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Review article

Functional silver nanoparticles synthesis from sustainable point of view: 2000 to 2023 – A review on game changing materials

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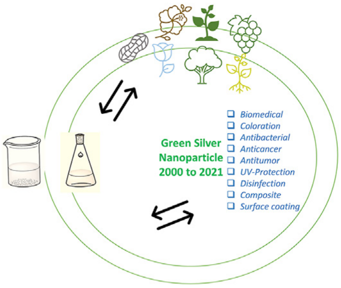
GRAPHICAL ABSTRACT



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ABSTRACT

The green and facile synthesis of metallic silver nanoparticles (AgNPs) is getting tremendous attention for exploring superior applications because of their small dimensions and shape. AgNPs are already proven materials for superior coloration, biocidal, thermal, UV-protection, and mechanical performance. Originally, some conventional chemical-based reducing agents were used to synthesize AgNPs, but these posed potential risks, especially for enhanced toxicity. This became a driving force to innovate plant-based sustainable and green metallic nanoparticles (NPs). Moreover, the synthesized NPs using plant-based derivatives could be tuned and regulated to achieve the required shape and size of the AgNPs. AgNPs synthesized from naturally derived materials are safe, economical, eco-friendly, facile, and convenient, which is also motivating researchers to find greener routes and viable options, utilizing various parts of plants like flowers, stems, heartwood, leaves and carbohydrates like chitosan to meet the demands. This article intends to provide a comprehensive review of all aspects of AgNP materials, including green synthesis methodology and mechanism, incorporation of advanced technologies, morphological and elemental study, functional properties (coloration, UV-protection, biocidal, thermal, and mechanical properties), marketing value, future prospects and application, especially for the last 20 years or more. The article also includes a SWOT (Strengths, weaknesses, opportunities, and threats) analysis regarding the use of AgNPs. This report would facilitate the industries and consumers associated with AgNP synthesis and application

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through fulfilling the demand for sustainable, feasible, and low-cost product manufacturing protocols and their future prospects.

1. Introduction

The field of nanoscience blossomed significantly nearly in the last two decades, and scientist are exploring more and more fields of applications continuously. Nanotechnology is a scientific method to synthesize particles in the nanoscale range, from 1 to 100 nm [1]. The high surface to volume ratio of NPs facilitate enhanced optical characteristics [2]. Numerous NPs are being reported to this day, like AgNP, TiO_2, SiO_2, rGO, gold, cupper, and so on [3, 4, 5]. However, AgNPs are gaining significant attention by the scientific community and the industries due to their tremendous potential. There are different processing routes like physical, chemical, biological, and green approaches are found in order to synthesize metallic NPs like Ag. Green synthesis of metallic NPs is becoming a central research interest for interdisciplinary scientists throughout the world as the traditional chemical methods require more energy and reagents (sometimes harmful and toxic, too) consumption, compared to biological methods. The biological approaches used for AgNP synthesis are plant extracts (stems, flowers, barks, and heartwoods) [6, 7, 8, 9], chitosan [10], bacteria [11, 12], fungi [13], algae [14], and so on. Nowadays multiple ago-industrial wastes [15, 16] like rice husk, coffee husk, and sugarcane bagasse are also gaining popularity for NPs like crystalline SiO_2 synthesis via annelids [17]. Moreover, different animal by product [18] like sheep blood serum are also used for AgNPs synthesis having the sizes of 32.49 nm (spherical) [19] with improved antibacterial and less toxicity effects. After plant and microorganism, this is one of the most significant routes of biological synthesis of AgNP. However, due to availability and cost effective features, plant extracts have become more popular for research purposes. Hence, enormous research is directed to exploring plants and their different parts around the world. On the other hand, microorganism based AgNPs extraction requires some additional processing like identification, isolation, and developing special media, besides controlling the temperature. Comparatively, plant extracts are more convenient, as there is no risk of bacterial development/con tamination during storage, as opposed to microorganism-based synthesis [20, 21, 22].

The chemical-based synthesis of AgNP is challenging for biomedical applications, because of its enhanced toxicity in some cases [23]. Conversely, plant-based AgNPs are getting tremendous attention in biomedical applications, especially for bacterial resistance [24, 25], anticancer [26], and antioxidant properties [27]. Moreover, AgNPs are also getting popular in the field of textile, food sensing, pharmaceutical, water purification, structural composites, and so on [28]. However, the significant increase in the consumption of AgNPs also increases their release in the surrounding environment, which may cause a risk to the aquatic systems, humans, and animals [29, 30]. Therefore synthesized NPs are considered cheaper, facile, eco-friendly, and convenient, hence attaining more popularity to the manufacturers and scientists [31, 32, 33, 34]. Moreover, there are also reports found on various other biomolecules like carbohydrates, sugars, alkanoids, proteins, fats, tarpenoids, flavonoids, phenols, enzymes, and tannins for the efficient synthesis of AgNPs, which promotes the binding of NPs with the applied substrates [28, 35]. As nature is a big source of sustainable materials available throughout the globe, green synthesis of AgNPs using various plant extracts is showing new opportunities and routes to develop sustainable and bio-based green products through minimizing the consumption of inorganic chemicals. Furthermore, as the plant extracts function both as reducing and stabilizing agents at the same time, the consumption of energy and utilities to run the operation is also getting minized significantly.

The increased surface, different shapes, and comparatively smaller sizes have made the NPs like AgNP a potential candidate for multifaceted applications. However, besides the enormous advantages of AgNPs and associated products, there are also some limitations that need to be solved through applying advanced scientific knowledge and technologies to eliminate the issues related with human health and the surrounding environment. Chemical-based stabilizing and reducing agents like different organic solvents such as $NaBH_4$ (sodium borohydrate), ascorbate, hydrazine, trisodium citrate, and so on, were used with silver precursors in order to synthesize AgNP through following chemically mediated protocols at the beginning of the last decades, and prior to it [36, 37]. A review of all relevant aspects of AgNPs with a significant focus on green AgNPs, like synthesis protocol, characterizations, performance charateristics, associated applications, and an overall SWOT analysis regarding the different positive and negative factors, points to the significant potential of this innovative, biologically synthetized nanomaterial. Although there are some reports found regarding AgNPs and their applications, they are still limited to some particular areas/fields. However, a complete review covering all the fields is not yet available at this time. Hence, this review combines all fields/areas to help readers gain a full perspective of this topic. This work would facilitate the researchers and manufacturers to gain a complete understanding regarding the routes to sustainable and economical synthesis of green AgNPs.

2. Synthesis mechanism and protocols of green AgNPs

Principally, there are two main categories of AgNP synthesis (Top down and Bottom up), which are further categorized in terms of probable toxicity and so on (Figure 1). The most common approaches for AgNPs synthesis are chemical reduction, physical and biological/green synthesis methods. Earlier, chemical synthesis methods were widely used as biological synthesis was not explored significantly. However, the utilization of chemical synthesis protocols entailed the use of some reagents that were not always considered safe [38]. Biosynthesis of metallic AgNP has received tremendous research attention recently to minimize the toxic and environmental burdens from the associated products [39, 40]. Most plants are natural capping agents that are free of health hazards. Therefore, they provide a significant and better platform to greenly synthesize AgNPs. The principal mechanisms related to AgNP synthesis is the stabilization and reduction of silver precursors like $AgNO_3$ with different plant/carbohydrate extracts or microorganisms. The functional groups (OH) present in the biomolecules or microorganisms traces the stabilization and reduction of Ag^+ to Ag^0 [41,42]. Moreover, the biological synthesis of AgNP possesses higher tolerance to metallic NPs, hence could easily be handled. However, the mechanism involved with AgNP is not yet fully understood, especially for the variation from plant to plant, species to species, and plant part to plant part, making it more complex, as nearly 4000 phytochemicals have been found in plants to date [42]. Furthermore, through adjusting the cultural parameters like time, temperature, pH, concentrations of precursor, concentrations of stabilizers (plant extracts), AgNPs with adequate size and shape could be synthesized [43, 44].

2.1. Chemical-based synthesis

This is a very common and widely used method for AgNP synthesis, which is performed through reduction mediated by inorganic and organic reducing and stabilizing agents. Generally, most commonly used reducing agents include $NaBH_4$, ascorbate, sodium citrate, Tollens reagent, N, N-dimethylformamide, elemental hydrogen, poly (ethylene glycol)-block copolymers, and so on, in aqueous and non-aqueous solutions [45, 46, 47]. The main function of using such kind of reducing agent is to form the metallic Ag^0 through reducing Ag^+, where the agglomeration occurs in the oligomeric clusters. Consequently, the metallic and colloidal AgNP are

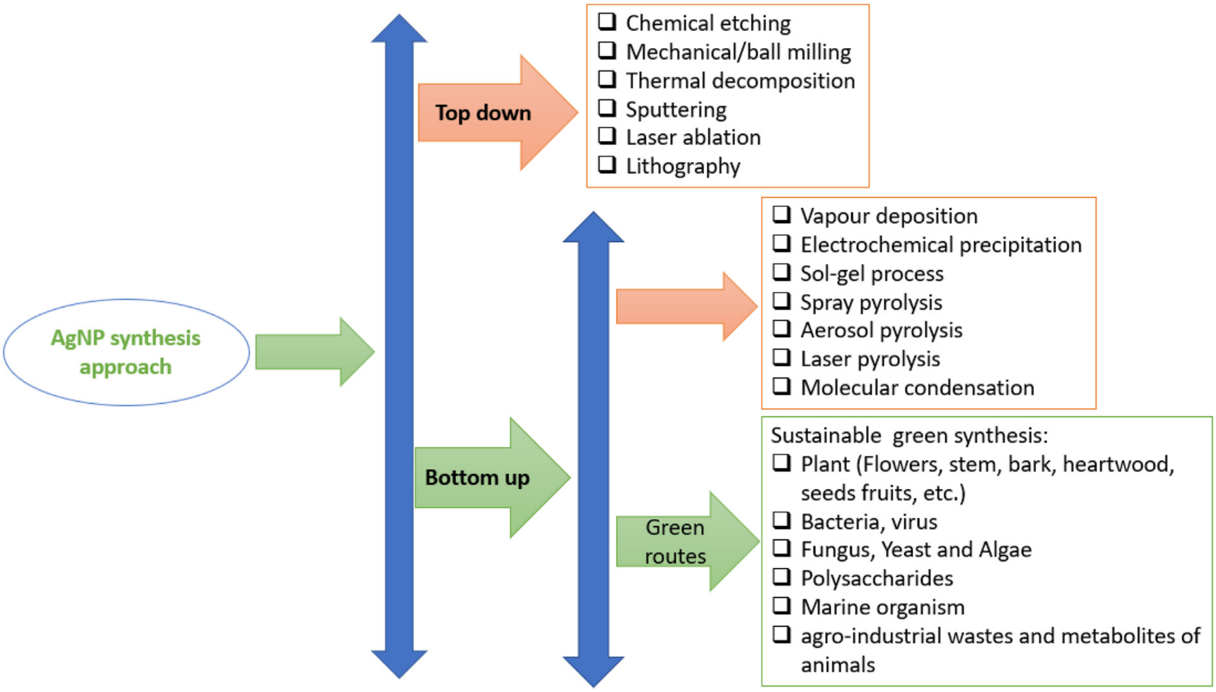


Figure 1. Different synthesis approaches used for AgNPs synthesis.

formed through these clusters [48, 49]. However, agglomeration could be created when the NPs are bound or adsorbed onto the surface, hence, stabilizers are needed to ensure uniform dispersion through avoiding such kind of problems. Moreover, the presence of amines, thiols, alcohols, and acids in the surfactant could interact with particle surfaces, and stabilize their growth through protecting agglomeration, sedimentation, and any kind of surface property loss.

On the other hand, although there are various types of inorganic and organic (amines, ethylene glycol, ethanol, dimethyl formamide, and so on) solvents available, water is extensively used as solvent (in more than 80% of the cases) [50]. Awasthi et al. chemically synthesized AgNPs from citric acid, sodium citrate, and $NaBH_4$ where they found all the typical characteristics of metallic Ag having UV-vis absorption spectra at 408–410 nm, and sizes within 5 ± 1 nm (measured by TEM analysis) in 2013 [51]. Consequently, they have found the existence of some cellular toxicity effects in terms of cellular visibility and viability [51]. However, to minimize such toxic effects, different efforts were conducted by using chemical reduction technology, beyond the biological synthesis approach. Likewise, Quintero-Quiroz et al. recently conducted a study on optimizing the AgNP synthesis through controlling the parameters: (a) concentration of $AgNO_3$, (b) concentration of $NaBH_4$, (c) concentration of sodium citrate, and (d) pH of the reaction system [52]. They claimed further that such a synthesizing protocol could improve the physico-chemical properties besides the increase in antibacterial capability [52]. Moreover, the chemically synthesized AgNPs could be of different shapes like spherical, nanorods, nanowires, cubic, and triangular [53]. However, research is ongoing to replace chemical-based synthesis of AgNPs through more sustainable approaches.

