Silver Nanoparticles and Its Polymer Nanocomposites—Synthesis, Optimization, Biomedical Usage, and Its Various Applications

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Abstract Nanomaterials have emerged as an extremely valuable asset in the world of material science. It's unique, and substantial properties lurk scientist all over the world into incorporating them in various material synthesis. Composites are yet another powerful tool for the development of specific material according to our needs. Fusion of the above-mentioned two mighty tools results in birth of a whole

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new domain called nanocomposites. This unit provides details about different aspects of nanomaterials, composites, and their categories. This chapter talks thoroughly about the basics behind the various synthesis process involved along with optimization of various parameters related to fabrication of such nanocomposites. Among the pool of nanocomposites, silver nanoparticles and the composites based on these particles have harnessed much attention because of the striking properties of Ag nanoparticles like high electrical and thermal conductivity, chemical stability, catalytic activities, antimicrobial properties, nonlinear optical behavior, and surface-enhanced Raman scattering. Synthesis and development of AgNPs in the literature have been mentioned, and techniques have been reviewed. Detailed discussions based on each individual property have also been carried out along with exploring the applications in numerous varied fields.

1 Introduction

A "composite material" is defined as a mixture made up of materials having strikingly different physical and chemical properties on the macroscopic levels (Fadiran et al. 2018). The resultant material usually possesses properties different from those of any of their constituents. By using composites, it is possible to have properties like high strength and stiffness at high temperature, corrosion resistance, ability to withstand extreme temperature conditions, and desirable thermal expansion coefficient. Composite materials comprise of two phases: the matrix which is generally the continuous phase and the other phase(s) embedded in this matrix is known as the "reinforcement." A variety of unique combinations of these matrices (e.g., polymers, carbon, metals, and ceramics) and reinforcements (e.g., particles, fibers, and layered materials) have been employed for the synthesis of various composite and nanocomposite materials.

Quite recently, nanocomposites have garnered a lot of attention since they are nearly 1000 times tougher than their bulk counterparts. Sincere steps have been taken, and lots of work is still undertaken towards creation of controlled nanostructures using novel and innovative techniques. The field of synthesis and characterization of nanocomposites of both organic and inorganic materials is a rapidly growing area of research. The characteristic properties of nanocomposites materials synthesized depend mainly on the features of the fundamental material from where it is originating. In terms of physical properties, nanocomposites and conventional composite materials differ a lot in terms of surface area, where

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nanocomposites have strikingly high surface to volume ratio. The matrix materials are having various properties such as it binds the dispersed phase together. It protects the dispersed phase from chemical action and keeps it in proper position and orientation (Ajayan et al. 2003). It is commonly observed that with polymer nanocomposites, the properties associated with chemistry, extent of thermoset cure, mobility of polymer chains, conformation of polymer chains, extent of ordering in polymer chains can all differ from the interface between the reinforcement and the bulk of the matrix.

1.1 Types of Nanocomposites

1.1.1 Ceramic Matrix Nanocomposites

This category of composites has ceramic as the main portion of the volume. Ceramic is a chemical compound which is part of the group of oxides, nitrides, borides, etc. More often, the second component of the ceramic matrix nanocomposites consists of a metal as their second component. Theoretically, both the components, i.e., the metallic and the ceramic component, are finely dispersed in each other in order to get uniformly distributed and embedded into each other to elicit the particular nanoscopic properties. These results in the formation of nanocomposites, which shows improvement in their optical, electrical, and magnetic properties (Kruis et al. 1998), and apart from optical, thermal, conductive, electrical properties, it shows tremendous corrosion resistance and other protective properties (Popelka et al. 2018).

1.1.2 Metal Matrix Nanocomposites

Metal matrix nanocomposites are made up of reinforced metal as matrix to form composites. These kinds of composites can be divided into two categories, i.e., continuous and non-continuous reinforced materials. One of the most important categories of nanocomposites is where carbon nanotube and metal are embedded as matrix to form composites (CNT-MMC), which is new emerging trend of materials that is being worked upon taking full advantage of the characteristic features of CNTS which includes high tensile strength and electrical conductivity. CNT-MMC has properties aptly required for the development and synthesis of synthetic techniques that will lead to the production of nanocomposites which will be advanced in many aspects. Although carbon nanotubes metal matrix composites possess various optimal properties, recent research emphasizes mostly upon the synthesis techniques consisting of boron and carbon nitride reinforced metal matrix composites (Bakshi et al. 2010).

1.1.3 Polymer Nanocomposites

Polymer nanosciences are the study and application of nanoscience in field related to polymer-nanoparticle matrices. These kinds of composites are made up of a polymer/copolymer with nanoparticles/nanofillers dispersed in the polymer matrix. These reinforcements could be of a variety of shapes (like platelets, fibers, spheroids) one among which at least should have dimension in the range of 1–50 nm. These systems have strict requirements in each of its steps. The mixing/compounding should be controlled and optimized, dispersion should be stabilized, and orientation of the dispersed phase should be controlled for all MPS.

The transition of any particle from micro to nano is due to drastic changes in its physical as well as chemical structure, which further appears in the form of unique properties. The enhanced surface area-to-volume ratio, which further accelerates as the particles get smaller, leads toward the increasing dominant behavior of atoms in comparison with the surface area of particle. This greatly affects the properties of such particles when they react with other particles. Now, since nanoparticles have a higher surface area, there is more likely greater one-to-one interaction with the other kinds of particles present inside. This in turn increases the mechanical strength, thermal resistivity, and many such factors of the mixture. Addition of nanoparticulates to a polymer matrix enhances its performance by inclusion of the nanoscale filler (Evangelos 2007). These are also called nanofilled polymer composites. Uniform dispersion of the filler is essential as it substantially improves the properties of the composites. Nanoparticles like graphene, carbon nanotubes, molybdenum disulfide, and tungsten disulfide are more generally used as reinforcing agents for the fabrication of mechanically strong biodegradable polymeric nanocomposites for applications in bone tissue engineering. These nanocomposites have huge potential in terms to be used as a novel, mechanically strong, lightweight composite as substitute for bone implants. These emphasizes the relation that inclusion of mechanical reinforcement is largely dependent on the nanostructure morphology, defects, amount of dispersion of nanomaterials in the polymer matrix as well cross-linking density of the polymer. Hence, extremely low amount of filler is needed to achieve the desired requirements. In general, these kinds of polymeric nanocomposites are opening up a whole new generation of macromolecular materials having low densities along with multifunctional properties (Paul and Robeson 2008; Fayyad et al. 2018).

1.1.4 Polymer/Silver Nanocomposites

Nanoproducts and nanoparticles produced with the help of nanotechnology depict significant physicochemical properties differing from the bulk materials (Ponnamma et al. 2018). Among them, silver nanoparticles (AgNPs or nanosilver) have strikingly huge popularity owing to their unique physical, chemical, and biological properties in comparison with gold and platinum, their counterparts (Sharma et al. 2009a, b). Silver nanoparticles are precisely interesting regarding usage in the industries concerning

polymer composites since these particles have remarkable properties like excellent electrical and thermal conductivity, surface-enhanced Raman scattering, chemical stability, catalytic activity, and nonlinear optical behavior (Krutyakov et al. 2008). Although they are frequently described as being "silver," some of them really comprise a huge amount of silver oxide. A variety of shapes are possible for such nanoparticles which can be devised based on the application required. The most commonly used shapes are spherical. Other shapes like diamond, octagonal, and thin sheets are also quite popular. The silver nanoparticles are currently under investigation for their usage in human health treatments. In laboratory, studies are being carried for assessing potential efficacy, toxicity, and costs.

Some of the other highlights of polymer/silver nanocomposites in between the wide range of available hybrid materials are their unique properties (Temgire and Joshi 2003; Zheng et al. 2001). In particular, the antimicrobial action of silver has led to its increased usage in numerous applications like incorporation in apparel, footwear, paints, wound dressings, appliances, cosmetics, and plastics (Brett 2006). It has been reported previously that the dispersed silver ions are responsible for biological actions, especially against microorganisms (Raffi et al. 2008; Choi et al. 2008). Generally, inorganic nanomaterials can be effortlessly bonded to the polymer matrix for the synthesis of a metal complex (Radheshkumar and Münstedt 2005; Espuche et al. 2005). The ability of the polymer matrix in preparation of composites is to form a metal chelate as well as its application as an ion capping agent (Khanna et al. 2005). Varied forms of magnetite and silver nanocomposites in dispersed form are used as corrosion inhibitors (El-Mahdy et al. 2013, 2014; Atta et al. 2011; Blinova et al. 2009). Polymer acts as an excellent host for embedding nanoparticles as well as terminates the growth of the particles by controlling the nucleation process, and the Ag nanoparticles enhance their overall performance (Li et al. 2012).

2 Methods of Synthesis

2.1 Synthesis of Silver Nanoparticles

Silver nanoparticles can be synthesized by physical, chemical, and biological approaches. Evaporation–condensation and laser ablation are the most important physical approaches. In evaporation–condensation method, the particles are generated using an evaporation–condensation technique (Scheibel and Porstendörfer 1983). Sample amount of bulk silver is kepton the ceramic crucibles which are further kept inside the ceramic boat to be finally kept in a tube furnace. The silver is evaporated from the center of the furnace at a very high temperature. The metal vapor formed is carried outside the furnace. The dilution is carried out using inert N_2 gas streams which makes sure that only the silver particles are present in the furnace. Due to such sudden temperature shock, the silver vapor tends to condense which leads to formation of primary nanoparticles. These particles coagulate to form agglomerates of the nanoparticles. It has been previously reported that with

such setup of particle generation formation of chain-like silver agglomerates, bonds consisting of spherical primary particles can be formed (Weber and Friedlander 1997; Ku and Maynard 2006). The evaporation/condensation technique is quite simple; however, it lacks in many aspects. This technique consumes a large amount of energy and is quite slow. Also, it requires the development of nanoparticles in large concentrations. However, in cases where long-term synthesis is required, this method is the most reliable one (Jung et al. 2006). At high concentration with high heater surface temperature, spherical NPs without agglomeration were observed.

Laser ablation synthesis in solution (LASiS) is the other commonly used methods for obtaining colloidal solution of nanoparticles in a variety of solvents (Amendola and Meneghetti 2009; Amendola et al. 2006). LASiS is the process in which laser ablation of a bulk metal plate dipped in a liquid solution is used to generate the condensation of a plasma plume formed which in turn is utilized for the synthesis of nanoparticles. Previously, LASiS has proved itself as a reliable alternative in comparison with conventionally used reduction methods including chemicals for the development of noble metal nanoparticles (NMNp). LASiS is clearly greener approach which will be harmless for the environment. Laser ablation of metallic bulk materials in solution has been used for the synthesis of silver NPs in lot of studies (Mafune et al. 2000, 2001; Kabashin and Meunier 2003; Sylvestre et al. 2004; Dolgaev et al. 2002). The efficiency of ablation as well as the characteristics of the produced nanosilver particles by laser ablation depends largely upon the type of laser used along with the surfactant requirements (Kim et al. 2005; Link et al. 2000; Tarasenko et al. 2006; Kawasaki and Nishimura 2006). One of the major advantages of using laser ablation in place of other technique is that no chemical agents are required for this process (Tsuji et al. 2002). Silver nanospheroids (20–50 nm) have been synthesized by the application of femtosecond laser pulses at 800 nm (Tsuji et al. 2003). The synthesized particles were studied and compared with those of colloidal particles prepared by nanosecond laser pulses. As a consequence, it was observed that the formation efficiency for femtosecond pulses was significantly less in comparison with that for nanosecond pulses. The particulate size of colloids matter obtained by femtosecond pulses was quite less dispersed than that of colloids prepared by nanosecond pulses. Furthermore, it was also observed that the ablation efficiency was quite less in water than that in air.

