surface using polyethylenimine as reducing and stabilizing agent. The GO/$Fe_3O_4$/PEI/Ag nanocomposites highly enrich the low-abundant glycopeptides from complex biological samples. These nanocomposites might be used as low-abundant disease biomarkers. Dendritic polymer encapsulated silver nanoparticles have antimicrobial activity, besides this, they are also used as markers for cell labelling [94]. Lesniak et al. [95] demonstrated the synthesis of silver/dendrimer nanocomposites that can be used for in vitro cell labelling.

Carbohydrates such as glucose, lactose, and oligosaccharides significantly improve the cytotoxicity and cellular uptake nature of silver nanoparticles. To kill the cancerous cells in phototherapy, the carbohydrate modified silver nanoparticles can be used as a new tool [96]. Silver nanoparticles are used for the identification of calf thymus DNA (*ct*-DNA) due to their strong fluorescence signal [97]. For environmental protection and some disease detection applications such as disease diagnosis, drug screening, epidemic prevention, the oligonucleotide probe bound silver nanoparticles are used as an indicator in electrochemical DNA sensors that are able to pair with the sample DNA sequence. Based on aggregation, induced by sequence-specific hybridization, silver nanoparticles are used in the design of colourimetric assays [98]. In mouse models, silver nanoparticles exhibit anti-inflammatory property by inhibiting the interferon gamma activity and tumour necrosis factor alpha. Hence, they can play an important role in anti-inflammatory therapies [99, 100].

The emerging field of nanomedicine seeks to exploit the novel properties of engineered nanomaterials for diagnostics and therapeutic applications. The engineered nanoparticles are used to carry drug payloads, image contrast agents or gene therapeutics for diagnosing and treatment. Due to the antimicrobial activity of silver nanoparticles, they are now increasingly used in wound dressings, catheters, and various household products. The chitin-AgNP composite scaffolds have good blood clotting ability hence they are widely used in wound healing and tissue engineering applications [101]. In orthopaedic implants, prostheses, vascular grafts and wound dressings, nanosilver reinforced polymers are commonly used. Surgical instruments, contraceptive devices, creams, gels also contain nanosilver [102–104].

Cattles are affected and die by a tick *Rhipicephalus microplus* (Boophilus) leading to economic losses associated with milk, meat, and leather production [105]. Continuous use of acaricides (used for control of ticks) not only contaminates the environment and animal products but also helps in selection of chemical-resistant ticks. Bergeson [106] has reported that more than 100 silver containing pesticides are synthesized due to their antimicrobial and photocatalytic properties. Sodium dodecyl sulfate (SDS) modified photocatalytic $TiO_2$/Ag nanomaterial conjugated with dimethomorph (DMM) are used as nanopesticide in agriculture [107].

### 4.2 Food Industry

Active packaging is one type of innovative food packaging concept in which active functions like scavenging of oxygen, moisture or ethylene, emission of ethanol and flavours in addition to the antimicrobial activity are involved. Whereas in antimicrobial packaging, to reduce pathogen contamination and extend the shelf-life of food, an antimicrobial substance is included in the packaging system [108]. But the antimicrobial substances are neutralized or diffuse rapidly into the food, so their direct application has limited benefits. Incorporation of the antimicrobial substances into polymers allow their slow release in the packaging system for an extended period and prolong their effect during transport and storage of food [108]. The biopolymer-based films and coatings provide physical protection to foods, improve food quality and enhance the shelf life of food products due to their properties like - acting as barriers against moisture, oxygen, flavour, aroma, and oil [109]. Furthermore, biopolymer films act as antioxidants, antifungal agents, antimicrobials, colours, and other nutrients which are important in the food preservation [110, 111]. Due to these potential applications, biopolymer-based antimicrobial films are used in the food industry including meat, fish, poultry, cereals, cheese, fruits, and vegetables [112–114]. One of the promising candidates in this field is chitosan-based nanocomposite films. Chitosan is nontoxic, biodegradable, and biocompatible so the chitosan-based Ag nanocomposites are used in films and coatings [115, 116]. Silver nanoparticles are cost-effective and have a wide range of applicability than other antimicrobial substances. Hence, they are most commonly used polymer additive for antimicrobial food packaging [108, 117]. Besides the antimicrobial activity, they also extend the shelf life of fruits and vegetables by absorbing and decomposing ethylene from these foodstuffs [118].