2.1.1. *Toxicity of chemical-based synthesis approach of metallic silver*

The main objective of the green chemistry is the toxicity free metallic silver synthesis. However, it is also seen in some recent studies that, metallic NPs also exist cytotoxic effects on human body, principally for the cardiovascular and respiratory systems, DNA, osteoblasts and osteoclasts, and embryo evolution of malfunctions [54, 55]. In some other study, the effects of AgNP on lungs cells on human body also studied and found that release of Ag+ is proportional to the size of the NP [56]. It was also reported that the toxicity of metallic silver also depend on the various organisms coming contact with the respective materials [57]. Therefore, it is necessary to understand the potential toxic effects of the NPs and to take corrective actions against them.

2.2. *Physical synthesis*

The most popular synthesizing protocols for AgNPs are laser ablation, evaporation condensation, gamma and electrical irradiation, and lithography [53]. Physical synthesis methods are advantageous compared to chemical-based synthesis protocol due to the uniform dispersion of AgNPs and free from any solvent-based contaminations. The tube furnace used in case of the physical approach occupy a large surface area, has high energy consumption (more than several kilowatts), and requires more time to attain thermal stability, as the temperature rises from the atmospheric level [38]. However, physical approaches also facilitate the production of AgNPs with high concentration, stable NPs production, simple operation protocol, and inhibition of toxicity [58]. Similarly, the laser ablation technique is convenient for attaining chemical reagent free metallic colloids. In this method, NPs of smaller dimensions could be attained in water, just using the high power laser and smaller spot sized beams emitted from laser [59]. Moreover, controlled particles with specific sizes in nanocolloids could be produced further through changing the laser pulse number [60]. In this regard, Menazea et al. reported on AgNP synthesis by femtosecond pulsed laser ablation in various liquid media like distilled water, deionized water, Tetrahydrofuran, and dimethylformamide and found significant antibacterial capability in case of deionized water [58]. On the other hand, Harra et al. developed AgNPs with 50–130 nm dimensions within 398–448 nm wavelengths through following another method (evaporation condensation) where the NPs were collected through an electrostatic precipitator on a glass substrate [61]. However, more green and sustainable synthesis protocols were in urgent demand to utilize green AgNPs in more sophisticated and sensitive applications like in the biomedical field to a greater extent.

2.3. Plant-based synthesis

In order to fulfill environmental requirements and standards, biosynthesis of the metallic Ag is gaining much popularity with the advancements of science and technology. Although there are various routes of AgNP synthesis, bioinspired methods are most popular due to providing minimized risk issues in terms of health hazard problems (Figure 2). Plant-based extracts are encouraging in terms of large scale production of extracellular AgNP synthesis to fulfill the increasing demands of AgNPs worldwide. Various active biomolecules present in plants are capable enough to stabilize and reduce the silver ions present in the precursors. This is the key distinction between the plant extract mediated nanosilver compared to the chemical-based protocols. The size and shape of AgNPs depend on certain factors [62], listed below:

(a) Concentrations of silver precursor like $AgNO_3$,
(b) Plant extracts volume,
(c) Types of plant and associated parts used,
(d) Reaction time,
(e) pH, and
(f) Temperature.

Initially, identification of plant parts like the materials listed below need to be confirmed for the green (Figure 3) synthesis of AgNPs:

(a) Heartwood,
(b) Leaf,
(c) Bark,
(d) Flower,
(e) Fruit,
(f) Roots,
(g) Pulp,
(h) Stem,
(i) Latex,
(j) Seeds, and
(k) Rhizomes

Later, the selected plant parts (Figure 4A-P) are purified, then washed with clean water to remove any adhered debris, mud, and stones from the surfaces. The plant materials were then dried at room temperature to evaporate the volatile biomolecules. The collected plant materials are then crushed to a powder form to facilitate the easy extraction in aqueous form using water, neither using any other solvents, nor applying heat to bring to boil. The boiled plant extracts are then filtered using laboratory-grade filter paper. The filtered aqueous solutions are then stored at around 4 °C in the refrigerator for future usage. Detailed discussions were also provided in our recent publications [6, 63, 64, 65]. Later, the silver salts were prepared usually within 0.5–5 mM concentrations using the precursor. Different amounts of plant extracts like 2/3/4/5% MW (v/v) are then added to the silver precursor for the synthesis of nanosilver. The solutions were then homogenized by constant stirring and the color of the solutions started to turn from a milky/colorless state to a transparent yellow/brown, demonstrating a successful synthesis/formation of metallic silver [66]. Generally, such kind of color changes appeared even at ambient temperatures like 25 °C, however, some of the studies also report applying heat around 80 °C or higher [67] in case of in situ synthesis in the presence of textiles. The fabric/fiber materials are then washed several times to remove any adhered nano seeds from the surfaces of the substrates in case of textiles functionalization. In this regard, more research is necessary to find the right biomolecules functioning as the stabilizer and capping agent. A detailed mechanism regarding the synthesis of AgNPs from different plant extracts are shown in Figure 5, whereas a schematic reaction mechanism regarding the reduction of Ag^+ toward green AgNP synthesis is shown in Scheme 1. *Ginkgo biloba* leafs contain polyphenols confirmed by an FTIR study [68]. The macromolecular compounds possessing hydroxyl groups are oxidized, hence Ag^+ is reduced to AgNP (Scheme 1). A similar reaction mechanism was also reported in another study (Scheme 2), where two benzene rings present in the phytochemical taking part in reduction of Ag^+, the tannin was oxidized by Ag^+ leading to an intermediate silver complex formation and finally producing the silver ion and quinone [69]. The free electrons produced during the synthesis process facilitate the reduction of silver ions toward zero valence silver [69]. The overall interactions occurred possibly due to the polyphenolic compounds present in the leaf extracts. Moreover, different reports nearly in the past 20 years regarding plant extracted AgNP synthesis is listed in Table 1.

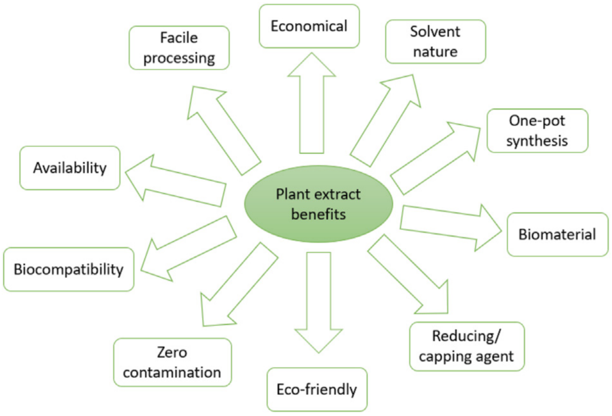


Figure 2. Benefits of biosynthesized green AgNPs.

Furthermore, different microorganisms (like yeast [127], algae [128], fungi [129], and bacteria [130]) also have great importance in green AgNPs synthesis. Nowadays various microorganisms are employed for new metallic NP synthesis due to their excellent potential. Bacterial cells are continuously exposed to various stressful conditions/situations and they are capable in so many cases to survive in such rivalry situations. Hence, they have a certain resistance capability against high concentrated metallic salts as well. The reason behind such a resistance is the efflux system [131]. Microorganisms can provide intra- or extracellular inorganic materials depending on nanostructured materials development. Likewise, silver precursor-isolated *Pseudomonas strutzeri* bacteria is capable of reducing Ag^+ ions to produce AgNP, where the reported size range was 16–40 nm [132, 133].

3. Characterizations used for of AgNPs and associated products

Like other NPs, AgNPs also undergo certain characterizations like UV-absorption spectroscopy, elemental compositions in terms of SEM mediated EDX (energy disruptive X-ray), XRF (X-ray fluorescence), iCP OES (inductively coupled plasma optical emission spectroscopy). The morphological studies are generally carried out using Scanning electron microscopy (SEM) and transmission electron microscopic (TEM) analysis at different magnifications. Moreover, the size of AgNP is also measured by TEM analysis. The chemical bonding in the AgNP coated substrates is characterized in terms of FTIR (Fourier transform infrared spectroscopy) analysis. The most prominent test for greenly synthesized AgNP is the measurement of antibacterial performance characteristics which is generally tested against gram positive and negative bacteria [134]. Figure 6 illustrates chemical structure of different phytoconstituents responsible for the green synthesis of AgNPs.

3.1. Studying phytochemicals in extracted materials

The phytochemicals present in the naturally extracted materials could be evaluated and determined through phytochemical screening analysis. A recent study [136] on medicinal plant extracts phytochemical screening test found that there is explicit presence of phenols, flavonoids, saponins, and triterpenes, see Table 2. The *R. acetosa* extracts contain

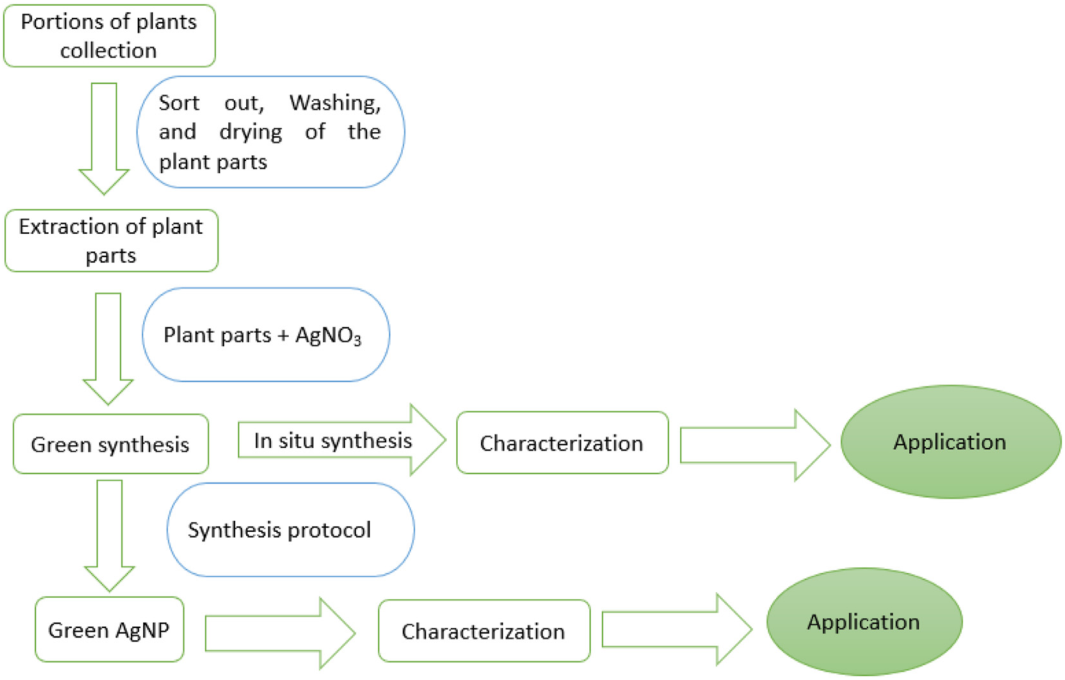


Figure 3. Green synthesis flow process of AgNPs.

xanthoproteins, carbohydrates, and flavonoids [137]. Aome other types of phytochemicals, like carboxylic acid, aldehydes, ketones, and amides are also present [138]. The chemical structure of the phytochemicals is shown in Figure 6. Flavones, quinones, and organic acids are some of the water soluble compounds that could reduce the Ag^+ immediately. Some other studies reported similar explanations too [139, 140]. Moreover, the stability of synthesized AgNPs depends on the reaction of such phytochemicals [137, 138]. This is why it could be imperative to study the presence of phytochemical elements in the plant materials used before using them for AgNP synthesis.

3.2. UV-vis absorption spectra

The UV-vis spectrophotometer is a widely used tool for analyzing the absorption spectra of developed AgNPs. The improvement of synthesized AgNPs can be monitored by UV-vis spectroscopic analysis. The LSPR property of metallic NPs is one of the most important characteristics, which depends on the size and shape of synthesized metals. AgNPs contain free electrons that are stimulated through the absorption of visible light, and are transmitted to the higher level of energy, although the electrons in excitement stage remains unstable, but return to base level of energy upon emitting the photon [141]. Generally, successful development of AgNPs show a peak at nearly around 430 nm wavelength, possibly due to the excitation of surface plasmon resonance (Table 1). A homogeneous particle distribution appears in case of *Enicostemma axillare* nanosilver, demonstrating no agglomeration or settling of the NPs [142]. Metallic NPs like Ag contain free electrons, providing an LSPR absorption band for the light wave resonance of vibration electrons. However, the sharp bands started to increase from 417 nm (Figure 7 A) with the increase of time duration, see Figure 7 A [142]. On the other hand, *Garcinia mangostana* stem extracted AgNP confirms the formation of metallic Ag through providing the broadened peaks at 430 nm (Figure 7 B) [143]. In another study by Behravan et al. reported that *Berberis vulgeris* leaf extracted AgNPs show a wide absorption peak at 450 nm, confirming successful formation of NPs [144]. Different hollow nanostructures like nanotubes, nanocages, and nanoshells are getting considered as emerging noble types of plasmonic nanostructures compared to solid structured nanoparticles [145]. The plasmonic hybridization of hollow nanostructures facilitate them as a potential candidate for the biomedical field as they could be tuned from visible to near infrared range.