The most commonly used method for the production of silver NPs is via chemical reduction of materials. Conventionally, reducing agents like sodium citrate, ascorbate, sodium borohydride ($NaBH_4$), elemental hydrogen, polyol process, Tollens reagent, N,N-dimethylformamide (DMF), and poly(ethylene glycol)-block copolymers are used for reduction of silver ions (Ag^+) in various solutions. These agents reduce Ag^+ which lead to the formation of metallic silver (Ag^0). Afterward, these are agglomerated into oligomeric clusters. This in turns initiates the formation of metallic colloidal silver particles (Wiley et al. 2005; ChumanovEvanoff and Evanoff 2004; Merga et al. 2007). Protective agents are used which also protect the NPs from getting adsorbed, binded, or agglomerated (Oliveira et al. 2005).

There is an urgent need regarding development of high-yield, low-cost, non-toxic, and environmental-friendly procedures for synthesis of metallic

nanoparticles. Therefore, the approaches concerning biological and greenways for the synthesis of nanoparticles become important in this regard. A vast number of biological resources which are available in nature including plants and plant products, algae, fungi, yeast, bacteria, and viruses can be employed for synthesis of nanoparticles. It is noteworthy that both unicellular and multicellular organisms have been known to produce intracellular or extracellular inorganic materials. Chemically, synthesis of AgNPs requires a silver salt (usually $AgNO_3$), a reducing agent (i.e., ethylene glycol) and a stabilizer or aping agent (i.e., PVP) which will control the growth of the NPs as well as regulate them from aggregating. The living organisms are quite capable of replacing the reducing agent and the stabilizer in the biological synthesis of AgNPs. These reducing and regulating compounds can be picked from bacteria, fungi, yeasts, algae, or plants (Sintubin et al. 2012). It has been reported that the AgNPs in the particle size of 4 ± 1.5 nm was formed using the metal-reducing bacterium, *Shewanella oneidensis*, with a silver nitrate solution (Suresh 2010). This method of synthesis is based on utilizing natural bacteria. This would be economical, simple, and reproducible and would consume less energy in comparison with harmful chemical synthesis routes.

2.2 Microwave Synthesis and Related Properties of Silver Nanoparticles Synthesis

The conventional methods to synthesize AgNPs include physical, chemical, and biological methods. The typical processing methods for nanosized silver particles includes: (1) the classical Turkevich preparation of metal colloids, (2) reversed micelle process, (3) photoreduction, (4) ultrasonic radiation, and (5) [60]Co g-irradiation.

Through the above-mentioned processes, we can synthesize AgNPs consisting of varying shapes and sizes, but these processes are limited to Ag colloids having low concentration (in millimoles) and in presence of suitable stabilizers and surfactants, which are difficult to remove from the surface of the nanoparticles after synthesis, which further hinder the catalysis process and disrupt physical nature of the NPs. Also, the conventional methods of the preparation of AgNPs have lower yield, higher cost, and lower size control over the produced NPs. Thus, a recently developed method of NP synthesis via microwave (*MW*) heating is adopted to counter these disadvantages. The advantage of MW heating is that it provides uniform heating of the solvents and reactant mixtures, which leads to uniform nucleation and growth of the agglomerates, which in turn leads to the formation of homogenous smaller nanoparticles (Ajayan et al. 2003). MW heating is a new emerging technology for rapid synthesis of various inorganic NPs. In MW heating-assisted silver NP synthesis, we can have better control on size distribution of the synthesized NPs compared to conventional thermal convection heating having the same reactant compositions and having larger silver yield. The first and
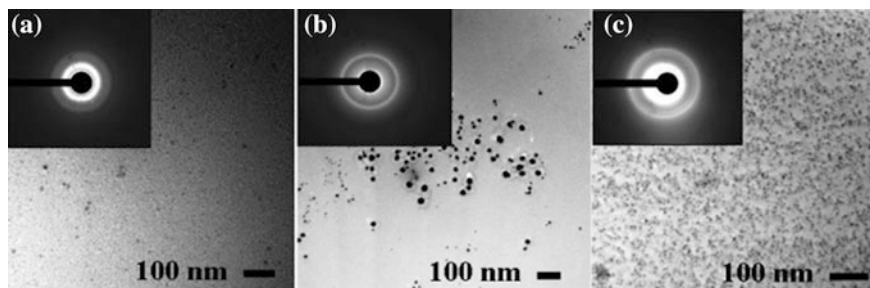
Fig. 1 TEM images of Ag and Pd nanostructures synthesized using MW irradiation in the presence of PVP as capping agent **a** Ag with **a**-D-glucose. **b** Ag with sucrose. **c** Ag with maltose (Huang and Yang 2004). Copyright 2004. Reproduced with permission from Elsevier

foremost process of large-scale AgNP synthesis by MW heating was demonstrated by Yin et al. in 2003 in which the NPs were prepared from aqueous solution of silver nitrate and trisodium citrate in the presence of formaldehyde as reducing agent (Chen et al. 2008).

The MW synthesis of AgNPs is basically a "bottom-up" process that involves capping agents such as surfactants and polymers to stop the growth of the agglomerates at nanoscale regime. These capping materials are often harmful and detrimental to the environment in view of green chemistry (Huang and Yang 2004; Mukherjee et al. 2001). Thus, a variety of methods of synthesis have come up in last few years for green synthesis of the nanoparticles using environment-friendly polysaccharides that are biodegradable and environmentally benign. Some of the methods are spontaneous reduction using MW heating-assisted methods using aqueous solution of **a**-D-glucose, sucrose, and maltose as reported by Verma et al. (Mukherjee et al. 2001), the TEM images of which AgNPs are shown in Fig. 1, synthesis of gold and silver nanoparticles using polysaccharide both as reducing and a stabilizing agent as reported by Huang and Yong (Mukherjee et al. 2001), use of fungus Verticillium to prepare silver and gold nanoparticles as reported by Mukherjee et al. (Pal et al. 2009; Sreeram et al. 2008).

With time, different variations have come up in the process of MW-assisted synthesis of AgNPs, such as MW-assisted green synthesis using organic capping agents as mentioned above, and some variations are listed in Table 1.

2.3 Synthesis of Polymer/Silver Nanocomposites

2.3.1 In Situ Polymerization

Silver nanoparticles are also synthesized using a quite simple yet effective method following in situ methodology. It is a one-step method of fabrication of nanoparticles which uses the corresponding precursors for the synthesis. The nanoparticles

Table 1 Variations of AgNP synthesis by MW irradiation

Process variation	Results obtained	References
AgNP prepared from MW irradiation from an aqueous solution of silver nitrate and trisodium citrate in the presence of formaldehyde as a reductant	Silver citrate colloids support the nucleation of AgNP by reduction with formaldehyde under MW irradiation	Chen et al. (2008)
Generation of nanospheres of Ag via MW-assisted spontaneous reduction of noble metal salts using an aqueous solution of a-D-glucose, sucrose, and maltose	Bulk and size-controlled synthesis of nanostructures of Ag having varying shapes and sizes can be generated from aqueous sugar solutions using MW irradiation	Huang and Yang (2004)
Carboxymethyl cellulose sodium (CMS) is used to work both as a reducing and a stabilizing reagent in the reaction to produce AgNP from the solution using MW heating	The AgNPs prepared by this green synthesis method are uniform and stable, which can be stored at room temperature for a period of 2 months without any significant change	Mukherjee et al. (2001)
AgNPs were prepared by MW irradiation of (AgNO$_3$) solution in ethanolic medium (which acts as reducing agent) using (PVP) as a stabilizing agent	Spherical, highly monodispersed AgNPs were synthesized under MW heating	Saifuddin et al. (2009)
Use of starch as a template and reducing agent in the controlled, directed, and MW heating-assisted synthesis of AgNPs and comparing them	Comparing altogether the MW-assisted, controlled, and directed heating methods of AgNP synthesis, MW heating was found to give better results for reduction of Ag ions to AgNPs as they had smaller particle size and particle size distribution. The pure AgNP produced by MW heating is more suitable for medical and biological applications, as non-toxic stabilizing agents were used in this work	Singh and Raykar (2008)
Novel rapid, simple, and "green" combinatorial synthesis approach for the synthesis of metallic nanostructures of noble metals such as AgNPs by using a combination of culture supernatanant of *Bacillus subtilis* and microwave (MW) heating in water in the absence of a surfactant or soft template	The kinetics of AgNP synthesis using the cell filtrates in combination with MW irradiation indicates that the rapid synthesis of nanoparticles would be suitable for developing a green nanotechnology biosynthesis process for mass-scale production	Wang et al. (2010)
MW synthesis applied to prepare stable Ag nanofluids in ethanol by reduction of AgNO$_3$ with polyvinylpyrrolidone (PVP) and used as stabilizing agent, having Ag concentrations of 1% by volume	Stable nanofluids containing AgNPs of 30 and 60 nm have been prepared by MW-assisted one-step method. MW method being fast is suitable for large-scale production of nanofluids	Li et al. (2011)

(continued)

Table 1 (continued)

Process variation	Results obtained	References
AgNPs were prepared by MW irradiation of silver nitrate solution with carboxymethyl chitosan as reducing agent and a stabilizer	The AgNPs were chemically generated in the $AgNO_3$ and CMCT alkalic aqueous solution by MW irradiation, and sizes of the NPs were varying between 2 and 20 nm range having FCC structure	Li et al. (2011)
MW-assisted synthesis of cellulose–Ag NC with AgNPs dispersed homogenously in the cellulose matrix using cellulose solution, $AgNO_3$, and ascorbic acid in N, N-dimethylacetamide (DMAc)	This MW-assisted method does not need any seed/template/surfactant and thus is a convenient and fast pathway for large-scale and low-cost production of cellulose-based NCs	Zhao et al. (2014)
A facile MW-assisted method to fabricate cellulose–Ag NC by reducing $AgNO_3$ in EG, which acts as a solvent, a reducing reagent, and a MW absorber in the system, thus canceling the requirement of additional reductant	Cellulose–Ag NCs with superior antimicrobial properties have been successfully produced through this MW-assisted method	Singh and Rawat (2016)
A simple, green, MW-assisted method of synthesizing AgNPs was developed using sodium alginate as stabilizer and reducer	Use of environment-friendly and renewable materials like sodium alginate for the synthesis of AgNPs in an aqueous medium offers a number of benefits in fields such as biomedical, textile, and pharmaceutical applications. MW irradiation accelerates the formation rate of particles	Chen et al. (2009)
AgNPs were rapidly synthesized using aqueous leaf extract of *O. majorana* and *C. sinensis* on MW irradiation	MW irradiation and its mode of heating make the synthesis of the NPs fast, uniform, and reproducible. AgNPs showed superior antibacterial activity toward *E. coli* and *B. subtilis* pathogens. It is a green process for the production of SNPs and is completely free from toxic solvents and chemicals	Melvin et al. (2014)

can be directly grown using this method. The most important advantage of this route is that it prevents particle agglomeration, maintaining a good spatial distribution in the polymer matrix at the same time whereas, the major drawback of this method is the slight probability of left unreacted educts in course of the reaction. This might be having influence on the properties of the final product.