Although silver releasing systems are commonly used as food additives in antimicrobial food packaging the single form of silver-releasing system is used in ion-exchange from microporous minerals sector in which silver ions partially replace the naturally occurring sodium ions in clays or other porous minerals [119]. When silver ions come in contact with moisture, they are again substituted by sodium ions present in the release environment and leached from the surface. This is practical, as the release of silver ions will depend on the amount of saline moisture, which is a crucial risk factor for the development of microbes on surfaces. A wide range of polymers and other surfaces are used to incorporate the substituted minerals. They are able to withstand any kind of plastic processing or operating temperature compared to natural antimicrobial substances for their low migration rate and high melting point [120]. Different clays like montmorillonites (MMT) [121] or tobermorites [122], silver zirconium phosphates [123] and silver zeolites [124–128] are used as minerals in this technology. These materials are generally manufactured as a 3–6 μm thick layer containing 1–5% silver content for coating on polymeric or stainless steel surfaces. The food processing equipment like cutlery, cutting boards, countertops, containers, etc. are coated with this type of layer.

Recently silver nanoparticles are marketed as nutrition supplement in form of a colloidal solution. The colloidal silver has high particle surface area for maximum effectiveness. Among the all-metal colloidal mineral supplements, the silver products are most popular [129].

In wine making $SO_2$ is an important antioxidant that inhibits fungal growth, effects of dissolved oxygen and endogenous enzymes of grape-polyphenoloxidase, tyrosinase and peroxidase [130]. $SO_2$ also improves the colour and stability of wine during ageing but it produces a negative effect on taste and odour [131–133]. Due to the antimicrobial activity of silver nanomaterials towards a wide range of Gram-negative and Gram-positive bacteria, some fungi and viruses can replace the $SO_2$. It has been shown that use of colloidal silver complex (CSC) in the production of white and young red wine, displayed very similar chemical and sensory activities as that of $SO_2$ [134].

**Electronic devices**

Silver (Ag) is superior in electrical and thermal conductivities among all the noble metals. With increased surface energy, the melting point of the small-sized silver nanoparticle is drastically low which make them useful as conductive fillers in microelectronic materials [135]. The electrical loss is reduced with the lower surface roughness that gives better packing when the electrical conductors are fabricated with a thick film of silver nanoparticles [136]. Silver nanoparticles are used in electro-optical devices and sensors due to their electro reflectance (ER) effect. In this field, silver nanoparticles alter the absorption spectrum of the particle ensemble by changing the stored electronic charge on the particles with 100 times more effective than a bulk metal surface. Absorption spectroscopy directly monitors the changes in the electrostatic charge stored on small metal particles [137].

Silver nanoparticles have the ability to enhance electrical and optical properties of the polymer composites. Due to these superior properties of Ag, various conducting polymers like—polypyrrole, polythiophene, polyaniline based Ag nanocomposites are used in producing newer materials with high conductivity. Ag nanocomposites are produced in combination with silver nanowires (AgNWs) with conducting polymer matrices which are used as conductive filler and thermal interfacial material in sophisticated nanodevices [138–140]. The silver nanoparticle embedded dielectric Teflon matrix nanocomposites showed higher electrical conductivity with an increased film thickness at various silver nanoparticle concentration [141]. Multiwalled carbon nanotube (MWNTs) with high electrical and mechanical properties are used as electrodes. Silver (Ag)/polymer composites prepared by incorporating multiwalled carbon nanotubes (MWNTs) with Ag nanoparticles significantly improve the electrical conductivity [142]. To improve an optical sensor fiber, Ag-doped silica nanocomposite is coated along with bent silica on the surface of it, which is useful to trace ammonia in a gas sample [143]. Silver-poly vinyl alcohol (Ag-PVA) composites are used for light guiding and optical sensing applications [144, 145]. Silver nanoparticles rapidly trap free electrons so they are used in semiconductor applications. $TiO_2$ is a known photocatalyst capped with the silver nanoparticle to form $TiO_2$–AgNP nanocomposites which are used for better semiconductor efficiency [143, 146]. Conventional solar cells coated with silicon was not efficient because silicon is a poor absorber of light. To enhance the light trapping efficiency of such solar cells, undercoating silver nanoparticles along with silicon layer was performed [147]. Similarly, in ultra-thin light filters, the silver-Poly-methylmethacrylate-Poly ethylene terephthalate membrane (Ag-PMMA-PET) composite has been used. Li et al. [148] suggested that use of PVP nanofibers-silver nanoparticle composites as a thin layer in organic solar cells increase 19.44% power conversion efficiency.

Glucose oxidase (GOx) immobilized stimuli-responsive silver nanocomposites are used in optical enzyme biosensor for sugar concentration analysis. When a sugar solution like glucose is applied to the surface of optical enzyme biosensor, the interparticle distances of the silver nanoparticle present in the silver nanocomposite are increased and absorbance strength of surface Plasmon resonance is decreased [149]. In a variety of techniques like fluorescent, radiochemical, piezoelectric technology and quartz crystal microbalance, silver nanoparticle probes are also used.