3.3. Chemical and elemental analysis of AgNP treated products

Elemental presence of AgNPs could be detected and quantified by SEM deployed EDX spectrum analysis. Generally, metallic silver nanocrystals give signals at 2.96/3 keV [136, 146]. The EDX spectrum for *Garcinia mangostana* stem and *Artemisia nilagirica* leaf extracted AgNPs are shown in Figure 8, where the detection of the NPs is clearly observed. Moreover, the presence of chemical elements could also be observed further using elemental mapping analysis [10, 147]. In another investigation for *Averrhoa bilimbi* fruit extracted AgNPs (having 50–150 nm size) [148], showing the confirmed peak of metallic Ag, whereas there is also another peak (Al) related to impurities. On the other hand, Rao et al. claimed that the presence of weaker O, C, and Al may have originated from the biomolecules bound to the metallic surfaces in *Ocimum sanctum* leaves used for green AgNP synthesis [149]. There are also other peaks (Cu, N and C) observed beside the Ag, possibly originating from carbon coating on copper grids (potentially appearing as impurities), even in biosynthesized AgNPs [150].

Moreover, XRF analysis of the AgNPs deposited as solid samples could provide the concentrations of metallic silver present in the AgNP treated products. In our previous studies [6, 67, 147] on various biosynthesized materials, XRF analysis was carried out to investigate the concentrations of AgNPs deposited on solid surfaces of textiles. The concentrations of AgNPs showed an increased trend with the increase in silver precursor in the deposited material surfaces. In case of *Taxus baccata* heartwood extracted AgNP, there were 322 (10), 837 (14), and 912 (15) PPM NPs found where 0.5, 1.5, and 2.5 mM $AgNO_3$ was used as the precursor and 3.0 % MW (v/v) was used as the reducing agent [150]. This result also goes in line with another study that used *Ferulago macrocarpa* flowers for the extraction [151].

Furthermore, iCP OES is another significant characterization profile that could provide the concentration of developed AgNPs in liquid medium. This is one of the most convenient ways to prove that the AgNP develops in the nanocolloid [152], beside investigating the UV

Figure 4. Various plant extracts (Seed/fruits, heartwood/roots, and leaves/flowers) used for green AgNP synthesis: (A) *Dillenia indica* [70]; (B) *Zingiber officinale* [71]; (C) Platycodon grandiflorum [8]; (D) *Manilkara zapota* [72]; (E) *Crataegus douglasii* [73]; (F) *Panax ginseng* [74]; (G) *Ficus benghalensis* [75, 76]; (H) Grape seed [77]; (I) Emblica officinalis [78, 79]; (J) *Morinda citrifolia* [80, 81]; (K) *Skimmia laureola* [82, 83]; (L) *Piper nigrum* [84, 85]; (M); Solanum lycopersicums [86] (N) *Taxus baccata* [6]; (O) Atrocarpus altilis [87, 88]; (P) Buniu persicum [89]. Adapted with permission from Elsevier. Copyright, Elsevier, (A) 2013; (B) 2017; (C) 2019; (D) 2014; (E) 2014; (F) 2018; (G) 2012; (H) 2018; (I) 2015; (J) 2013; (K) 2015; (L) 2010; (M); 2013; (N) 2021; (O) 2016; (P) 2016.

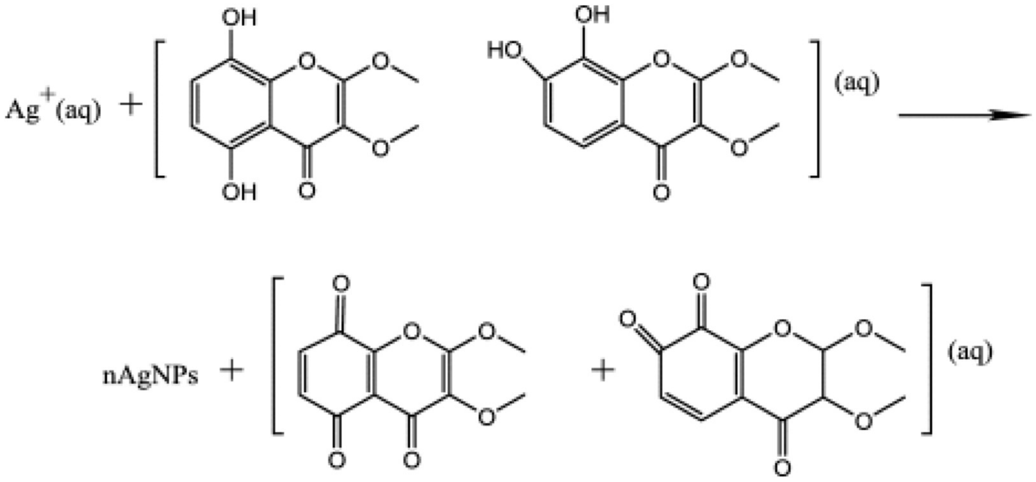
absorbance of the liquid samples. A quantification study was reported for metallic Ag presence in the nanocolloid, and found the value of 100 ± 2 mg/L, obtained after the centrifugation, possibly due to synergic effects toward free metals [153].

3.4. Morphological studies

The metallic shape or morphology of NPs could play a vital role for determining their chemical and physical properties. The NPs may be of various shapes, such as nanowires and nanorods, tetrahedral, triangular, hexagonal, decahedral, and so on [154]. Moreover, different nanosilver seeds, nanosilver rods, nanosilver disks, nanosilver spheres could also be observed by TEM analysis [155]. The appearance of AgNPs is observed through morphological characterization of materials surfaces. The treatment of textile surfaces with AgNPs also display smooth and uniform appearances. A starch-capped and one-pot AgNP synthesis protocol was reported, where the spherical NPs were observed [155]. The size of the NPs was within 15–20 nm, signifying the successful synthesis of Ag [155]. In the same study, alkali treated starch was reduced from Ag^+ to Ag^0; whereas an aggregation was observed in higher concentrations of $AgNO_3$ loading (1.0 and 2.0 mM), possibly due to the preparation conditions, where the AgNPs are condensed and crowded [155]. A schematic photograph of TEM analysis, along with particle size histograms are shown in Figure 9 A and B.

SEM is another important tool for morphological studies of NPs. The morphological photographs may be taken at different magnifications at certain voltages to observe the particles clearly. Sometimes gold plating is used for the clear observation of AgNPs, and to minimize the risk of sputtering. Figure 10 (A, B) and (C) shows typical images of greenly synthesized AgNP from *D. Lotus* and *Artemisia vulgaris*, respectively. The spherical AgNPs are explicit in Figure 10 (A, B). However, there is an agglomeration (A, B), resulting for sustainable plant extract mediated

Figure 5. A schematic representation of green AgNPs synthesis from *Taxus baccata* heartwood. Republished with permission from Wiley & sons [6]. Copyright, Wiley 2021.

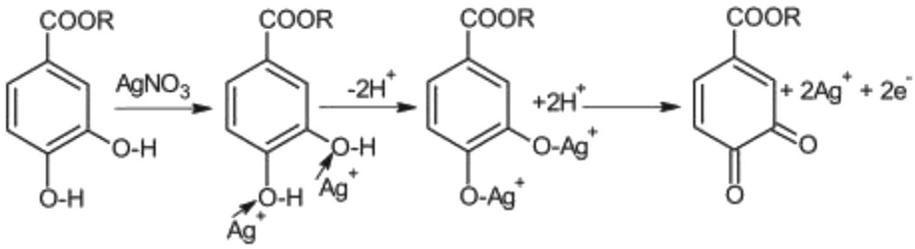


Scheme 1. A schematic reduction mechanism of Ag^+ for *Ginkgo biloba* leaf extracted AgNPs. Republished with permission from Elsevier [68]. Copyright, Elsevier 2021.

AgNP synthesis [156]. Generally, the AgNP formation happens in three stages: (a) nucleation/atomic formation, (b) growth, and (c) stabilization [156]. In case of nucleation, the Ag^+ ion is reduced by the reducing agent (plant extract is used here Figure 10 A, B, C). Secondly, the atom is continuously anchoring to form atomic clusters, and thirdly aggregation occurs again and reaches a maximum nucleation level, thus developing larger particles formation. However, a successful stabilization occurs due to polymeric interaction, and metallic AgNP is finally formed [157, 158]. In some cases, SEM assisted studies could also provide the sizes of metallic NPs [159]. Likewise, in another study, the size of the *Bacillus licheniformis* mediated AgNPs was found nearly 50 nm, using SEM analysis [160]. On the other hand, the in situ chitosan mediated AgNP coating on textile fabrics also displays the clear presence of metallic particles on the surfaces [67].

3.5. XRD and XPS analysis of AgNPs

XPS is a well-known method for analyzing the surface chemistry of materials. The elemental composition, electronic and chemical state of the atomic presence in the materials can be investigated too. On the other hand, crystallographic features like crystal structure and crystalline phases of the materials are typically determined using the XRD analysis. In this regard, Peng et al. reported about the development of AgNPs (sized within 8.39–14.00 nm) where hemicellulose extracted from bamboo was used as the stabilizer, and glucose functioned as the reducing agent [162]. The same study also conducted both XRD and XPS analyses beside the other necessary tests to characterize greenly synthesized AgNPs [162]. The typical face-centered cubic crystal structures of the AgNPs are reflected at 38.2° (111), 44.3° (200), 64.5° (220), 77.4°



$$2Ag^{+} + 2e^{-} \rightarrow 2Ag^{0}$$

Or

$$2H^{+} + 2e^{-} \rightarrow H_2$$

$$2Ag^{+} + H_2 \rightarrow 2Ag^{0} + 2H^{+}$$

Scheme 2. Reduction of Ag^{+} by *Aegle marmelos* leaf extracted nanosilver synthesis. Republished with permission from Elsevier [69]. Copyright, Elsevier 2013.

(311), and 81.6° (222) [162-163]. However, the prominent orientation of peaks found in Figure 11 is nearly around the 111 plane, compared to the other peaks (200, 220, 311, and 222). Additionally, the size determined using the Debye-Scherrer method was found to be, on average 14.52 nm, which is comparatively higher than the one measured by the TEM study [162]. The possible reason behind such a deviation maybe due to the larger AgNP agglomerations, which happened at the higher temperature (300 °C) for the prolonged period (1 h). However, the AgNPs are still in the nanoscale dimension. The calculated lattice is also found to have a constant value obtained from the pattern of XRD (4.0897 Å) [163].

Moreover, the double peaks at 371.17 and 365.4 eV encompassing a high energy band, Ag $3d_{3/2}$ and a low energy band, Ag $3d_{5/2}$, respectively are shown by the XPS spectrum analysis [163]. The observed peaks found due to the attributions of reduction and oxidation states due to the coexistence of Ag (0) and Ag (I), respectively at 365.4 and 371.17 eV binding energy after thermally treating the AgNP-carbohydrate complex although after the calcination process. Furthermore, the reduced Ag(0) content is higher compared to the Ag (I), oxidized state (Figure 11 B). Similar studies by other scientist that deal with XRD and XPS investigations of greenly synthesized AgNPs were also found [8, 164].

4. Performance characteristics of AgNPs

4.1. Coloration properties

The development of coloration effects through incorporating AgNPs especially in the field of textiles is one of the most significant objectives of the research by many scientists. The coloration of different substrates (Figure 12 A to E) using AgNP became extremely popular for providing striking coloration effects due to the LSPR optical characteristics. The practice of traditional coloration is not a recent invention, it has been used for centuries, e.g. coloration of ceramics and glass, etc. [45]. Green nanosilver-based coloration is also free from the usage of enormous chemicals like as traditional dyestuffs-based dyeing [165, 166, 167]. There are many attempts published by scientists for coloring textiles using AgNPs [10, 168, 169, 170, 171]. Generally, the colors are evaluated with computer aided CIELAB color measurement systems (commission international de l'Eclairage) using color coordinates [172, 173]. The following Eq. (1) is taken into consideration for calculating the color values:

$$\Delta E^{*} = \left[(\Delta L^{*})^{2} + (\Delta a^{*})^{2} + (\Delta b^{*})^{2}\right]^{\frac{1}{2}} \qquad \text{Equation 1}$$

Where, L*, a* and b* denote the lightness/darkness, redness/greenness, yellowness/blueness dimensions, respectively, and ΔE* indicates the color difference. Moreover, color strength (K/S) value is determined according to Eq. (2) [174].

$$K/S = \frac{(1-R)^{2}}{2R} \qquad \text{Equation 2}$$

Where, K is absorbance, S is scattering coefficient, and R is reflectance. AgNPs provide brilliant coloration effects due to the LSPR characteristics. The coloration effects on deposited materials can be tuned through regulating the size, shape, and concentration of silver precursors used. The more silver precursor used, the higher the K/S value and the associated fabric color darkness, which also confirms the controlling of the color depth through regulating the nanosilver precursor in the colloid system [6, 175]. The colorful products also provide superior color fastness, which is another very important requirement of dyed products [176]. In Table 3, the characteristics of some greenly synthesized colorful AgNPs are provided. Almost all colored products provide satisfactory washing and rubbing fastness to the textiles; although dry rubbing fastness is somewhat better compared to wet rubbing fastness ratings. Light grey materials were nearly white/white/extremely light in terms of K/S values, however, they started to become darker with the increased loading of AgNPs [6]. The versatile coloration effects obtained through nanosilver treatments range from light yellow to brown/reddish brown, or even blue colored effects [45, 177]. Moreover, the increase in reductant could increase the synthesized AgNP content, reflecting a change in the color appearances [178]. The increase in particle size changed the shift in absorbed wavelengths towards longer wavelengths. The color turns into dark brown when the AgNPs of same sizes are present together, which could be anchored by the increased loading of silver precursor/reducing agents [6, 178]. It has been further stated that the interband transition of Ag occurred at 4d to 5sp at an energy level nearly to 430 nm [179].