2.3.2 Ex Situ Polymerization

The ex situ synthesis method is more suitable wherever large-scale industrial applications are required. The key challenge related to this method is preparation of
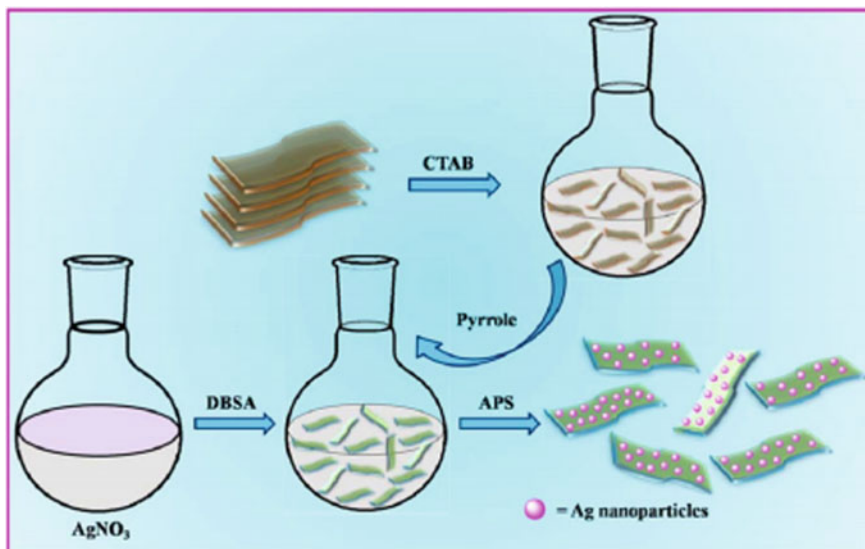
Fig. 2 Schematic illustration of silver/polypyrrole/graphene (Ag-PPy/Gr) nanocomposite synthesis (Dhibar and Das 2017). Copyright 2017. Reproduced with permission from Wiley

nanoparticles which possess higher dispersibility in the polymer and have long-term stability against aggregation. In the ex situ method, firstly the silver nanoparticles are formed and these are then dispersed into a polymer matrix. The nanoparticles that are formed possess higher dispersibility in the polymer and have long-term stability against aggregation. Dispersion of nanoparticles is generally obtained through sonication (Guo et al. 2014).

Dhibar et al. reported a simple method to synthesize silver/polypyrrole/graphene (Ag-PPy/Gr) nanocomposite as an efficient supercapacitor electrode material as shown in Fig. 2. The graphene sheets are homogeneously coated by polypyrrole polymer in presence of silver nanoparticle. The Ag-PPy/Gr nanocomposite achieved a specific capacitance of 472 F/g at a 0.5 A/g current density. The presence of both silver nanoparticles and graphene is the key factor for the enhancement of the electrochemical properties of the nanocomposite.

3 Applications of Polymer/Silver Nanocomposites

3.1 Biomedical Applications

Figure 3 illustrates the various applications of silver nanoparticles in the biomedical field including antimicrobial activity, protein detection, cancer therapy, clinical fabrics, antimicrobial catheters, and biological assays. The wide applicability of the

silver nanoparticles is due to the novel properties of the nanoparticle, which help with applications in good biocompatibility. Table 2 summarizes the biomedical applications of the silver nanoparticles.
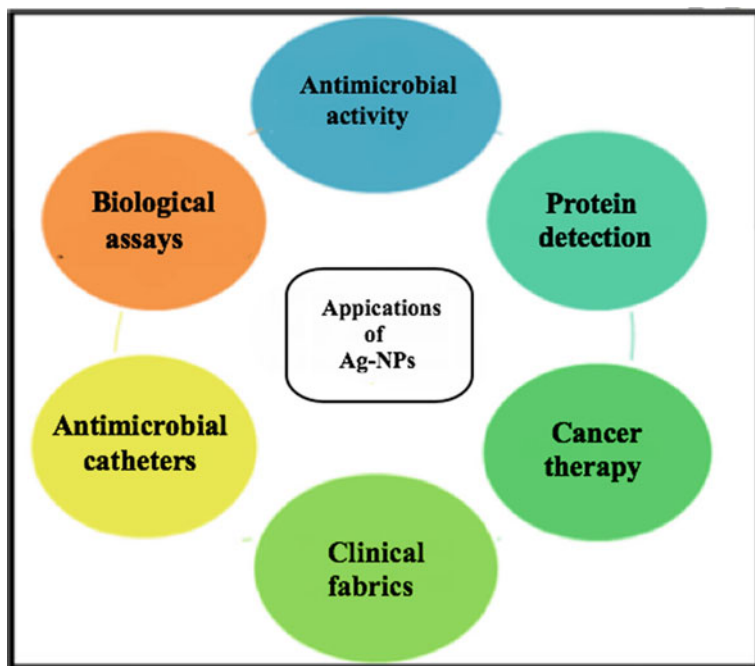

Fig. 3 Biological applications of AgNPs

Table 2 Biomedical application of AgNPs and their mode of action

Biomedical applications	Mode of action	Reference
Dressing for surgical wound	Disruption of cell membrane and electron transport	Sondi and Salopek-Sondi (2004)
Antifungal agent	Production of ROS	Mallikarjuna and Varma (2007)
Portable water filters	Release of Ag^+ ions	Pal et al. (2007a, b)
Antibacterial agent	DNA damage	Yin et al. (2004)
Coatings for medical devices	Disruption of cell membrane and electron transport	Noorbakhsh et al. (2011)
Infected wound and diabetic foot treatment	Production of ROS	Sondi and Salopek-Sondi (2004)

3.1.1 Antibacterial Agent

Silver nanoparticles (AgNPs) have now been established as an effective biocidal agent and acts on a wide range of both gram-negative and gram-positive bacteria as shown in Fig. 4a (Jones and Hoek 2010). It has also been successful in demonstrating its antibacterial property on drug-resistant bacterial strains, qualifying it to be a potential candidate for pharmaceutical use (Lara et al. 2011). Several studies have been carried out on the mode of antibacterial action of AgNPs on bacteria and summarized in Table 3.

Sondi et al. 2003 investigated the effect of AgNPs on *E. coli, Vibria cholera, P. aeruginosa,* and *Syphillis typhus* using advanced microscopic tools. AgNPs were able to restrict bacterial growth at concentrations beyond 75 µg/mL (Sondi and Salopek-Sondi 2004). The cell wall damage was inspected and has been inferred to be caused due to the high level of interaction of AgNPs with compounds containing phosphorus and sulfur. Moreover, the results suggest that an oxygen-rich environment induced the antibacterial activity of AgNPs in comparison with an anaerobic environment. These interactions can be assumed to be the reason for prevention of DNA replications, which eventually lead to bacterial death (Melaiye et al. 2005; Feng et al. 2000; Zhang et al. 2008; Nasrollahi et al. 2011).

Another study reported the antibacterial activity of AgNPs against *S. typhus, E. coli, B. subtilis,* and *Klebsiella mobilis* in where the nanoparticles had an average size of 14–40 nm (Kim et al. 2012).

Three probable antibacterial mechanisms have been proposed (Sondi and Salopek-Sondi 2004; Kim 2007; Yin et al. 2004). They can elicit an antibacterial response by hindering the production of ATP and DNA replication due to uptake of
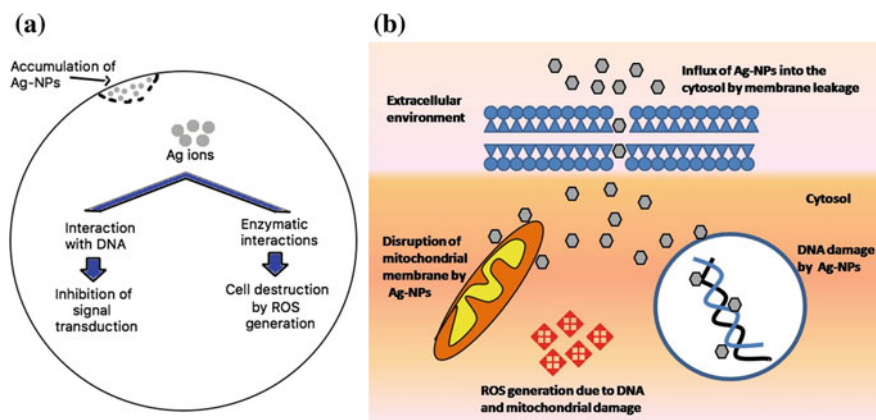

Fig. 4 **a** Modes of action of silver nanoparticles on bacteria. **b** Cellular basis of the antimicrobial activity of AgNP-coated catheters (Jones and Hoek 2010). Copyright 2010. Reproduced with permission from Springer

Table 3 Antimicrobial effects of AgNPs

Type	Microbial strain	References
AgNP powder	*E. Coli*	Sondi and Salopek-Sondi (2004)
AgNP powder	*Salmonella typhus*	Morones (2005)
AgNPs in aqueous media	*S. aureaus*	Shrivastava et al. (2007)
AgNPs in culture media	*Streptococcus* sp.,	Le (2012)
AgNPs	*V. cholerae*	Le (2012)
AgNPs	*T mentagrophyte*	Roe et al. (2008)
AgNP-coated plastic catheters	*C. albicans*	Panáček et al. (2009)
AgNPs	*Candida spp.*	Monteiro et al. (2011)
AgNPs	*T. rubrum*	Monteiro et al. (2011)
AgNPs	*Candida glabrata*	Elechiguerra et al. (2005)
AgNPs	HIV-1	Rogers et al. (2008)
AgNPs	HBV	De Gusseme et al. (2010)
AgNPs	MNV-1	Matsumura et al. (2002)
AgNPs	MPV	Sondi et al. (2003)

free silver ions or by the generating reactive oxygen species or by damaging the cell membranes (Fig. 1). However, the exact mechanism is yet to be unraveled.

Silver is known for its fantastic antimicrobial and antibacterial properties and has rapid healing properties (Imai et al. 2010; Jing et al. 2005). Every year, thousands of patients, all over the world, die succumbing to infections from the contracted post-injury of surgery. AgNPs have shown good and desirable properties in prevention of contraction of infectious bacteria such as *E. coli* (found on contaminated wounds), Enterococcus, *Staphylococcus aureus*, *Candida albicans*, Staphylococci, and *Pseudomonas aeruginosa*. Li et al. in 2011a, b measured the growth of *E. coli* (gram-negative bacteria) and *S. aureus* (gram-positive bacteria) for antibacterial activity in cellulose–silver nanocomposites. They found that for both the bacteria samples, the growth of the bacterial assay was retarded, showing the antibacterial activity of the cellulose–silver nanocomposite (Eswaraiah et al. 2011). In 2013 Zhao et al. synthesized AgNPs by green MW synthesis using sodium alginate as stabilizer and reducer to study antibacterial activity of the AgNPs on same *E. coli* and *S. aureus* bacteria. The results showed good antibacterial activity from both gram-negative *E. coli* and *S. aureus* bacteria, with higher antibacterial activity for *E. coli*. This can be attributed to the fact that gram-positive bacteria have thicker cell wall than gram-negative bacteria, thus leading to lesser penetration of AgNP and consequently lower antibacterial activity (Chen et al. 2009). They are widely used as an antibacterial silver coating for dressing the wounds.

These days owing to its antibacterial properties silver nanoparticles are extensively incorporated in apparel, footwear, paints, wound dressings, appliances, cosmetics, and plastics. Silver nanoparticles are highly stable, which supports the production of silver nanoparticle embedded in homogeneous paints. These serve as an optimal coating material. It can be used to cover various surfaces including

wood, glass, and polystyrene. Moreover, the surface coated with the nanopaints exhibits antibacterial properties (Kumar et al. 2008).

3.1.2 Antifungal Agent

Fungal infections are on the rise, and fungi are being recognized as major pathogens (Enoch et al. 2006). AgNPs have now been known to demonstrate antifungal activities. AgNPs have been reported to act against *C. albicans* by cell membrane disruption and inhibition of normal budding (Kim et al. 2009). The results of the study to investigate the antifungal activity of AgNP-coated plastic catheters affirmed the complete inhibition of *C. Albicans* (Roe et al. 2008). Minimum inhibition against *C. albicans* was revealed at 0.21 mg^{-1} using naked AgNPs. AgNPs were also effective in growth inhibition of yeasts against the tested human fibroblasts. Antifungal activities have also been reported in case of *C. glabrata* and *Trichophyton rubrum* (Noorbakhsh et al. 2011).