## 4.3 Water Treatment

As silver has antimicrobial property, Ag nanoparticles and nanocomposites are used in water purification devices to retard the growth of waterborne microorganisms. The Ag-containing nanomaterials can be a more cost-effective way for water treatment than the chemical method. The stabilization and immobilization of AgNPs in polymeric ion-exchange matrices is a promising approach for water treatment processes. Porous silver nanocomposites such as cellulose/Ag nanocomposites [150], chitosan-silver nanocomposites [151], silica silver composite [152] etc., have antibacterial characteristics and are also used in water treatment system. Silver nanoparticle loaded biocompatible and biodegradable polymer, sodium carboxymethyl cellulose (CMC) is used for water treatment application [153]. Zeolite, sand, fibreglass, anion and cation resin loaded silver nanoparticles are used in groundwater purification systems as antibacterial agent [154]. Porous ceramic Ag nanocomposites and thin-film layer containing nanosilver particles are used as an antibacterial substance in water filter [155]. The silver incorporated nanocomposite ceramic membranes exhibit good salt rejection capacity and effective membrane permeability [156]. Ceramic membrane fabricated silver nanoparticles have also been used to prevent biofouling [157]. Ceramic materials, casting with nanoparticles have more nanoscale pore sizes than ceramics with conventional sintering [158]. Silver-decorated ceramic membrane removes all *E. coli* after 24 h of contact time, whereas, bacterial growth was observed on undecorated membranes [159]. Silver nanoparticles incorporated polymeric membranes are also used to mitigate the biofouling and reduce the microbial activity by releasing silver ions from the membrane. The released silver ions lyse the bacterial cell by adhering to the cell and change the permeability of the cell wall [160, 161].

$Fe_3O_4$-silver nanomaterial is a bifunctional composite that has the superparamagnetic and antibacterial properties against *E. coli*, *Staphylococcus epidermis*, and *B. subtilis*. This nanocomposite easily removes material from water with its superparamagnetic property. To enhance the water treatment efficiency and recyclability, mesoporous polymer nanofiber membranes can be designed with specific pore sizes and desired filtration properties. So, the nanocomposites of super magnetic/silver nanoparticle/polymer nanofiber can be a promising water disinfectant [162, 163].

## 4.4 Textiles

The silver nanoparticles form bonds with the fibers of different fabrics like nylon, polyester, cotton and produce the nanoengineered fabrics. High surface area relative to the volume of particles that increases their chemical reactivity with the fibers helps the nanoparticles stick to fabrics more permanently. The silver nanoparticle coated fabrics prevent moisture, odour, dirt and have antibacterial activity. Due to these properties, they are used in medical bandages, bed linings and sports socks [164]. For prevention of foot odour, use of silver containing socks has been reported. Polymer nanofiber coated fabric materials are applied in textiles to act as a waterproof textile material. Polymer nanofiber layered fabrics with dirt-proof, stain-proof, and superhydrophobic properties are also available. Perelshteinet al. [165] prepared the silver nanocomposite coated fabric and experimented with its antibacterial activity against *E. coli* and *Staphylococcus aureus.* Silver nanocomposites of Polyvinyl alcohol (PVA) and polyvinyl pyrrolidone (PVP) are the type of polymer nanocomposites that form hydrogen bonds with polar species [166].

## 4.5 Nanopaints

Polymer matrices give high stability to the silver nanoparticles in polymer-silver nanocomposites. Without significant oxidation and aggregation, the polymer nanocomposites can be stable up to 200 °C. This property enables the production of silver nanoparticle embedded homogeneous paints. The nanopaint is an excellent coating material with outstanding antibacterial properties that can be applied to various surfaces including wood, glass, and polystyrene [167].

## 4.6 Personal Care Products

Silver nanoparticles used in cleanser soap has been found useful in treating acne due to their bactericidal and fungicidal properties [168]. Nanosilver containing hand wash of 15 mg per litre concentration has been found highly efficient with short exposure time to prevent transmission of infectious diseases [169]. Some toothpaste and tooth creams contain silver nanoparticles which produce a natural tooth enamel like a thin layer in teeth to reduce sensitivity and pain. For imparting freshness to the skin, certain day and night creams contain silver nanoparticles [170]. Zinc oxide (ZnO) or titanium dioxide ($TiO_2$) effectively absorb UV light. Incorporation of silver nanoparticles in ZnO and $TiO_2$ make them small and transparent, enabling them to exclusively absorb UV light excluding the absorption of visible light. Silver nanoparticles are also used in face and body foams, wet wipes, deodorants, lip products etc. [171].

## 5 Conclusion

The present review focuses on a vivid discussion relating to various synthesis methods and applications of silver nanocomposites. This would help in our understanding and enrich our knowledge on the recent developments in the area. However, further research is needed for nanocomposite synthesis through faster, economical and cheap processes and the extension of their applicability that would result in increased specificity, competence and efficiency. Keeping in view the increasing environmental pollution due to different anthropogenic activities care should be taken to focus on green synthesis methods that would not release any harmful chemicals in the environment. Novel strategies can also be implemented towards the development of recyclable and biodegradable nanocomposite materials preventing their accumulation in the environment after disposal.

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