4.2. Biocidal properties

The unique synthesis protocol and eco-safety features of greenly synthesized AgNPs increase their biocidal potential in terms of antibacterial, anticarcinogenic, and antioxidant properties. AgNPs synthesized from naturally extracted reducing and capping agents like leaves, stems, roots, heartwood, flowers, and so on display superior antibacterial performance

Table 1. Examples of various greenly synthesized AgNPs with associated particle sizes, extracted reducing and stabilizing agents, synthesizing period, characterization, wavelength, and shapes (available cases).

Year	Biological agent	Parts of biological agent	Size of AgNPs (nm)	Functionalities	Characterizations	Wavelength (typical absorbance peak) (nm)	Shape	Ref.
2023	Apple, orange, tomato, red pepper, white onion, garlic, radish	-	9 to 30 ± 2	Antibacterial performance	XRD, TEM, UV-Vis, DLS, antibacterial,	370 to 430	-	[90]
2022	*F. Vulgare*	Seed	49.62	Anticoagulation, antibacterial, antioxidant, biofilm inhibitory	SEM, TEM, XRD, UV-Vis, DLS, FTIR, antibacterial, anticoagulant	425 to 460	Spherical	[91]
2022	Chitosan and *Sygyzium aromaticum*	-	-	Anticoagulation and antibacterial,	Platelet function, toxicity, brine shrimp cytotoxicity, Thrombin, antithrombin test, SEM, TEM	–	–	[92]
2021	*Fraxinus excelsior*	Flower	15–115	Coloration	SEM, EDX, XRF, FTIR, iCP OES, K/S, Color characteristics	–	–	[93]
2021	*Araucaria angustifolia*	Nuts	91 ± 5	–	UV-vis, TEM, SWV, DPV, CV, EIS, and so on	–	–	[94]
2021	*Aaronsohnia factorovskyi*	Plant	104–140	Antibacterial, medicine	FTIR, FE-SEM, Chromatography, Zeta, potential, Antibacterial	430	–	[95]
2021	*Berberis vulgare, Brassica nigra, Capsella bursa-pastoris, Lavandula angustifolia and Origanum vulgare*	Plant	14.7 ± 7.9 to 75.7 ± 17.1	Antibacterial	UV-vis, TEM, ZP, PCCS, EDS	412, 421, 422	Spherical, octahedral	[96]
2020	Black rice		84 to 144 and 60 90	Coloration, antibacterial	UV-vis, SEM, colorimetric, antibacterial, UV-protection	380 to 415	–	[97]
2020	*Diospyros lotus*	Leaves		Green AgNP synthesis, Photocatalytic activity	UV-vis, SEM, EDX, XRD	400 to 410	–	[98]
2020	*Felty Germander*	Stem and flower	10 to 1000	Antifungal activity	UV-vis, XRD, DSL, FESEM, SEM, FTIR, TEM, PSA	450	–	[99]
2020	*Thunbergia grandiflura*	Flower		Catalytic reduction	UV-vis, SEM, EDX, XRD, FTIR	430	–	[100]
2019	*Tectona grandis*	Seeds	10 to 30	Antimicrobial activity	UV-vis, XRD, FESEM, EDX, SEM, FTIR, TEM, XRD	440	–	[101]
2019	Fritillaria	Flower	5 to 10	Antimicrobial activity	UV-vis, SEM, TEM, XRD, FTIR, XRD, TGA	430	–	[102]
2019	*Impatiens balsamina and Lantana camara*	Leaves	3.2 ± 1.2 to 20 ± 3.3	Antimicrobial activity	UV-vis, TEM, Antibacterial	420 to 450	–	[103]
2018	Grass waste	Dried grass	15	Anti-cancer, anti-fungal, anti-bacterial	UV-vis, XRD, TEM, Antibacterial	–	–	[104]
2018	Turmeric	Plant	5 to 35	Antimicrobial activity	UV-vis, SEM, TEM, EDS, FTIR, Antibacterial	432	–	[105]
2018	*Coriandrum Sativum*	Leaf	6.45	Green AgNP synthesis	UV-vis, SEM, TEM, EDS, FTIR, XRD, TGA/DTG, Antibacterial	316	–	[106]
2017	*Argemone Mexicana* and *Turnera ulmifolia*	Concentrated glooms	23 to 28	Antibacterial activity, antimicrobial activity	UV-vis, SEM, TEM, EDS, FTIR, XRD, Antibacterial	398 to 423	–	[107]
2017	*Azadirachta indica*	Leaves		Antimicrobial activity	UV-vis, DLS, Antibacterial	420 to 450	–	[108]
2017	*Artemisia vulgaris*	Leaves	~25	Biomedical	UV-vis, SEM, TEM, AFM, EDS, Antioxidant, Cytotoxic	~400	–	[109]
2016	*Lonicera japonica*	Leaves	20 to 60	Antidiabetic activity	UV-vis, HR-TEM, FTIR, XRD, Antioxidant,	–	–	[110]
2016	*Prunus amygdalus*	Almond nut	2 to 400	Colorful and green AgNP synthesis	UV-vis, DLS, SEM, FTIR	~420	–	[111]
2016	*Cydonia Oblong*	Seed	38	Green AgNP synthesis	UV-vis, SEM, FTIR, XRD.	400 to 450	–	[112]
2015	*Skimmia laureola*	Leaves	46	Green AgNP synthesis and antibacterial activity	UV-vis, SEM, FTIR, XRD, Antibacterial	460	Spherical and hexagonal	[82]
2015	Banana peel	Bark of fruits	23.7	Antimicrobial activity	UV-vis, SEM, EDX, TEM, FTIR, XRD, Antibacterial	433	Spherical	[113]
2015	*Salacia Chinensis*	Plant	100 to 200	Green AgNP synthesis and antibacterial activity	UV-vis, DLS, SEM, EDX, TEM, FTIR, XRD	434	–	[114]
2014	*Malus domestica*	Fruit	145	Green AgNP synthesis	UV-vis, DLS, SEM, EDX, TEM, FTIR, XRD, Zeta potential	422	Flower-like	[115]
2014	*Schizophyllum commune*	Mushroom fungus	54 to 99	Biomedical	UV-vis, SEM, FTIR, Antimicrobial	440	Spherical	[116]
2014	*Calendula officinalis*	Flowers		Green AgNP synthesis	UV-vis, FTIR	440 to 460	–	[117]

(*continued on next page*)

Table 1 (*continued*)

Year	Biological agent	Parts of biological agent	Size of AgNPs (nm)	Functionalities	Characterizations	Wavelength (typical absorbance peak) (nm)	Shape	Ref.
2013	*Ixora coccinea*	Leaves	15 to 37	Green AgNP synthesis	UV-vis, FTIR, XRD, FESEM	430	–	[118]
2012	*Iresine herbstii*	Leaves	44 to 64	Green AgNP synthesis, biological activity	UV-vis, SEM, EDX, FTIR, XRD, Antioxidant, Cytotoxicity	460	–	[119]
2011	*Citrus sinensis*	Fruit peels	23.81	Green AgNP synthesis	UV-vis, DLS FESEM, HRTEM, EDX, FTIR, XRD, Zeta potential	422	–	[120]
2010	Banana	Fruit peels	–	Green AgNP synthesis	UV-vis, SEM, EDX, FTIR, Anti-fungal, Antibacterial	~440 to 460	–	[121]
2009	*Carcia papya*	Fruit	60 to 80	Green AgNP synthesis	UV-vis, FTIR, SEM	440	–	[122]
2008	*Fusarium acuminatum*	Zinger (*Zingiber officinale*)	5 to 40	Antibacterial activity	UV-vis, TEM, Antibacterial	420	–	[123]
2007	*Capsicum annum L.*	Chili plant	30 to 70	Green AgNP synthesis	UV-vis, XPS, XRD, TEM, FTIR	440	Spherical	[124]
2006	*Bacterium aeromonas sp.*	Cell	–	–	UV-vis, SEM, XRD, TEM	425	–	[125]
2006	*Aloe vera*	Leaves	15.5 ± 4	–	TEM, AFM, UV-vis NIR, FTIR, UV vis absorption	560	Spherical	[126]

*UV– Ultra violet; TEM–Transmission electron microscopy; SEM– Scanning electron microscopy; FTIR– Fourier transform infrared spectroscopy; XRD–X-ray diffraction; DLS–Dynamic light scattering; AFM–Atomic force microscopy, EDS/EDX–Energy dispersive X-ray spectroscopy/Energy dispersive X-ray analysis; FESEM– Field emission scanning electron microscopy; HRTEM–High resolution transmission electron microscopy; K/S–Color strength; iCP PES– inductively coupled plasma optical emission spectroscopy; XRF– X-ray fluorescence; TGA–Thermogravimetric analyzer; DTG–Derivative thermogravimetry.

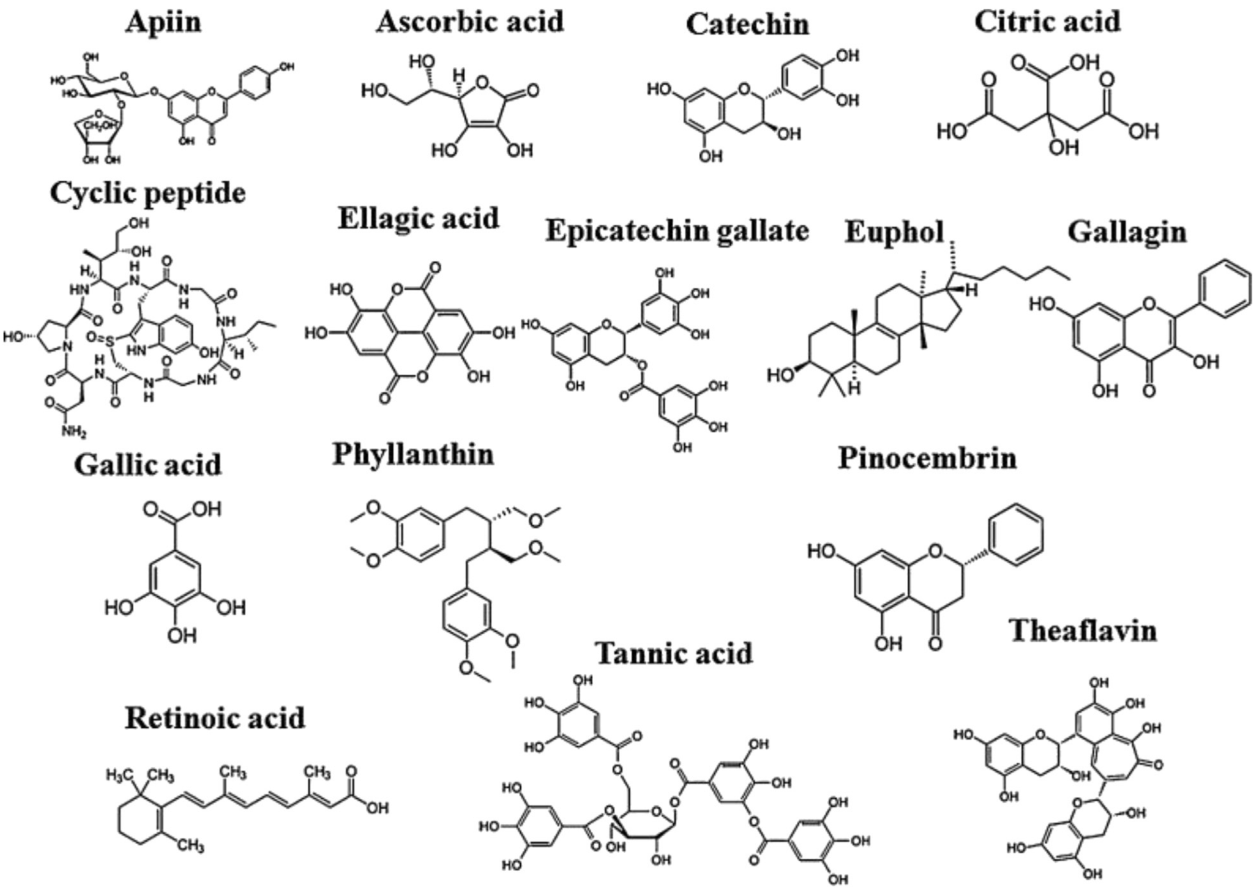


Figure 6. The chemical structure of different phytoconstituents responsible for the green synthesis of AgNPs. Adapted with permission from Elsevier [135]. Copyright, Elsevier 2015.

(Figure 13). There is ongoing research to this day to show the antibacterial properties of greenly synthesized AgNPs [96, 183, 184, 185, 186, 187, 188, 189]. AgNPs are also reported for protection against yeast and fungal pathogens [190, 191]. Furthermore, biosynthesized AgNPs are also studied by researchers for their antioxidant [192, 193], antitumor [194], and anticarcinogenic [186, 195] functioning as an emerging material of significance. Silver has a long history in terms of antibacterial functionality against microbes and bacteria. The Phoenicians used Ag for coating

Table 2. The results of Acalypha wilkersiana leaf extracts' phytochemical screening test. Adapted with permission from Elsevier [136]. Copyright, Elsevier 2019.