Nasrollahi et al. 2011 investigated the antifungal effects of AgNPs on *Candida albicans* (ATCC 5027) and *Saccharomyces cerevisiae* (ATCC 5027) and found that AgNPs has considerable antifungal activity in comparison with other antifungal drugs (Das et al. 2015). The study was carried out using the technique of minimum inhibitory concentration (MIC), and the drugs tested along with AgNPs were amphotericin B and fluconazole. They also found several changes in the membrane reactions of yeasts which was visualized using scanning electron microscopy (SEM).

Kim et al. (2012) evaluated the antifungal properties of AgNPs on various plant pathogens. AgNP sat concentrations ranging from 10 to 100 ppm along with 18 different plant fungi were used for this study. Fungal inhibition was calculated, and the results showed various levels of antifungal activities of AgNPs (Park et al. 2014). WA-CV-WB13R AgNPs were found to be potent against most fungi, and significant inhibition of fungi was observed at 100 ppm concentration of AgNPs. Therefore, AgNPs seem to possess antifungal characteristics which can aid in prevention of fungal infections.

3.1.3 Antiviral Agent

Apart from being an antibacterial and antifungal agent, AgNPs have also been recognized as antiviral agents. The first report on the antiviral study of AgNPs on HIV-1 reports that the interaction occurs through the preferential binding of AgNPs to the sulfur residues of glycoproteins on the membrane which eventually inhibits the binding of the virus to other host cells. The interaction was reported to be size-dependent in which NPs of 1–10 nm yielded attachment to the virus. The binding of AgNPs with the virus results in the prevention of CD4-dependent virion binding, fusion, and infectivity which makes AgNPs an effective virucidal agent (Lara et al. 2011). The effects of AgNPs on H1N1 influenza A virus has also been

investigated, and AgNPs were shown to induce apoptosis in MDCK cells (Xiang et al. 2011). The antiviral effects of AgNPs are based on their binding to cells that target host cells proteins.

Park et al. (2014) evaluated the efficacy of AgNPs against the inactivation of bacteriophage X174, murine norovirus (MNV), and adenovirus serotype 2 (AdV2) by using molecular methods. Ag30-MHCs were able to demonstrate the highest level of inactivation into viruses (Raimondi et al. 2005). Although the antiviral mechanism of AgNPs is yet to be elucidated, they exhibit great potential as antiviral agents (Galdiero et al. 2011).

3.1.4 Antimicrobial Catheters

Reduction in infections at hospitals was observed when AgNPs were used for coating plastic catheters (Roe et al. 2008). In vitro and in vivo determination of silver release from these devices was carried out using radioactive silver. These improved catheters demonstrated commendable in vitro antimicrobial activity and also prevented the formation of biofilms against pathogens as shown in Fig. 4b. These catheters are capable of sustained releasing silver ions at a specific target site. The released silver ions cause leakage of the cell membranes of microbial cells, thereby entering the cytosol. Once inside the cell, the Ag ions start damaging the mitochondrial membrane. This leads to the initiation of apoptosis and also the generation of reactive oxygen species (ROS). The ROS thus generated along with AgNPs cause DNA damage inside the cell. The ROS also causes the oxidation of certain proteins which eventually render them incapable to carry out their designated roles (Fig. 2). Due to the non-toxic and efficient antimicrobial action, AgNPs may be a boon in the prevention of infections arising due to long-term use of catheters.

3.1.5 Antimicrobial Therapeutic Gel

AgNPs are now being used for therapeutic purposes, especially for dealing with wounds caused from burns. A gel of antibacterial AgNPs was used, and it was found to be as effective as conventional silver compounds even at a 30 times lower concentration (Jain et al. 2009). Toxicity studies reported the mitochondrial localization of AgNPs (IC_{50} = 251 µg ml^{-1}). AgNPs resulted in apoptosis resulting in healing of wounds without leaving behind scars. The effect of AgNPs gel in Sprague-Dawley rats was studied, and the results rendered it completely safe for tropical use. Therefore, AgNP gels can be considered to be an efficient alternative to other antimicrobial agents used conventionally for tropical use.

3.2 Clinical Fabrics

Contamination of clinical clothing is common due to the highly contaminating environments prevalent in the hospitals. Pathogenic bacterial strains have the capability to survive up to 3 months on fabrics worn by patients or healthcare professionals. These strains sometimes are potent enough to survive on freshly laundered clothes as well. The transfer of these strains from nurses' uniforms, surgical wounds to patient beddings and clothing is very likely. These strains are often transferred to the visitors clothing creating a wide web of pathogenic environment. The investigation on the efficacy of AgNP-impregnated clinical scrubs was carried out, and it was found that modified scrubs had lower bacterial counts on them (Freeman et al. 2012). The results confirmed the use of AgNP-impregnated fabrics was highly effective in the reduction of bacterial contamination in hospitals.

3.3 Cancer Therapy

Compared to the conventional forms of cancer therapy, photodynamic therapy is recognized as a promising noninvasive method of treatment. It involves the targeting of a tumor followed by its destruction caused due to irradiation with UV light of specific wavelengths (Ghosh and Das 2015). When AgNP are irradiated by UV light, electron and hole pairs are created leading to the generation of oxidative radicals (Serpone et al. 2006) which eventually destroys the tumor cells. However, the focus on the aspect of toxicity needs to be evaluated largely in the future. AgNPs have also been known for its capacity in biosensing. The plasmonic properties of nanosilver make it an ideal candidate regarding this aspect. These biosensors can be used for biosensing abnormal proteins and can find their application in diagnosis of a wide array of diseases including cancer (Zhou et al. 2011).

3.4 Biological Assays

The escalating research using an OMICS approach leads to the generation of colossal amounts of data which requires high-throughput screening technologies (Klasen 2000). The array technologies are being used for such analysis, and they are also almost reaching their saturation points due to the huge number of array elements. A 3D approach, based on optical "bar coding" of polymer particles in solution can be used for reliable detection and analysis (Han et al. 2001). Single quantum dots of compound semiconductors like AgNPs were successfully used for replacing organic dyes in various biotagging applications (Parak et al. 2003).

3.5 Protein Detection

Proteins play an essential role for maintenance of human well-being. Immunohistochemistry involves the use of nanoparticles for the identification of interaction between proteins. However, this technique is not very successful in detection of simultaneous interactions. Surface-enhanced Raman scattering spectroscopy is used for the identification of single molecules that has been dyed. There can be drastic improvement in the multiplexing of protein probes by the combination of these methods in a single nanoparticle probe. Gold nanoparticles coated with solution of Ag(I) and hydroquinone have been successfully used for the detection of the substrate in question. Apart from the recognition of small molecules, proteins can also be recognized by modifying the probe to contain surface antibodies. Since now, no cross-reactivity has been reported of this method (Cao et al. 2003).

3.6 Other Miscellaneous Applications

Energy storage devices (batteries and supercapacitors) possess capacity to store electrical energy to be used at a later time. Incorporation of Ag nanoparticles into these polymers can upshot their electrochemical storage capacity. Hydrogen storage applications using silver nanoparticle increase high efficiency of fuel cells which is used in transportation, portable uses, and stationary installations. Another application related to inclusion of silver nanoparticles in polymer nanofibers is that they speed up the hydrolysis of the bulk material. Pertaining to their unique properties, such as surface area, nanoparticles have found to be highly active catalytically. Silver nanoparticles exhibit strong catalytic properties for hydrolysis and electrolysis of organic materials, particulary when they are used to manufacture and conversion into silver nanoparticle/polymer composites (Bu et al. 2013; Salehi-Khojin et al. 2013).

Thermal conductivity of polymers is a vital property when it comes to applications of polymer related materials. Traditionally, polymers themselves have intrinsic thermal conductivity of the lower order than those for metals or ceramic materials. These are good thermal insulators at room temperature. Further elevation of this thermal insulating quality can be achieved via incorporating silver nanoparticles into these polymers. Applications with requirement of high degree of thermal conductivity are generally required in a lot of fields. Hence, they become useful in electronic packaging, encapsulations, and satellite devices.

Silver nanoparticles can be combined with metal-enhanced fluorescence (MEF) and surface-enhanced Raman scattering (SERS) to effectively harvest sunlight. These may also be used as antireflection coatings, light-based sensors for cancer diagnosis (Mrlik et al. 2018). Ag nanoparticles are used effectively in density storage media to increase its capacity, nanomagnetic particles to create improved

detail and contrast in MRI images. The presence of the nanoparticles up to an optimum amount facilitates the dipole direction to align well under external electric fields, which in turn leads to increase in the polarization of the entire film. On the other hand, the nanoparticles agglomerate to enhance the charge transport, which results in increased leakage current and decreased piezoelectric properties. Ag nanoparticles may be useful in medical centers to reduce contamination in polluted derange and liquid wastes materials as well as some other devices. It can also be used to protect medical and laboratory equipment to provide protection against interfering signals, including FM, TV, emergency services, dispatch, and pagers. It can also be utilized to protect the equipment at the FM or TV broadcast facilities. Silver nanoparticle-based selective colorimetric sensor has been successfully applied for the determination of Cd(II) ions in groundwater and industrial effluent wastewater samples. This method could also be used as colorimetric assay for sensing applications of ammonia in water. The silver nanoparticles incorporated in polymer matrix give the better dielectric constant which gives better ability to store electric potential energy under the influence of alternative electric field. Silver nanoparticles are used in conductive inks, and their incorporation into such composites enhances the thermal and electrical conductivity. Ag nanoparticles embedded into polyaniline resulted in an increased electrical conductivity and improved dielectric properties by two orders of magnitude in comparison with pure polyaniline matrix and are generally used in microelectronic devices. Nanosilver can prove to be very useful and handy in the textile industry by embedding them into the fiber (spun) or embedded in filtration membranes of water purification systems.

4 Polymer-/AgNP-Based EMI Shielding

Quite recently, electronics and communication have witnessed a technology boom. This have been realized with the development of advanced products like cellular phones, high-speed communication systems, military wireless devices, advanced radars, etc. Sometimes electromagnetic waves are emitted out from the electronic circuits. These EM waves combine and create hindrance in the normal functioning of other electronic circuits. Adjacent electronic devices experience several malfunction by processing several noise signals. This interference is known as Electromagnetic Interference (EMI). It has been reported that exposure to electromagnetic waves for a substantial amount of time may poses health hazards to the human life (Kalia 2015). Therefore, a considerable amount of efforts in terms of research has been put toward development low-cost and lightweight EMI shielding materials which can minimize the impact of EMI (Chen et al. 2014; Meng et al. 2018; Azim et al. 2006). EMI shielding is the property of a material which can attenuate EM waves or a part of it either by reflection and/or by adsorption (Azim et al. 2006). Reflection occurs because of the impedance mismatch between incident wave and shielding material (Li et al. 2013). For lowering the impact of the