Screened photochemical test	Leaf extract (*Acalypha wilkersiana*)
Phenol	+
Triterpenes	++
Saponins (Froths)	+
Steroids (Salkowskis)	–
Alkaloids (Mayers)	–
Flavonoids (Lead acetate)	+
Flavonoids (Alkali)	+

Note: + = Present; ++ = Abundantly present, – = Absent.

the milk bottles as a natural biocide material [179]. AgNPs provide protection against different gram positive and gram negative bacteria, viruses, and fungi.

AgNP extracted from various plants display significant antibacterial potential against various pathogens: *P. aeruginosa*, *S. aureus*, *E.coli*, *Staphylococcus aureus,* and *Streptococcus aureus* showed inhibition zone diameters of 19 mm, 18 mm, 17 mm, 17 mm and 17 mm, respectively, at 35 μg of AgNP loading (Table 4) [197]. *Tribulus terrestris* fruits mediated spherical AgNPs having 16–28 nm particle dimensions show excellent potential to improve bacterial resistance to medically isolated multidrug resistant bacteria like various gram negative and positive pathogens [198]. The obtained zone of inhibition (ZOI) value was 9.75 mm for *Staphylococcus aureus*, 9.25 mm for *Bacillus subtilis*, 10.75 for *E. coli*, 9.25 for *Pseudomonas aeruginosa*, and *Streptococcus pyogens*, respectively

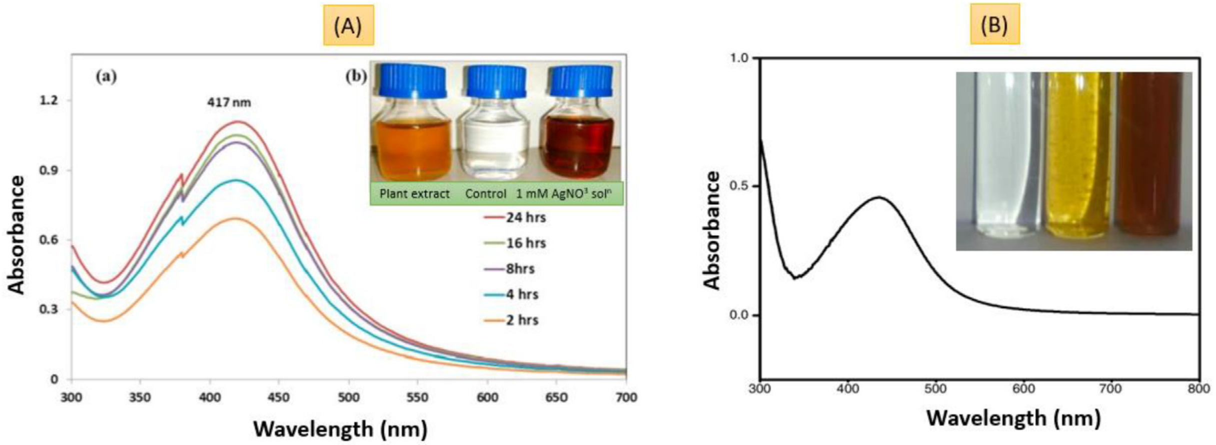


Figure 7. UV-vis absorption spectra: *(A) Enicostemma axillare* leaf extracted nanosilver: *(a)* 1mM $AgNO_3$ aqueous solution, *(b)* physical images of different solutions; *(B) Garcinia mangostana* stem extracted AgNP (430 nm). Adapted with permission from Elsevier (7A) and created under creative common license attributions (CC BY-NC-ND 4.0) [142,143]. Copyright, Elsevier 2018, respectively.

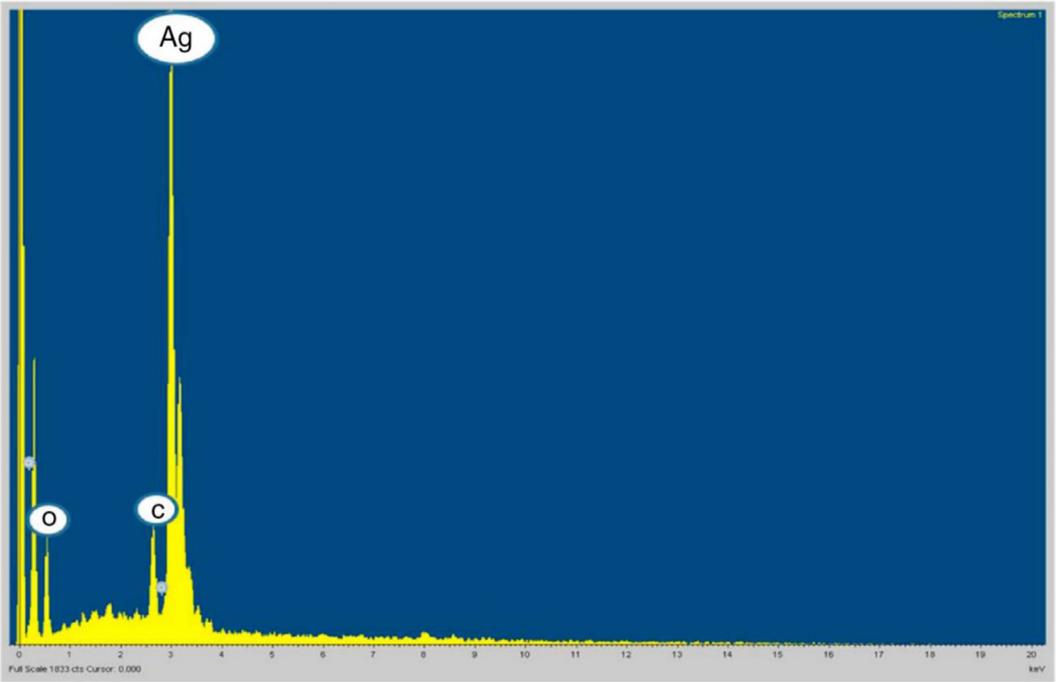


Figure 8. EDX analysis of extracted AgNPs (A) *Garcinia mangostana* stem extract. Created under creative common license attributions (CC BY-NC-ND 4.0) [143]. Copyright, Elsevier 2018.

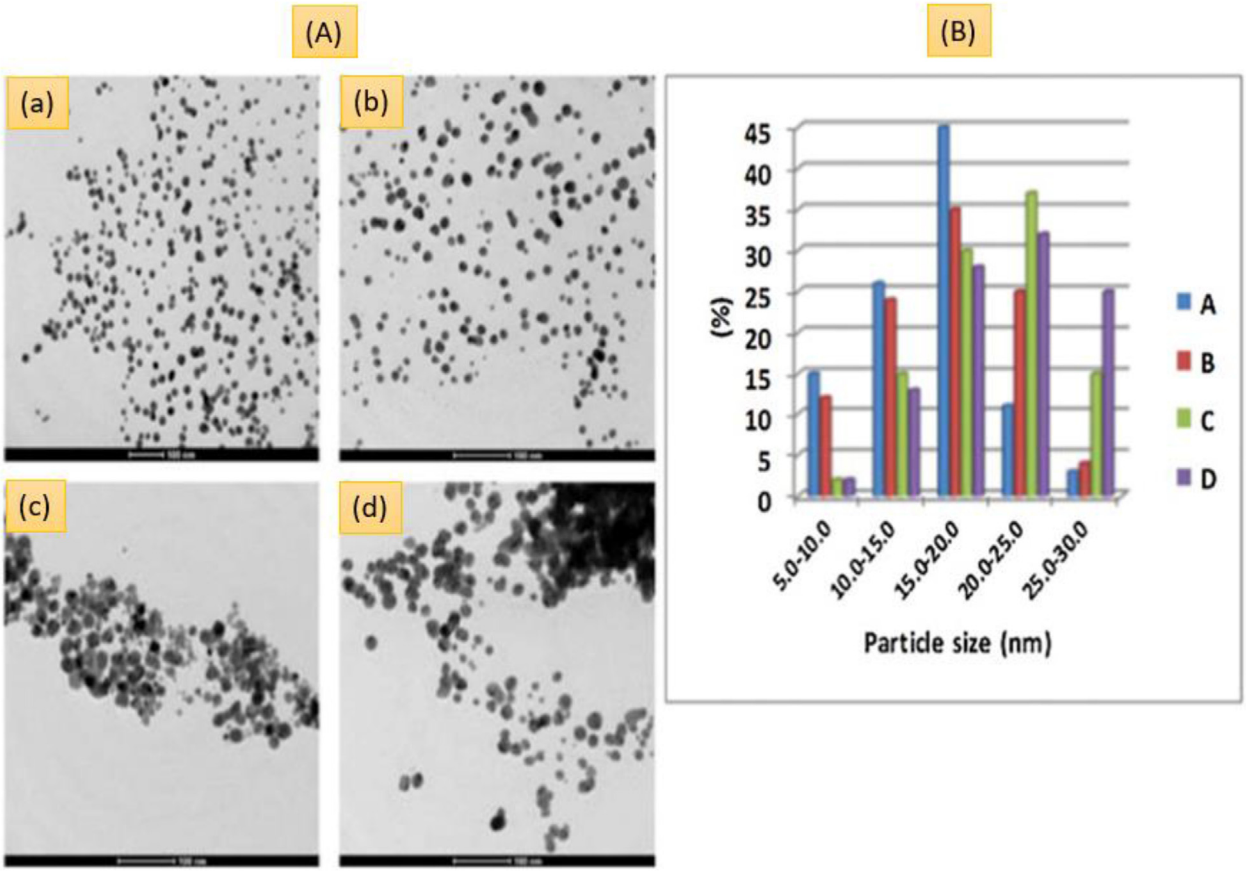


Figure 9. (A) TEM photographs of AgNP in powder form from 0.1, 0.5, 1.0, and 2.0 mM $AgNO_3$ concentrations, respectively, from a to d. (B) Histogram illustrations of AgNP sizes according to different concentrations of silver precursor used. Adapted with permission from Elsevier [155]. Copyright, Elsevier 2016.

[198]. The results mentioned here also agree with other studies on *Sesbania grandiflora* leaf extracted AgNPs [199]. In case of gram positive bacteria, a thicker peptidoglycan layer is the principal constituent that is formed further by linear polysaccharide chains along with short peptide cross link develops comparatively more rigid structure, creating difficulty for AgNP to penetrate, compared to gram negative bacteria [200]. The principal reason behind this antibacterial capability is the release of silver ions from the NPs, which function as the reservoir for Ag^+ bactericidal reagent. The structural membrane of the bacteria changes significantly due to the interaction with the cationic Ag, leading to increased bacterial membrane permeability [201, 202]. The nanosize dimensions of AgNPs facilitate the penetration of NPs in the membrane cell of bacteria [203]. Another study found that, the silver ions released from metallic silver become attached to the bacterial cell wall (negatively charged), which results in the rupturing and denaturalization of protein, leading to the death of the bacterial cell [204]. AgNPs may inhibit bacterial signal transduction. Protein substrate phosphorylation is affected by this bacterial signal transduction, whereas AgNP could dephosphorylate the tyrosine residuals present on peptide materials. Furthermore, cell apoptosis may occur for the disruption of bacterial signal transduction, which could result in terminating the cell multiplication [205]. Besides, an envelope protein precursor is accumulated for the attachment of AgNP to the bacterial cell wall, causing the protein motive force to deteriorate. AgNPs also possess a higher affinity toward phosphorous or sulfur retaining cell biomolecules too [206]. Therefore, the sulfur possessing proteins inside the cell or in the protein membrane and DNA (phosphorous containing elements) are tempted to bond with the AgNPs [199, 207], leading to the cell's demise too.

The efficiency of antibacterial effects depends significantly on the dissolution property and the surrounding media. Comparatively, the smaller AgNPs having larger surface area are prone to release more silver [208]. Moreover, the capping agent used for AgNP synthesis can modify the surface of the NPs, resulting in a change in their dissolution behavior [209]. However, another study claimed that AgNPs release silver ions more in an acidic condition than in a neutral one [210]. Conversely, gram negative bacteria are more susceptible to the AgNPs, compared to the gram positive bacteria. The reason behind this is the presence of narrower cell walls in case of gram negative bacterial strains than in gram positive ones [211]. Furthermore, the uptake of AgNP is extremely important in order to provide an effective antibacterial effect. Moreover, AgNPs having the size 10 nm or less are capable of altering the cell permeability and directly enter into the cells of the strains, and cause destruction [212]. Additionally, not only AgNPs, but also the plant extracts (obtained from sumac leaf) that are used as the capping agents also contribute to the antibacterial performance [213]. Therefore, when the AgNPs are synthesized biologically, they may display better antibacterial performance. Figure 14 A and B shows the antibacterial characteristics of some greenly synthesized AgNPs.