absorption loss, the shield should have nomadic charge carriers and/or electric or magnetic dipoles which will interact with the EM field in the radiation (Yu et al. 2012; Choi et al. 2017). EM waves attenuate due to ohmic and heat losses of material when it enters in a current induced medium. This is known as absorption loss, and to deal with this problem, such kind of materials should have high amount of conductivity as well as permeability (Lee et al. 2016). EMI shielding works upon the principle of the good electrical conductivity of materials (Kim et al. 2016). However, major disadvantages associated with them are that they suffer from poor chemical resistance, corrosion, high density, and difficulty in processing. On this backdrop, the advent of conductive polymers and polymer composites has taken place. Flexibility, processibility, corrosion resistant, light weight are some of the key attributes of conducting polymer composites which makes them an ideal alternative for metal-based EMI shielding materials. However, modification of these polymer-based composites is highly desirable since they consume a large filler loading yet lack in providing adequate conductivity to the material (Lee et al. 2016). Polyaniline and polypyrrole (PPy) are the widely used conducting polymers for EMI shielding applications providing shielding efficiency in the range of 26–30 dB. Nanocomposites with thicker film offer better shielding efficacy, where absorption remains the principle shielding mechanism. Processability of these films can be enhanced by suitably blending with synthetic resin; however, shielding efficiency gets constrained in this process (Lee et al. 2016). Fillers with higher aspect ratio (higher length and/or lower diameter) provide more paths to create contact with each other which in term helps in providing higher electrical conductivity to the system. Higher aspect ratio of the filler provides more surface area; hence, percolation threshold gets lowered and shielding efficiency gets increased. The large surface area is also beneficial as it helps in multiple reflections near the surface. EM radiation at higher frequency penetrates only near the skin of material, and it is known as the skin depth. In this perspective, metallic nanowires with superior electrical conductivity are used in polymers nanocomposites. Initially, copper nanowires were used as reinforcement. However, oxidization under atmospheric condition limits the usage of copper in the nanocomposites, and thus, silver nanowires were introduced to the system (Ahmed et al. 2015). EMI shielding materials sometimes require flexibility and transparency of film for specified applications such as transparent coatings. Silver nanowires can be incorporated on the flexible substrate to obtain flexible transparent films. Hu et al. paved synthesized silver nanowires in assistance with polyethylene oxide (PEO) on flexible substrate of polyethylene terephthalate (PET). Further, a layer of transparent poly(ethersulfone) (PES) was given to prevent the corrosion of silver nanowires, and a sandwich system with enhanced shielding efficiency was fabricated (Gashti et al. 2015). Weak adhesion forces between Ag nanowires and substrate often restrict the viability for commercialization of the product in the field of transparent conducting films. Poly(diallyldimethyl-ammonium chloride) (PDDA) has been used as a substrate to mitigate the adherence problem. Li et al. in their research prepared a sandwich material consisting poly(diallyldimethyl-ammonium chloride) (PDDA) and AgNW as bottom layer and graphene oxide (GO) and PDDA as a overcoating

layer (OCL). The top layer has been fabricated in layer-by-layer (LbL) assembly route (Kwon et al. 2001). In another approach to increase the compatibility of Ag nanowires with different resin 3-Aminopropyltriethoxysilane (APTES) silane has been used as surface modifier (Kreuer 2001). Over the years, several methods have been incorporated with an aim to provide effective shielding effectiveness along with several other auxiliary yet essential properties as stretchability, flexibility, and transmittance. The overview of the literature on Ag nanoparticle-incorporated polymer nanocomposites for EMI shielding applications has been summarized in Table 4.

Table 4 Summary of the literature on Ag nanoparticle-incorporated polymer nanocomposites for EMI shielding

Key attributes in process	Obtained results and inferred conclusions	References
In situ polymerization of pyrrole. Variable loading of AgNPs (0.5–10 wt%)	Maximum shielding effectiveness (SE) was observed in the range of −30 to −35 dB for 5 and 10% Ag-loaded films	Lee et al. (2016)
Variation in deposition sequence of. Ag NWs and MWCNTS on cellulosic papers	Ag NW as top layer hybrid papers displayed better electrical conductivity compared to the hybrid cellulose papers with MWCNT top-coating layer	Mamlouk and Scott (2012)
Ag NWs were coated on cellulose papers by dip coating method Coatings were stabilized by poly (vinylpyrrolidone) (PVP)	Light weight, flexible material for EMI shielding applications	Zhang and Chen (2011)
Microporous SBS (styrene-b-butadiene-b-styrene) polymer was prepared from sugar templates Microporous SBS were dipped in silver precursor solution Infiltrated precursors were reduced to obtain the composites	Porous structures enables higher loading of AgNPs After 300 stretching cycles EMI SE values were still around 30 dB in 8–12 GHz frequency ranges	Agel et al. (2001)
AC electrodeposition of Ag into porous aluminum oxide templates Solution processing technique AgNWs in polystyrene matrix	Higher percolation threshold was observed with Ag NWs compared to multi-wall carbon nanotubes EMI SEs with Ag NWs/PS composites were found 31.85 dB at 2.5 vol. % filler loading	Ahmed et al. (2015)
Coating on wool surface with polypyrrole (PPy) by one-step UV-induced polymerization $AgNO_3$ was used as catalyst for oxidation of pyrrole monomers	Lightweight textile-based EM shielding material for civil applications	Wang et al. (2014)

Table 4 (continued)

Key attributes in process	Obtained results and inferred conclusions	References
Large-scale industrial reduction of AgNPs from lucose and silver nitrate at low temperature	10 wt% AgNPs in PVA matrix results in EMI SE of maximum 51 dB in the 1 GHz frequency Increasing filler loading reduces skin depth	Matsui et al. (1986)
Incorporation of Ag nanoflakes and AgNP decorated multi-wall carbon nanotube on NBR matrices Finally, bar coating on polyimide films	Reflction was dominant shielding mechanism. Maximum SE was observed 75 dB at1 GHz	Matsui et al. (1986)
Use of poly (diallyldimethyl-ammonium chloride) for enhancement of adhesion strength between Ag NWs and the substrate	Aggregation of Ag NWs gets reduced	Kwon et al. (2001)
PVDF-BaTiO$_3$-Ag composites were prepared by ultrasonic mixing, followed by solvent evaporation and finally hot pressing	EMI SE of PVDF can be enhanced with incorporation of nanolevel or micron level BaTiO$_3$ powders Small volume of Ag inclusion-enhanced SE significantly	Arranz-Andrés et al. (2013)
Enhancement of corrosion resistance of Ag NWS through poly (ethersulfones) (PESs)	EMI SE can be enhanced by increasing the thickness of Ag NWs	Gashti et al. (2015)
Use of APTES silane (aminopropyltriethoxysilane) for enhancement of compatibility of AgNPs with hydrophilic and hydrophobic resin	Loading of filler can be reduced up to 4 times by incorporating Ag NWs compared to AgNPs in epoxy resins	Kreuer (2001)

5 Polymer-/AgNP-Based Supercapacitor

There is a continuous search for new material to meet the requirements of high power density, long durability, moderate energy density, and long cycle for novel applications in energy storage.

Supercapacitors have attracted much attention due to their excellent high power density, safe operation, easy handling, and long cycle life. In order to achieve fast charging devices for the purpose of energy storage, supercapacitor devices are designed such as to traverse the gap between the batteries and capacitors. These energy storage devices are considered as the future of the next-generation electric vehicles. Supercapacitors can be used for harnessing more regenerative breaking energy and will deliver rapid acceleration due to their ability to charge and discharge quickly. Based on the variety of charge storage mechanism, supercapacitors are classified into two subclasses: (i) electrical double-layer capacitor (EDLC) where the capacitance comes from the charge separation at the electrode–electrolyte

interface and (ii) pseudo-capacitors where the pseudo-capacitance comes from the faradaic reaction occurring at the electrode–electrolyte interface (Sawangphruk et al. 2013; Lee et al. 2015; Das et al. 2017).

Nowadays, conducting polymer has attracted much attention because of its properties such as high electrical conductivity, chemical stability, and environmental firmness (Zang et al. 2008). An extensive review was reported by Snook et al. describing the background of conducting polymers as supercapacitor electrode materials (Abdelhamid et al. 2015). The cost-effective approach for fabrication of high-performance supercapacitor polymer composite materials with tunable energy and power densities is in high demand, and Table 5 summarizes the supercapacitors based on the silver/polymer composites. Thus, the synthesis of polymer/silver nanoparticle films as electrodes for supercapacitor offers the advantages of lower cost and high charge density in comparison with metal oxides. Over last few years, polymer-nanoparticle-based nanocomposites supercapacitors have gained prominence. The combination of two or more individual components enhances the electrical, mechanical, and thermal properties of the entire composite system. The combination of polymers with nanoparticle with attractive properties results in the formation of a material with unique electronic properties. The incorporation of

Table 5 Overview of supercapacitors based on various AgNP/polymer nanocomposites

Composition	Method	Capacitance result	References
Polyacrylic acid/ polypyrrole/ silver composite	Chemical polymerization method	Specific capacitance 226 F g^{-1} at 10 mV s^{-1} and energy density of 17.45 Wh kg^{-1} at 0.5 m A cm^{-2}	Patil et al. (2013)
AgNP film on PET substrate	Roll-to-roll process	(i) Specific capacitance of T/EDLC- (49.5 F g^{-1} at 5 mV s^{-1}) (ii) Specific capacitance of L/EDLC- (99.4 F g^{-1} at 5 mV s^{-1})	Yeo et al. (2014)
AgNP–PANI– graphene	In situ polymerization technique	The specific capacitance of 142 F/g^{-1} at applied current density of 1.5 A/g^{-1} was found for AgNP– PANI–graphene/CFP	Sawangphruk et al. (2013)
AgNP electrode on (PVA– H3PO4)	The roll-to-roll printing process	The areal capacitance of 45 mF cm^{-2} at 0.3 mA cm^{-2} was obtained for the electrode	Lee et al. (2015)
PEDOT: PSS– AgNP	Dip coating technique	The specific capacitance of about 140 F g^{-1} at 20 mVs^{-1} was obtained for PEDOT: PSS–AgNP electrode	Patil et al. (2016)
PGs–Ag (GPGs)	Compression method	The specific capacitance of 253 F/g at 1 A/g was obtained for PEDOT-coated GPGs (PGPG) electrode	Das et al. (2017)
Ag-(PPy/Gr) nanocomposite	Simple mixing	The specific capacitance of 472 F/g at a 0.5 A/g current density was obtained for Ag-PPy/Gr nanocomposite	Dhibar and Das (2017)

silver nanoparticles in polymers decreases the resistivity of the polymers with an acceptance level of specific conductance. Silver nanoparticles have unique optical, electrical, electrochemical, and catalytic properties. Thus, silver nanoparticles are employed with the selection of the organic and inorganic phases to develop specific properties in the novel materials.

So far, numerous strategies have been employed toward attainment of vividly unique and different conductive polymer nanostructures and devices based on it. Numerous methods have been employed for the synthesis of polymer silver nanoparticle nanocomposites via chemical or electrochemical treatment for various electronic applications. Afzal et al. studied the structural and electrical properties of the PANI/silver nanocomposite. Moreover, the optical and electrical transport properties of a PANI/silver nanocomposite were extensively studied by Gupta et al. (2010) PANI/silver nanocomposite as a function of silver weight percentage for vapor sensing application was studied by Choudhury (2009). The electrochemical properties of PANI/silver nanocomposite films were studied by Zhou et al. (2009). According to Patil et al. (2013), polyacrylic acid/polypyrrole/silver shows super-capacitive behavior of the electrodes by using cyclic voltammetry and charge–discharge test (Patil et al. 2013). For PPY/PAA/Ag composite electrodes, maximum specific capacitance 226 F g^{-1} at 10 mV s^{-1} and energy density of 17.45 Wh kg^{-1} at 0.5 mA cm^{-2} was reported.

Recently, there is an increasing interest in the development of flexible/bendable and lightweight supercapacitor for energy storage. Yeo et al. 2014 focus on the fabrication of flexible supercapacitors by printed silver nanoparticle films on polyethylene terephthalate substrate. The thermal and laser annealing treatment was employed to increase the conductivity of silver nanoparticle films effectively. The silver nanoparticles are linked together to form a continuous and bulk metal through melting and solidification steps. In comparison with the conventional thermal processed supercapacitor, superior electrical and thermal properties were obtained for laser-processed supercapacitors. The supercapacitors were fabricated by roll-to-roll process for developing wearable electronics. The thermally processed/ electric double-layer capacitor (T/EDLC) shows 49.5 F g^{-1} specific capacitance at 5 mV s^{-1} as compared to laser-processed/electric double-layer capacitor (L/EDLC, 99.4 F g^{-1} at 5 mV s^{-1}). Two times higher overall improvement was reported for laser-processed/electric double-layer capacitor.

Sawangphruk et al. (2013) synthesized nanocomposite of silver nanoparticle– polyaniline–graphene (AgNP–PANI–graphene) by an in situ polymerization tech-nique as shown in Fig. 5. Silver nanoparticles and graphene were obtained by their respective precursor, i.e., silver nitrate and graphene oxide. These materials act as co-oxidizing agents which enables the conversion of aniline monomers to PANI in the AgNP–PANI–graphene nanocomposite system. With increasing interest in the field of flexible supercapacitors, AgNP–PANI–graphene composites were dispersed in acetone and then coated on flexible carbon fiber paper (CFP) by simple spray-coating technique.

The electrochemical kinetic properties of the prepared electrodes were examined using cyclic voltammetry and galvanostatic charge–discharge methods. The specific
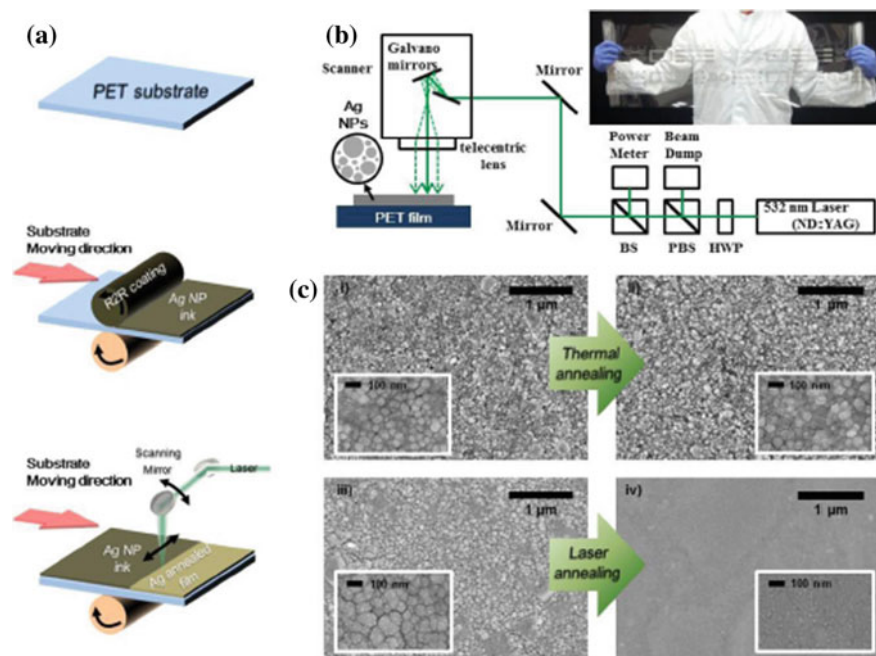
Fig. 5 Illustration of **a** Ag nanoparticle ink is deposited on the PET film. **b** Schematic diagram of optical experimental setup. **c** SEM image of fabricated AgNP films (Sawangphruk et al. 2013). Copyright 2013. Reproduced with permission from Royal Society of Chemistry

capacitance of 142 F/g^{-1} at an applied current density of 1.5 A/g^{-1} was found for AgNP–PANI–graphene/CFP. After the charge–discharge test, the AgNP–PANI–graphene/CFP electrode shows capacity retention of up to 3000 cycles with 97.5% of the original specific capacitance.

Among recent reports, Lee et al. (2015) fabricate solid supercapacitor with flexible silver nanoparticle current collector by a roll-to-roll printing process. The laser annealed silver nanoparticle electrode depicts excellent electrical conductivity. The as-prepared flexible electrodes with silver nanoparticle current collector along with active materials were sandwiched with a polymer medium layer (polyvinyl alcohol–phosphoric acid) as shown in Fig. 6. Both the electrolyte and separator are assembled together to form flexible supercapacitors that can be easily bent up to 135 °C. These kind of fabricated flexible electrodes were studied for electrochemical properties using cyclic voltammetry and charge–discharge test. The electrode retains its properties and performance even under physical disturbance such as bending. The areal capacitance of 45 mF cm^{-2} at 0.3 mA cm^{-2} was obtained, which was then marginally declined to 32 mF cm^{-2} at 3 mA cm^{-2}. In order to evaluate the cyclic stability of the supercapacitor based on laser annealing, the assembling supercapacitor was inspected with the help of galvanostatic charge–discharge measurement at 5 mA cm^{2} for 1200 cycles under varied kinds of bending
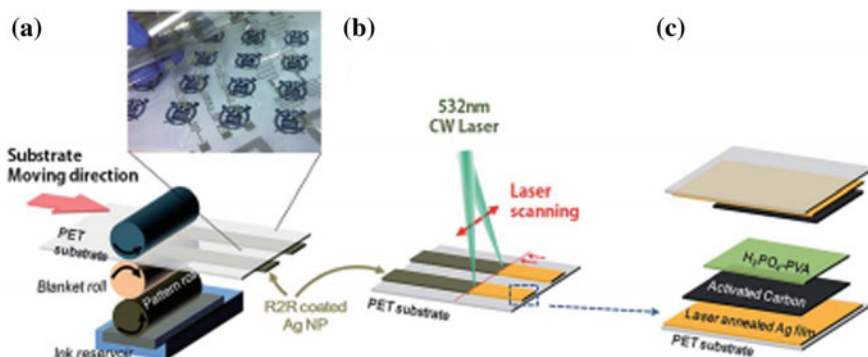
Fig. 6 Schematic depicting the fabrication of flexible Ag electrodes through **a** R2R gravure offset printing followed by **b** focused laser sintering. **c** Fabrication of an all-solid-state supercapacitor using Ag electrodes as current collectors (Lee et al. 2015). Copyright 2015. Reproduced with permission from Royal Society of Chemistry

conditions. The flexible supercapacitors exhibited electrochemical function of over 1200 operating cycles even under intense stressful bending conditions.

Recently, Patil et al. (2016) reported the synthesis of poly(3,4-ethylenedioxythiophene): poly(styrene sulfonate) (PEDOT: PSS)-silver nanoparticles (AgNP) electrode by a very simple yet cost-effective dip coating technique mainly used for supercapacitor application. Cyclic voltammetry was employed to study the supercapacitor behavior of the electrodes by three electrode systems with 0.1 M H_2SO_4 electrolyte. 140 F g^{-1} at 20 mV s^{-1} specific capacitance was obtained for PEDOT: PSS–AgNP electrode.

Very recently in 2017, Patil et al. (2016) reported PEDOT-coated GPGs composite for supercapacitor application which retains their specific capacitance even after the application of large compression. They also possess the ability to recover elastically even from a hundred compression–expansion cycles. Initially, the macroporous cross-linked polymer (PG) was impregnated with polyphenols derived from organic green tea. As the PG is insulating in nature, the conductivity was introduced by the deposition of gold on its surface. The gold was deposited by using two-step methods; firstly, the silver nanoparticles are formed using in situ reduction on the PG walls using polyphenols. Afterward, the gold films are deposited on these same walls. The gold coated PGs (GPGs) were then deposited on the surface of poly(3,4-ethylenedioxythiophene) as a pseudocapacitive material. The PEDOT-coated GPGs (PGPG) was then evaluated for electrochemical studies. The specific capacitance of 253 F/g at 1 A/g was found for PEDOT-coated GPGs (PGPG). Upon compressing the device to 25% of its original size, the capacitance was found to be 243 F/g. Thus, the large compression does not affect the performance of the device. Moreover, the macroporous nature of these PGPG makes it an ideal choice to fulfill the PGPG pores using gel electrolyte.

6 Polymer-/AgNP-Based Fuel Cells

Fuel cells are one of the promising means for generating power in the twenty-first century. Compared to the coal combustion engine, the fuel cell is highly efficient and eco-friendly. Recently, the polymer electrolyte membrane fuel cells encountered several drawbacks such as high fuel crossover and cost-effectiveness. This has diverted the focus of the researchers on making PEMs with low fuel crossover, high proton conductivity, durability, thermal stability, maximum power density, high proton conductivity, and low cost (Wang et al. 2013; Tedsree et al. 2011; Trogadas et al. 2011). This material has very promising applications in view and with regard of the progress in catalytic systems, electronic and photovoltaic devices, fuel cells, sensors, biomaterials, among various others. Recently, hybrid organic–inorganic composite membranes have arisen as an effective alternative approach toward application in the field of a fuel cell. This review mainly focuses on the study of polymer nanocomposites toward fuel cell application. In order to establish and maintain the basic standards of environment and clean energy technologies, they should be powered with fuels acquired from renewable and nonpolluting source with cost-effectiveness. Till now, many efforts are made by various researchers for the development of these technologies (Tang et al. 2011; Nguyen et al. 2012).

Currently, the available commercial fuel cells face the huge challenge of high manufacturing cost, mainly because platinum (Pt) is used as a catalyst to accelerate the reactions. Platinum is the major cost contributor in the fabrication of fuel cell which results in a high price of fuel cell stacks. In order to overcome these challenges, other catalysts need to be explored. Out of various metal complexes, silver (Ag) and nickel (Ni) are the cheaper catalysts used in alkaline media. The silver nanoparticles (AgNPs) exhibit significant physicochemical properties due to its high surface area and reactivity. Precisely, the low cost of silver nanoparticles replaces other noble metals such as (Au, Ru, Pt, and Pd) to become the best catalyst in fuel cells. The fuel cell application involves certain components like polymer in the proton exchange membrane, binder for the electrodes, and matrix for bipolar plates (Ostapova and Al'tshuler 2012). The electrodes typically comprise of nanoparticles as catalyst particles and polymers as a binder. The nanoparticles deposited with polymeric binder are designed to deliver improved performance over the conventional electrodes. The incorporation of nanoparticle in the proton exchange membrane enhances the proton conductivity and also improves the mechanical properties. The polymer serves as high surface and provides protection against the fouling of the metal surface, a scaffold for high dispersion and anchoring of the metal particle. Several kind of polymers are being used in fuel cell applications, such as a hyperbranched polymer with a hydroxyl group at the periphery, cross-linked sulfonated poly(ether ketone), sulfonated polybenzimidazole copolymer, phosphoric acid doped polybenzimidazole, sulfonated polyarylenethioethersulfone, and sulfonated polybenzimidazole. The availability of the finely dispersed particles in the polymer ensures high surface area and possible

enhancement of the unique characteristics of the composites. However, the one of the most important contributory factors adding toward the membrane decaying which in turn eventually limits the lifetime of polymer electrolyte fuel cells (PEFCs) and its degradation is this only (Chang et al. 2013; Park et al. 2014; Seo et al. 2015). The degradation in the PEFC is a multi-step mechanism. This review talks in detail about the technologies involved with Ag nanoparticle-based polymer nanocomposites fuel cell interests (Şimşek et al. 2016).

Over the last few years, several excellent comprehensive reviews have been published in the study of polymer silver nanocomposites for fuel cell application. Jiang et al. produced an extremely active electrocatalyst for oxygen reduction reactions (ORRs) in an alkaline media via coating carbon-based silver nanoparticles along with Pd (Pd@Ag/C) using a galvanic displacement method (Stoševski et al. 2016). Both the Pd and Ag coated catalyst were fabricated by employing galvanic displacement process along with the usage of carbon-supported silver nanoparticles as substrate. The ORR current degradation rate for the Pd@Ag/C was about 154 A cm^{-2} h^{-1}. The incorporation of Pd@Ag/C targeting the ethanol oxidation was found to be inactive making it a promising non-Pt catalyst for ORRs in alkaline media for the direct alcohol fuel cells (Stoševski et al. 2016; Jiang et al. 2010).