Greenly synthesized AgNPs also possess a significant role in pharmaceuticals like anticarcinogenic and antioxidant materials, as well [22]. AgNPs synthesized from *Melia dubia* plant extract provided significant cytotoxic effects against human breast cancer cells in terms of higher therapeutic index values [215]. Cancer cells show increasing mortality with the increase in nanosilver content. Nearly 50% of cancer cells died even at low concentration of AgNPs (31.1 μl/ml) [215] which is also seen clearly in the morphological and cell viability studies (Figure 15 A and B). Normal cells appear as regular structural forms, whereas AgNP treated cells are seen as irregular and round shaped structures. Furthermore, cells turn into stressed, enlarged, and cytoplasmic vacuole. In another recent study for *Tamarindus indica* shell extracted AgNPs also

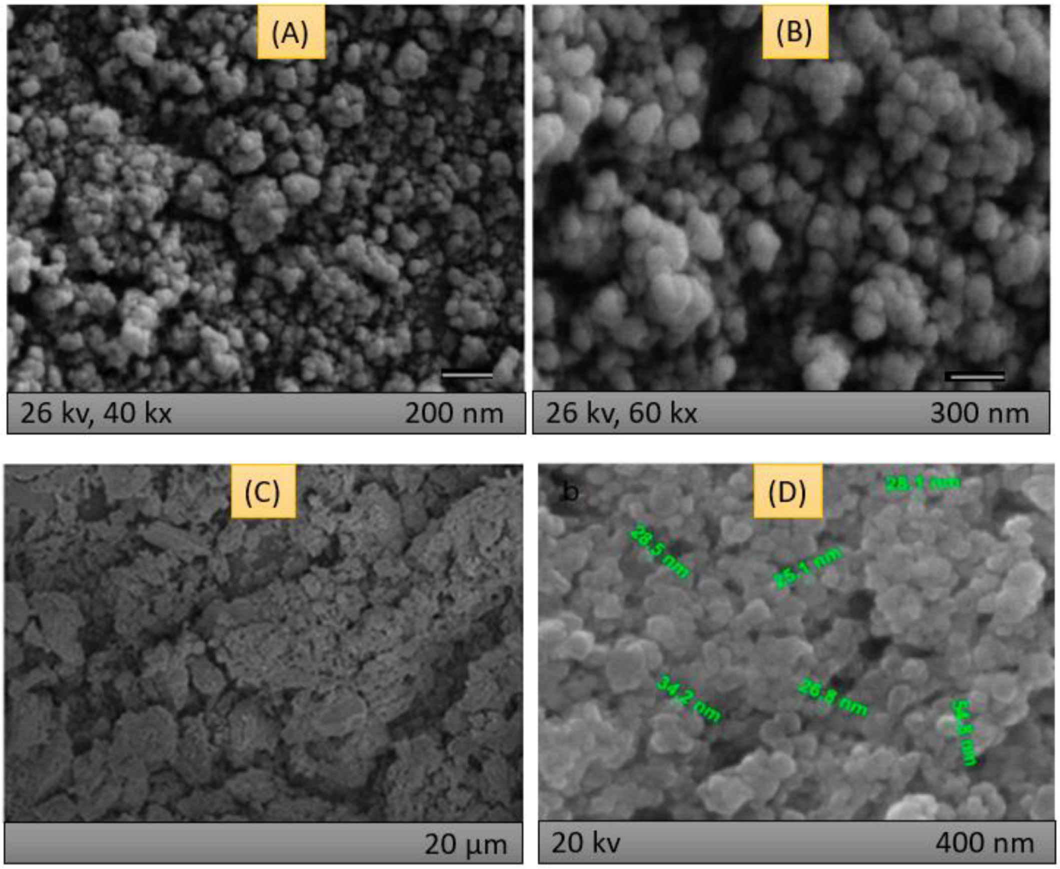


Figure 10. (A and B) SEM morphology of *D. lotus* leaf (10 mL) extracted and 1 mM $AgNO_3$ (60 mL) loaded green AgNPs at different magnifications, (C) SEM photograph of *Artemisia vulgaris* mediated AgNP, and (D) the size of the nanoparticles. Adapted with permission from Elsevier [156] (A, B) [161], (C), and created under creative common license attributions (CC BY-NC-ND 4.0) (D) [143]. Copyright, Elsevier 2019, 2017, and 2018, respectively.

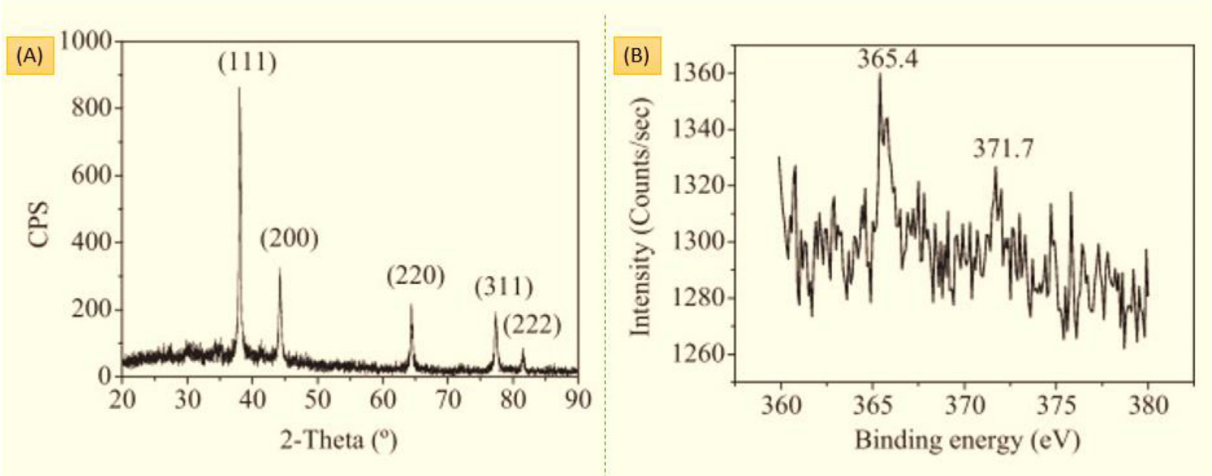


Figure 11. (A) XRD and (B) XPS analysis of microwave-assisted green AgNPs. Adapted with permission from Elsevier [162]. Copyright, Elsevier 2013.

reported similar results against the cell line of human breast cancer [216]. In the same study, AgNP treated cancer cells displayed more changes in nuclear morphology, compared to control cells. The principle behind the inhibition of cancer cells through AgNPs is the damage of DNA cells that causes apoptosis in the breast cancer cells [217, 218].

Nowadays, drug resistance is also becoming a well-known concern toward antibiotics. The greenly synthesized AgNPs can also help against multi-drug resistant bacteria for the large spectrum of the NPs. The widely used traditional antibiotics are losing efficiency against the bacteria day by day as the pathogens are altering the target side, decrease in membrane permeability, efflux pumping, and enzymatic degradations [219]. Therefore, nano-sized metallic particles are showing a better alternative to MDR strains for the next generations.

Greenly synthesized AgNPs also provide significant antioxidant characteristics, although it is difficult to find accurate methods for evaluating the samples [220]. The antioxidant properties are enhanced with the increase in AgNP concentration [220]. The *Cleistanthus collinus* plant was used as the potential Phyto reducer to synthesize green AgNPs

Figure 12. Colored photographs of green AgNP treated products reduced and stabilized by different naturally originated plant extracts: (A) cotton fabric, *Alternaria alternata* funges extract, (B) flax fabric, *Taxus baccata* heartwood extracts, (C) Sisal/hemp fabric, *Larix decidua* heartwood extract, (D) glass fabric, *Fraxinus excelsior* extract, (E) glass/flax laminated composite, *Tilia cordata* leaf extract. Adapted with permission from Elsevier (A) [180], Wiley & Sons [6] (B) Springer Nature (C) [39], Elsevier (D) [146], and Taylor and Francis (E) [63]. Copyright, Elsevier 2016 (A), Wiley & Sons 2021 (B), created under creative common license attributions (CC BY 4.0) Springer Nature 2021 (C), created under creative common license attributions (CC BY 4.0) Elsevier 2020 (D), and Taylor and Francis 2021 (E).

Table 3. Coloration/printing characteristics of different greenly synthesized AgNPs over textile materials.

Extracted medium	Applied substrates	L*	a*	b*	K/S	CFL	CFW	CFR (D)	CFR (W)	Reference
Sweet potato (*Ipomoea batatas)*	Cotton	26.31	76.25	23.59	–	2	4	4	4	[181]
Sweet potato (*Ipomoea batatas)*	Silk	22.22	70.21	22.56	–	3	4	4	4	[181]
Pluchea dioscoridis	Cotton	82.91	4.54	21.5	4.6 (4.6)	4	5	5	4/5	[182]
Pluchea dioscoridis	Polyester	69.55	13.93	33.6	2.5 (2.4)	3/4	5	5	4/5	[182]
Fraxinus Excelsior	Glass	50.04	3.8	17.57	4.72	–	4	3	2/3	[146]

Note: CFL–Color fastness to light, K/S– Color strength, CFW– Color fastness to wash, CFR (D) – Color fastness to rubbing (dry), CFR (W) – Color fastness to rubbing (wet).

having 20–40 nm particle sizes with significant scavenging capability (determined as per Equation 3) on freeing the radicals without showing any harmful toxic effects [221].

$$\textit{Radical scavenging activity}\ (\%) = \left(A_0 - \frac{A_1}{A_0}\right) \qquad \text{Equation 3}$$

Where, A_0 indicates control absorbance of DPPH (1,1–Diphenyl–2–picrylhyrazyl) and A_1 sample absorbance of the radical (DPPH) and sample of standard vitamin C/AgNPs. Figure 16 A to D shows the detailed antioxidant properties of *Cleistanthus collinus* plant extracted AgNPs, where DPPH radical scavenging activity displays an increasing trend with the increase in AgNP concentration. However, a 20–69% scavenging rate was noticed in case of 50–1000 μg/ml AgNPs [221]. Furthermore, the reducing capability of *Cleistanthus collinus* extract toward AgNP also increases with the increase in sample quantity. Overall, the inhibition at 1000 μg/ml was found to have 77.87 and 85.05%, respectively for vitamin C and AgNPs [221]. The reason behind the antioxidant activity is the presence of antioxidant components like flavonoids, phenolics, and polysaccharides capped on AgNP surfaces, facilitating radical scavenging activity [222].

The control of human and plant disease has become another crucial factor nowadays for different sectors like agriculture and human bodies (liver, eyes, lungs, skin, and so on). Various microorganisms like fungi are also significantly responsible for such problems. However, AgNP can help to prevent through functioning as potential antifungal agent because they are toxic to most of the fungi [223]. In another study, it was mentioned that fungal hyphae are damaged by the AgNPs through creating leakage in the cytoplasm and thus lead to the fungal death [224].

4.3. Thermal properties

The thermal properties of greenly synthesized AgNPs are also getting significant attention in the scientific community. The incorporation of *Alternaria alternata fungus mediated* AgNPs was reported to improve the thermal stability of cotton/binders compared to nanosilver untreated cotton/binders [180]. Another study found that the addition of more Marri and Neelagiri leaf extracts in the nanocolloid system also increased the thermal stability (Figure 17 A to E), possibly due to the increase in AgNP production [225]. A 6% incorporation of Marri and Neelagiri leaf extracted AgNP treatment facilitated nearly 25–30% less weight loss

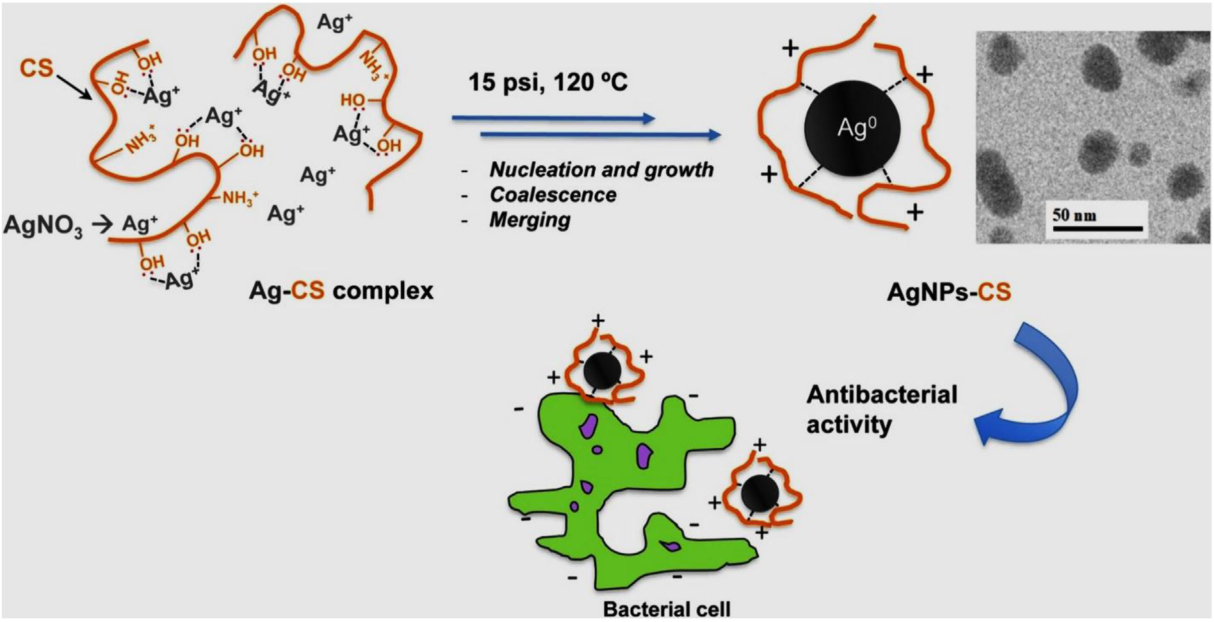


Figure 13. Schematic antibacterial process illustration of greenly synthesized AgNPs. Reprinted with permission from Elsevier [196]. Copyright, Elsevier 2018.