So far, the production of hydrogen from formic acid restricts at room temperature by the sufficiently active and/or selective solid catalysts. According to Tedsree et al., the Ag nanoparticle coated with a thin layer of Pd atoms can significantly enhance the production of H_2 from formic acid at ambient temperature (Mi et al. 2007). They have reported a new class of catalyst (Ag–Pd core–shell) with interfaces and can be tailored for structural and electronic effects. This catalyst affectedly promotes the production of hydrogen from the decomposition of formic acid, which favors the processing and separation at room temperature. The production of catalyst offers a number of exciting possibilities for the development and exploitation of small portable PEM fuel cell devices (Mi et al. 2007; Tedsree et al. 2011).

Trogadas et al. have focused on the efficiency of freestanding silica-supported metal (Pt, Pd, Ag, and Au) nanoparticles for (PEM) degradation in an actual working fuel cell (Frackowiak et al. 2006). The fuel cell performance and the macroscopic rate of PEM degradation were examined, depending upon the effect of incorporating the metal nanoparticles into Nafion. The composite membranes were prepared by unsupported and silica-supported Au, Ag, Pt, and Pd nanoparticles. Compared to the Nafion membrane (control), the addition of these freestanding nanoparticles lowers the fluoride emission rate (FER) by 35, 60, 80, and 90%, respectively. These results emphasize toward the fact that the incorporation of certain selected metal nanoparticles having radical scavenging abilities proves to be a promising approach toward mitigation of PEM degradation in a full-fledged operating fuel cell as shown in Fig. 7 (Frackowiak et al. 2006).

Tang et al. studied the synthesis of flexible and unique network structure of polyaniline (PANi) and polypyrrole (PPy) supported by Pt and Ag catalysts having membranes in the form of eggshells (Stankovich et al. 2006). The uniform dispersion of Pt and Ag nanomaterials along with the polymers resulted in the
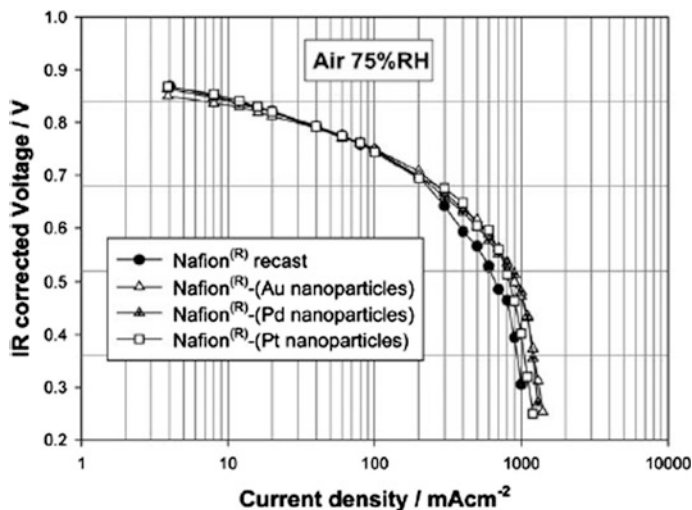
Fig. 7 Image depicting the performance of Nafion and composite Nafion (metal nanoparticles) membrane-based MEAs at 80 °C and 75% RH using air as oxidant and hydrogen as fuel (Frackowiak et al. 2006). Copyright 2011. Reproduced with permission from Elsevier

formation of catalysts depicting much higher electrocatalytic activities than those of bare Pt and Ag electrodes. The role of the conducting polymer network supports highlighted in this study could be of great importance and can eventually be applied for the designing and development of numerous efficient and effective MOR catalysts; also, these PANi and PPy supported Pt and Ag catalysts. The above-mentioned desirable properties allow these materials to be successfully used in high-temperature PEMFCs and other fields (Stankovich et al. 2006; Tang et al. 2011).

Nguyen et al. successfully synthesized Pt nanoparticles by modified polyol and using silver nitrate as an effective structure-modifying agent (Hirata et al. 2004). The as-prepared nanoparticles could be further used as an efficient catalyst for polymer electrolyte membrane fuel cells (PEMFCs) and direct methanol fuel cells (DMFCs) since they exhibited the complexity in terms of surface structure and morphology (Hirata et al. 2004; Nguyen et al. 2012).

In early publications, Ostapova et al. provide a study on the cross-linking of polymers based on macrocyclic polyphenols (Peng et al. 2008). In particular, the metacyclophaneoctols can serve as a matrix of proton-conducting membranes and electrode materials for generating chemical current sources. The metacyclophaneoctols were produced from coking coal, the main source of raw materials for the production. Furthermore, the conductometric and potentiometric studies were performed for the properties of polymetacyclophaneoctols and metal/polymer nanocomposites. According to the study, the H^+ form of polysulfonatotetraphenylmetacyclophaneoctol with 0.2 S/cm electrical conduction corresponds to the best performance characteristics for proton exchange membranes of hydrogen fuel cells.

Moreover, the polysulfonatotetraphenylmetacyclophaneoctol comprising 2% palladium and 10% silver was chosen as a material for the positive electrode, at which oxygen is reduced.

With the increase in technological demands, the polymer electrolyte membranes comprised of highly conductive metal nanowires for novel current collectors were fabricated in such a way to develop an extremely high stretchable function for flexible fuel cells. Moreover, this flexible current collector maximizes the clamping forces under bent conditions resulting in the reduction of ohmic resistance. These fuel cells show an increase in the power density with a decrease in radius of curvature of the cells. Recently, flexible power sources have been extensively studied by various researchers. Chang et al. synthesized polydimethylsiloxane-coated flexible current collect layer of silver nanowires by using a successive multi-step growth method for enhancing the length of the silver nanowires (Zang et al. 2008). Under high bending conditions of silver nanowires electrode, considerable improved electrical conductivity was achieved. The cell achieved a power density of 71 mW cm^{-2} under various bending conditions (Fig. 8).

Park et al. discuss the flexible polymer electrolyte fuel cell fabricated by polydimethylsiloxane coated with very long Ag nanowires percolation network (VAgNPN) current collector (Afzal et al. 2009). The cell shows a decrease in the tendency of electrochemical performances with an increase in torsion.
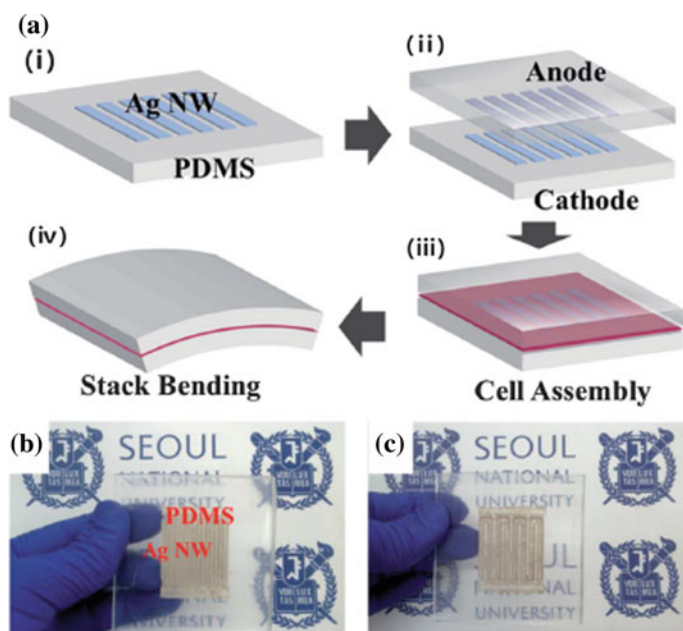

Fig. 8 Schematic of the process for fabricating p Ag NW percolation network electrode patterns on the flow channel patterned PDMS for bendable fuel cell (Zang et al. 2008). Copyright 2013. Reproduced with permission from the Royal Society of Chemistry

The investigation of electrochemical impedances shows loss of performance of flexible fuel cell with an increase of ohmic and faradaic resistances. The maximum power densities 16.8 and 10.9 mW/cm^{-2} were observed for a flexible fuel cell at no torsion and 25° of torsion. The result shows the decrease in the tendency of power density with increase of torsion.

Recently, Seo et al. devoted major time and attention in the synthesis of graphene nanosheet-supported Pd, Pd$_3$Ag, Pd$_3$Fe, and Pd$_3$Co nanoparticles through impregnation along with heat treatment (Gupta et al. 2010). These catalysts having similar metal particle size were used to compare the oxygen reduction reaction (ORR) activity under both acidic and alkaline conditions. The results of electrochemical testing exhibit the ORR activity of high loading Pd and Pd alloy catalysts on GNS. The exhibition of excellent ORR activity by GNS-supported Pd or Pd-based alloy nanoparticle catalyst makes it a strong potential candidate for replacing Pt for usage as cathode electrodes of fuel cells shown in Fig. 9.

Among the recent reports, Şimşek et al. synthesized multifunctional polymer electrolytes by various fabrication methods (Choudhury 2009). Polymer matrix (intercalated poly(vinyl alcohol)/octadecylamine montmorillonite), with partner polymer [poly(maleic anhydride-alt-methyl vinyl ether)], NaOH, and Ag-carrying polymer complexes was fabricated via solution blends as shown in Fig. 10. These fabricated novel nanofiber electrolytes are the potential candidates for applications in energy harvesting and fuel cell nanotechnology.

Very recently, Ivan et al. report the synthesis of carbon-supported silver nanoparticles (Ag: NPs/C) with the help of gamma irradiation-induced reduction
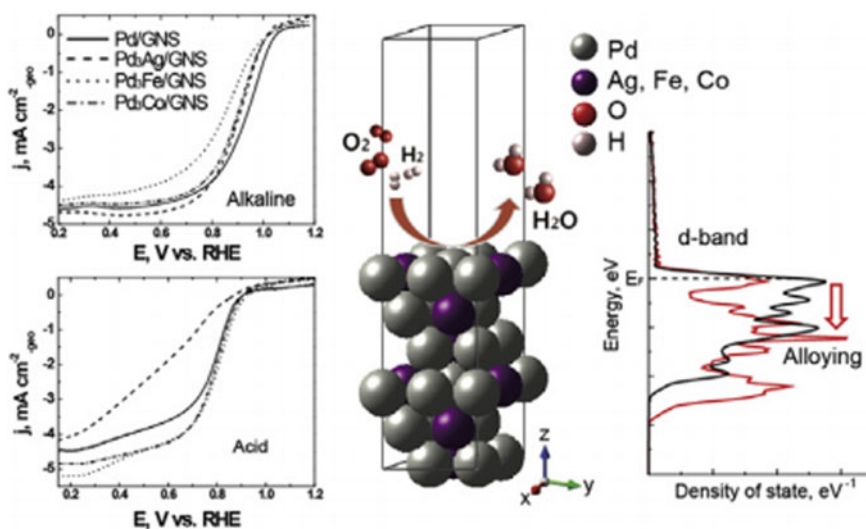