Table 4. Antimicrobial characteristics of greenly synthesized AgNPs from *C. longa* plant extract Adapted with permission from Elsevier [197]. Copyright, Elsevier 2020.

AgNP content (μg)	*Staphylococcus aureus* (mm)	*Streptococcus pyogenes* (mm)	*E.coli* (mm)	*Pseudomonas aeruginosa* (mm)	*Candida albicans* (mm)
15	13	13	14	14	13
20	14	14	15	14	14
25	15	14	15	15	15
30	16	15	16	17	16
35	18	17	17	19	17

(Figure 17), even at a high temperature (700 °C) [226], demonstrating a successful development of thermally stable AgNP coated colorful textiles. Similar effects were also found in our earlier study on chitosan mediated nanosilver coating over the synthetic polyester fabrics [134], where the AgNP loaded fabrics displayed better thermal stability compared to the untreated fabrics. In another research on gelatin capped-AgNP synthesis [227], the developed coordination bond was found to play a significant role as a heat barrier, which may consequently make the nanocomposites more thermally stable. The TGA study on gelatin was found to have values at 210.1 °C is T_{10}, 313.4 °C is T_{30}, 356.5 °C is T_{50}, and at 700 °C 1.2% char yield, whereas gelatin capped green AgNPs was found to have values at 221.1 °C is T_{10}, 322.3 °C is T_{30}, 383.5 °C is T_{50}, and at 700 °C 5.8% char yield [227]. In case of DTG analysis for the same study [227], it was noticed that maximum decomposition appeared at 315–657 °C for gelatin, whereas the AgNP capped gelatin decomposed at 386–667 °C. Furthermore, in another report [228] concerning *Givotia moluccana* leaf extracted nanosilver, the TGA thermogram showed that, the phase transition temperature reached 900 °C, which is near to the melting temperature of metallic Ag [229].

4.4. UV-protective properties

Even though ozone layer depletion has been improving steadily since the phaseout of CFC's in the ‘90s, there is still a concern about excessive UV light exposure that is harmful for humans and other life forms. Therefore, it is important to develop UV-protective materials to make the living species safer with sustainable products. Recently, AgNPs gained attention due to their superior UV-protection capabilities.

Generally, UV radiation is categorized into three classes [213]:

(a) UVC: ranged within 100–280 nm. This type of UV rays are adsorbed in the upper atmosphere by ozone and the oxygen layer, hence they cannot reach the earth's surface. However, these are the most harmful UV rays for living species.
(b) UVB: ranged within 280–315 nm.
(c) UVA: ranged within 315–400 nm

The UV protection of a fabric is measured in terms of the UPF value, calculated according to Eq. (4). Moreover, as the UVC cannot reach the earth, UVA and UVB is generally taken under consideration for the UV resistance protocol. In order to meet the standards (like as GB/T 18830-2009, solar UV radiation protective performance for textiles), the UPF value need to be at least 40, and UVA transmission should be less than 5% [230].

$$UPF = \frac{\sum_{280\ nm}^{400\ nm} E_\gamma \times S_\gamma \times \Delta\gamma}{\sum_{280\ nm}^{400\ nm} E_\gamma \times S_\gamma \times T_\gamma \times \Delta\gamma} \qquad \text{Equation 4}$$

Where, E_γ indicates solar irradiance, S_γ erythematic action spectrum, $\Delta\gamma$ is spectral change, and T_γ spectral transmittance of wavelength (λ). In this regard, a study [231] was conducted to functionalize silk fabrics by greenly synthesized AgNPs from tea stem extracts, providing a highest absorption peak at 412 nm and a shoulder peak around 270 nm. Moreover, the solution of AgNP showed high absorption intensity within 280–300 and 340–400 nm wavelength, which are considered as the range of UVB and UVA, demonstrating a strong UV protective capability of AgNP coated silk materials [231]. Increased concentrations of AgNP provide comparatively higher resistance against UV rays. 0.1, 0.2, 0.5, and 1.0 mM silver precursor treated samples provided 16.03, 17.53, 19.65, and 21.28 UV protection factor (UPF) values, respectively, showing a R^2 (coefficient of determination) value of 0.98, meeting the standard in Australia/New Zealand (AS/NZS 4399:1966) [231,232]. In another study [213], the reported mean UPF value was highest in case of maximum use of AgNPs, being 72.32 before washing, and 69.32 after 25

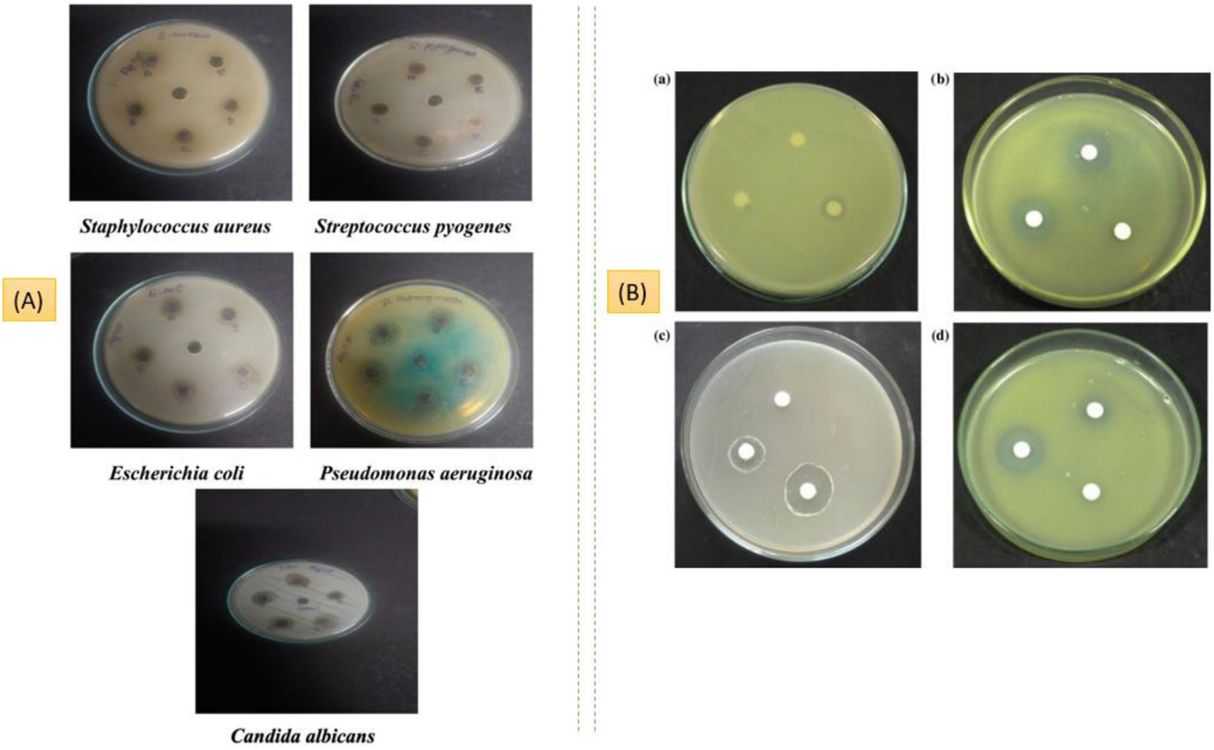


Figure 14. Antibacterial characteristics of greenly synthesized AgNPs: (A) *C. longa* plant extracted NPs functioning against various pathogens and (B) Zone of Inhibition for beetroot extracted AgNPs against (a) *E.coli*, (b) *Pseudomonas aeruginosa*, (c) *Staphylococcus aureus*, and (d) *Streptococcus aureus*. Adapted with permission from Elsevier [197, 214]. Copyright, Elsevier 2020 (A), 2015 (B).

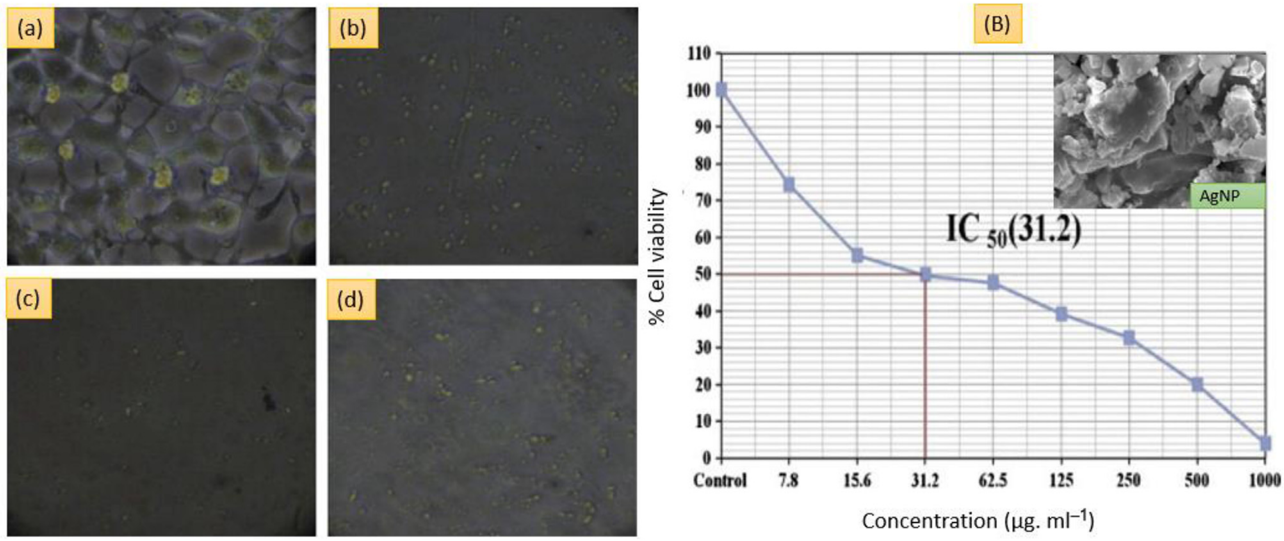


Figure 15. (A) The effect of AgNPs on breast cancer cell line: (a) Control cell line, (b) cell line treated with low concentration, (c) cell line treated with medium concentration, and (d) cell line treated with high concentration and (B) CC_{50} values of AgNPs against breast cancer cell line (MCF-7). Adapted with permission from Elsevier [215]. Copyright, Elsevier 2014.

washing cycles, both demonstrating excellent UV protection capabilities, although the release of a small amount of AgNPs after repeated washing causes some decline over time (Figure 18). A detailed schematic representation is shown in Figure 18 A to D.

4.5. Mechanical properties

AgNP coatings on various substrates like textiles result in improved mechanical strength. If the cellulosic fibers are modified with Cationizer like PDDA (poly(diallyldimethylammonium chloride), it may create an electrostatic interaction between the AgNP and the fiber/fabric substrates, facilitating the formation of hydrogen bonds, leading towards higher tensile strength [233]. A cellulose/AgNP film was developed by using *Ocimum sanctum* leaf extract and tested for tensile properties [234]. Researchers found an increase in tensile properties for the nanosilver treated materials compared to control sample [234]. In another study for greenly synthesized AgNP [235], the strength in warp (lengthwise yarns) direction of fabrics increased after the loading of AgNP. The tensile

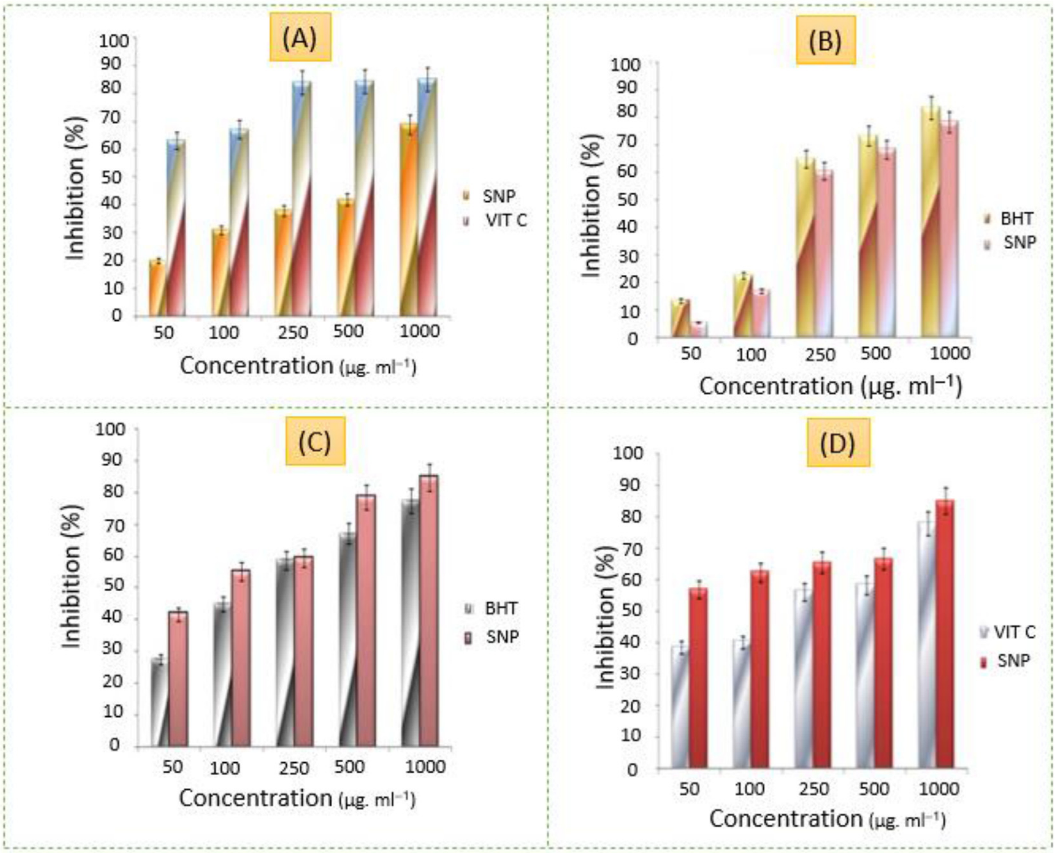


Figure 16. Antioxidant capabilities of greenly synthesized AgNPs from *Cleistanthus collinus* plant extracts: (A) Scavenging activity toward DPPH–radical, (B) Scavenging activity toward hydroxyl–radical, (C) Scavenging capability/power, (D) Scavenging activity toward H_2O_2. Adapted with permission from Elsevier [221]. Copyright, Elsevier 2014.