Fig. 9 Schematic of oxygen reduction reaction, ORR, performances of graphene-supported palladium (Pd) and palladium alloys (Pd$_3$X: X = Ag, Co, and Fe) catalysts (Gupta et al. 2010) Copyright 2015. Reproduced with permission from Elsevier
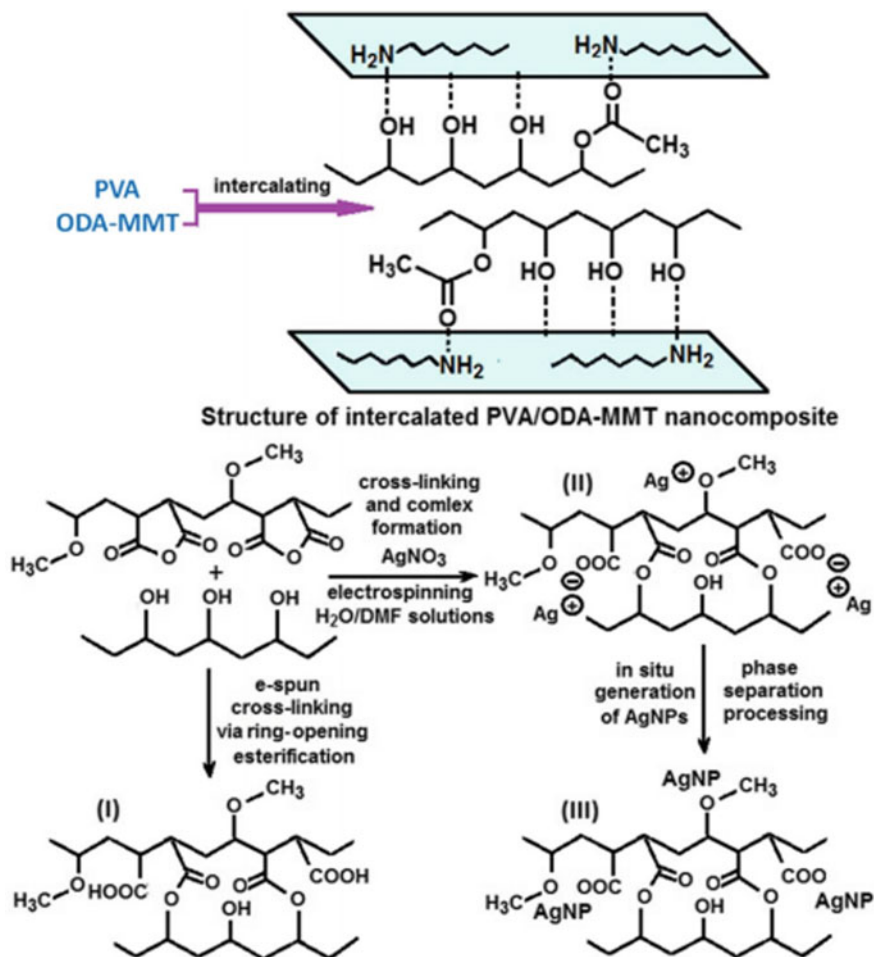
Fig. 10 Schematic depicting the synthetic pathways and chemistry of the multifunctional nanofiber structures (Choudhury 2009). Copyright 2016. Reproduced with permission from Wiley

method; the morphology is shown in Fig. 11 (Zhou et al. 2009). The as-prepared Ag: NPs/C was studied by rotating ring disk method. These can be potentially used as an electrocatalysts in alkaline fuel cells.

Marcos et al. focus on the permeation of silver nanoparticles in poly [sulfonated-co-AA] and poly[styrene sulfonated-co-AA] membranes with the help of electrochemical techniques (Patil et al. 2013). This report indicates the fact that sulfonated copolymer in the medium is more permeable toward the diffusion of silver nanoparticles in comparison with non-sulfonated film. Moreover, in the electrodes, the presence of polymeric film does not affect the redox process Ag^+/Ag^0. These membranes are a promising material for application in the development of fuel cells.
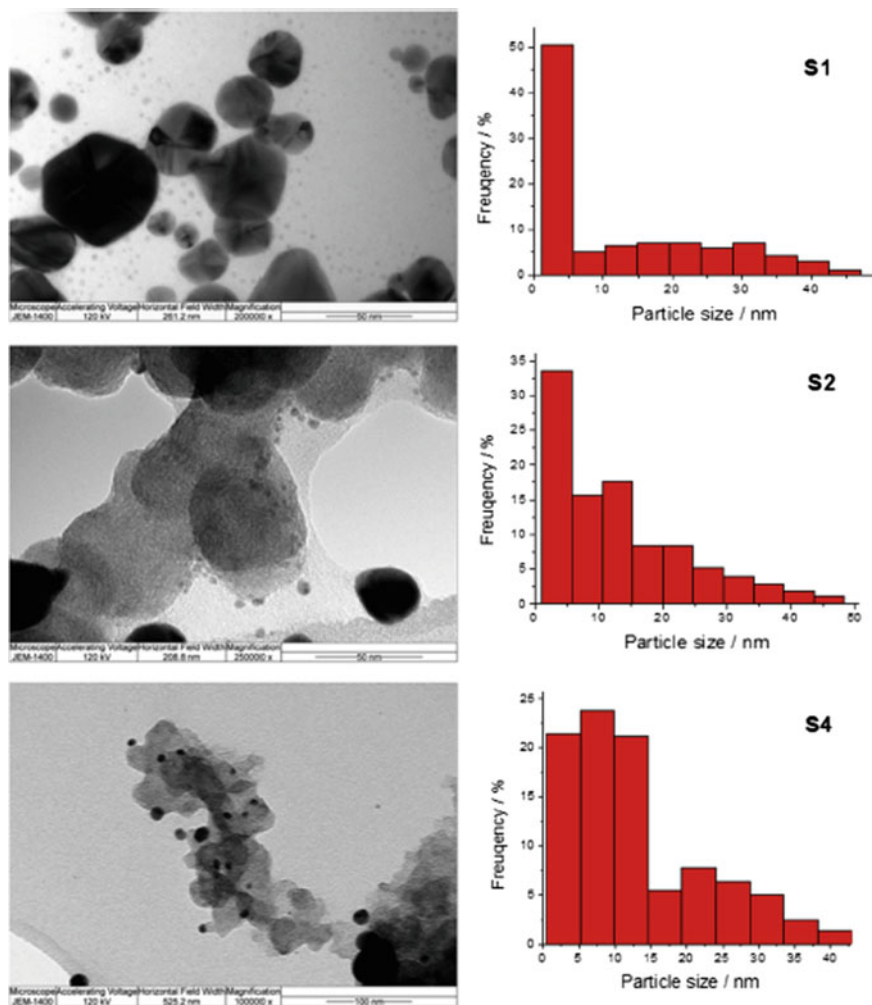
Fig. 11 TEM images of Ag:NPs/C/polymer electrocatalysts with corresponding Ag particle size distributions (Zhou et al. 2009). Copyright 2009. Reproduced with permission from Elsevier

7 Polymer-/AgNP-Based Sensors

Conducting polymer nanocomposites are widely reported as potential sensors with good sensitivity, response/recovery time, stability, durability, and selectivity. Nanoparticles significantly enhance these parameters which are very much essential for the commercialization; however, the selectivity and durability still remain as challenges. Many sensors work quite exceptionally under controlled laboratory atmospheres, whereas target detection in a complex environment stands difficult. PANI is an important polymer in fabricating sensors of various kinds. For instance,

PANI/AgNP sensors detect methanol vapor at room temperature with excellent repeatability and reversibility. The composite showed an increase in voltage when exposed to methanol vapors, and the value decreased when it was placed in nitrogen. PANI influences the composite microstructure by creating a porous fibrous structure with small grain size which enables superior methanol vapor detection compared to pure AgNP. PANI/tin oxide nanocomposites are also reported for its sensing performance toward aqueous ammonia. Several interactions such as hydrogen bonding, chemical bonding, and van der Waals forces exist between the vapor molecules adsorbed and PANI. Due to this effect, the conductivity of PANI increases when exposed to acidic atmosphere and decreases when exposed to basic atmosphere. When the sensor is kept in aqueous NH_3, the resistance value changes abruptly depending on the concentration. The response time and recovery time for the sensor to NH_3 exposure were, respectively, 1–7 and 14 min. At high NH_3 concentration (30%), the sensing material showed faster response.

NH_3 sensing at room temperature was studied for the P3HT:1.00 mol% Au/AgNP nanocomposite films by Kruefu et al. The samples were synthesized by single-step FSP process and further optimized. The optimal composite showed better NH_3 sensing over ethanol, CO, H_2S, NO_2, and H_2O compared to neat P3HT, 1.00 mol% Au/AgNP, and other composites. The higher sensing performance is because of the catalytic effect of Au/AgNP nanoparticles and the porous blended nanoparticle structure. Detection of aqueous HCl vapors at different concentrations (10, 20, and 30%) was done using PANI/AgNP composite. The resistance value decreased when exposed to the vapors and at 30%, and fastest response was achieved. Deprotonation happening in PANI reduces it from the emeraldine salt state to the emeraldine base state which reduces the hole density and increases the resistance. The sensitivity results of the PANI/AgNP composite show its high sensitivity and good repeatability toward both ammonia and HCl vapors as compared to neat PANI. The high-performance can be attributed to the porous structure due to the incorporation of AgNP nanoparticles. Another conducting polymer, PPy, was used to fabricate the AgNP nanocomposite by electro-polymerization method on Pt substrates. The AgNP affects the electro-polymerization, and the polymerization on composite initial layers is easier than the pure PPy initial layers. Humidity sensors from AgNP/PANI nanocomposite were also reported which showed change in resistance/impedance with water adsorption. Adsorption of water generates ions and leads to efficient directional charge conduction. PANI/AgNP showed three times better performance than the PANI due to the composite porosity.

The photo sensitivity of AgNP-10/PET composites towards different UV power densities were checked and compared with other photodetectors, these materials exhibited faster response/recovery, good orientation, high sensitivity, reproducibility, reliability, and multi-level photoresponse. This flexible sensor proved its high mechanical stability through bending test as well. Chen et al. reported the pressure sensing properties of AgNP nanowire-PMMA composite layers. The interacting surface area of the composite was maintained as ~ 1 cm^2 by keeping

0.1 g weighing plastic cup on the sensor surface. In the absence of external pressure, the dielectric constant and initial capacitance were 6.38 and 90.42 pF, respectively. The electrical and dielectric properties in addition to the capacitance values are influenced by the nature and type of polymer matrices and nanoparticles. Thin films of AgNP–PSS/PVA composites were characterized for their pressure sensing behavior by changing the applied dynamic strain. For the same strain, the voltage generated were compared and correlated to observe the piezoelectric response. With dynamic strain, the voltages generated were enhanced and the main reason for the piezoelectricity of (AgNP–PSS/PVA) films is the embedment of nanoparticles. The generation of piezoelectric potential across the composite thin film is a result of mechanical deformation occurring because of the periodically varying longitudinal tensile and compressive stress vibrations. The output voltage depends strongly on the vibrations, and the d_{31} piezoelectric coefficient measures the vibration sensing.

Humidity sensing curves for the PANI/AgNP composite showed a decrease in resistance with an increase in AgNP concentration. The sensitivity is calculated as the ratio of resistance in dry condition (20% relative humidity) to the resistance at a particular humidity. In the composite, charge transfer capacity of PANI increases in presence of zinc and gives distinct response to water vapor. Similar humidity sensors from PANI/AgNP composites are also reported. Lao et al. practiced electrochemical polymerization to fabricate PANI/AgNP composites and PANI-AgNP/PVA double layers to be useful in sensing applications.

Photoconductive responses of a device made using AgNP NBs functionalized with different polymers (PSS, PS-co-Mac, PNIPAM, and CMC) indicate interesting results. When the UV was radiated on, the photoconductance of PSS-coated AgNP NB (red line) increased by 75,000 times, differing from the other polymer-coated AgNPs. This can be due to the coupling effect formation between the AgNP particles and PSS polymer. At the time of UV illumination, the non-moving electrons trap photon-generated holes and reduce the rate of electron–hole recombination which in turn enhances the lifetime of the carrier. The UV absorption spectrum of PSS has a peak around 260 nm that is close to the applied UV source wavelength, 280 nm.

8 Conclusion

Although there are a variety of methods for the synthesis of AgNP, the one including MW shows the enhancement in various properties such as electrical, microwave absorption, transport, and antimicrobial. We found that MW synthesis of AgNP is a highly efficient, reliable, high-yielding, and low-cost method. The antibacterial and antimicrobial properties of AgNP and their nanocomposites are a huge interest area for research in present time as they show great potential for reducing infections and hence providing faster healing and better health to the patients.

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