resistance was 3.57 kg, and elongation at break 9.61% in case of dip coated AgNPs on cotton substrates, whereas tensile resistance was 4.20 kg and elongation at break 11.10% when using the ultrasonication methods [235]. In both cases, nanosilver coating displayed an increased tendency compared to the control sample (tensile strength was 3.18 kg and elongation at break 9.43%) [235, 236]. The increased loading of AgNPs could impart a higher resistance against tensile load [237] up to a certain limit. Another study for greenly synthesized AgNPs (around 20 nm sized) loading *from Eucalyptus citriodora* and *Ficus bengalensis* over cotton substrates confirmed these findings [226].

Nowadays, green AgNP treated textiles are also used for developing nanocomposites, where the metallic Ag imparts higher mechanical properties (Table 5). Generally, polymeric composites face some critical problems like delamination, proper fiber orientation in the matrix system, debonding, and lengthwise fiber defects [238]. However, if the fibers are treated with AgNPs, these problems could be mitigated to attain higher thermomechanical properties, along with isotropic material characteristics. Our research group made a similar attempt to produce multilayered hybrid nanocomposites from hemp and glass woven fabrics, where the incorporation of AgNPs imparted higher mechanical and thermal properties, due to the better bonding between the matrix and reinforcements [239]. In a recent study, AgNP was used for manufacturing composites from unsaturated polyester resin and wood flour, and found superior flexural strength (128.74 ± 1.27 MPa) and antibacterial performances as well [240]. Kumar and his colleagues developed hemp filler reinforced epoxy composites loaded with AgNPs, providing superior thermomechanical performance (28.66 MPa tensile strength, 2.36 GPa Young's modulus, and 0.76 ± 0.091 W/(m.K) thermal conductivity) [241].

5. Application of AgNPs

Metallic silver contains extensive application potential in numerous fields (Figure 19). Some authors mentioned that uses of novel AgNPs could be traced back even before in Neolithic revolution [242]. However, the use of AgNP as medicinal material was recorded first in the 8th century [243, 244]. AgNPs are becoming extensively used metallic materials due to their low cost, availability, and overall higher chemical solubility. Green AgNPs are displaying enormous potential for catalysis, electronics, optics, bioengineering and biotechnology, pharmaceuticals, biomedical, textiles, personal care products, cleaning agents, water treatment, and so on, due to their superior size dependent magnetic, electric, and optical characteristics [244, 245, 246, 247]. Specifically, AgNPs are also used for wound dressing, catheters, and household applications where bacterial resistivity is important [51]. Many people also use AgNPs for coating fine cutlery, ornamentation, and jewelry for their health benefits, besides providing attractive colorful appearances. AgNPs possess significant antibacterial characteristics as discussed in section 4.2. Besides, AgNPs are also gaining popularity for their potential to treat and prevent some viral infections like as HIV-1 and COVID-19 too [248, 249, 250].

AgNPs possess significant resistance against bacterial development, may be used to treat cells infected by HIV-1 [248], and for wound healing without residual scars [251]. HIV/AIDS is still a serious public health concern throughout the globe. One study showed that using some available drugs in the market showed only 5–78% efficiency against HIV-1 virus development, as mentioned in a report in 2008 [252]. Therefore, there is urgent demand to explore new routes of medication that could function at different viral stages like protease and retro-transcription, facilitating the treatment through preventing the

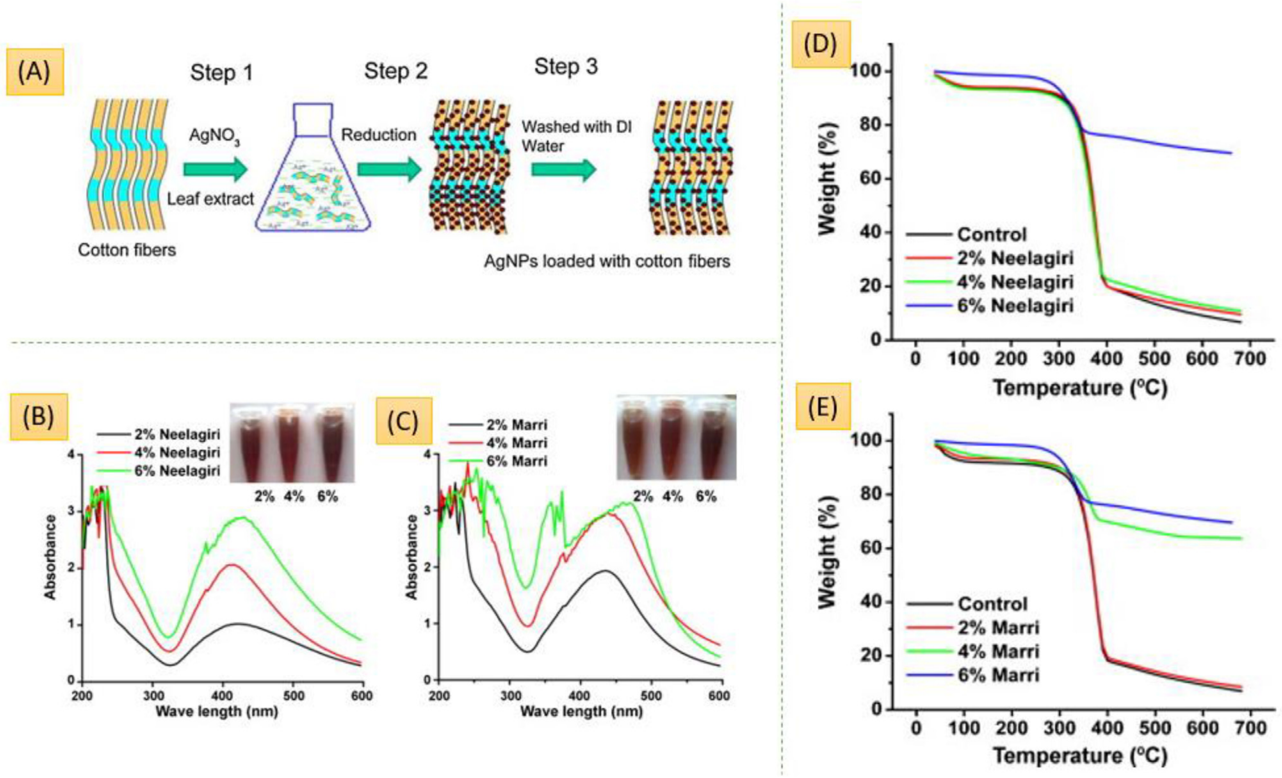


Figure 17. (a) Schematic illustration on green AgNP synthesis from leaf extracts, (b) UV -Vis absorption spectra of Neelagiri leaves (2, 4, and 6%) extracted AgNPs, (c) UV -Vis absorption spectra of Marri leaves (2, 4, and 6%) extracted AgNPs, (d) TGA analysis of Neelagiri leaves (2, 4, and 6%) extracted AgNPs, (e) TGA analysis of Marri leaves (2, 4, and 6%) extracted AgNPs. Adapted with permission from Elsevier [225]. Copyright, Elsevier 2010.

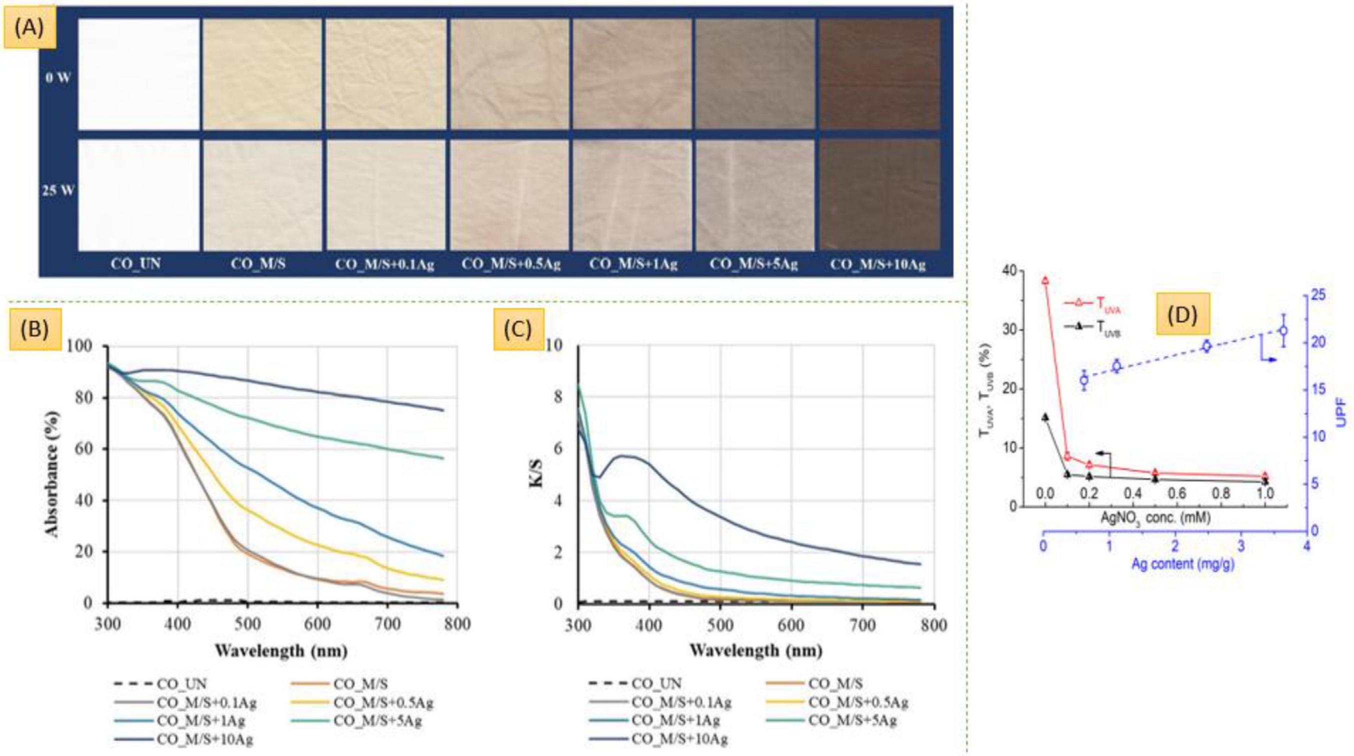


Figure 18. (A) photographs of control and AgNP treated samples (cotton fabric) before washing and after 25 washes, (B) UV-vis absorption spectra for control and AgNP treated samples, (C) K/S values of control and AgNP treated samples, (D) UV protection capability of AgNP coated silk fabrics. Adapted with permission from Elsevier [213, 231]. Copyright, Elsevier 2021, and 2020. All the images are adapted under creative common license attributions (CC BY 4.0).

Table 5. Concentration of AgNP, UPF factor, and mechanical properties of control and AgNP treated cotton fabrics [213]. Adapted under creative common license attributions (CC BY 4.0).

Specimen	Ag concentration (mg/kg)	Mean UPF value, Zero washes	Tensile strength (N/ mm^2)	Elongation at break (%)
Cotton/Sumac (control)	–	–	63.9 ± 1.7	20.2 ± 0.4
Cotton/Sumac/ Ag (1 mM $AgNO_3$)	410	60.87	64.1 ± 3.5	19.2 ± 0.4
Cotton/Sumac/ Ag (5 mM $AgNO_3$)	3500	69.07	65.1 ± 1.4	18.9 ± 0.5
Cotton/Sumac/ Ag (10 mM $AgNO_3$)	11,000	72.32	64.2 ± 2.1	19.1 ± 0.6

*UPF–Ultraviolet protection factor; Ag–Silver.

dissemination of the HIV/AIDS viruses [253]. The reason behind this activity is the release of Ag^+ from the metallic AgNP. However, AgNPs also exert anti-HIV functioning at the early stages of viral replications as a virucidal agent [253]. In this regard, commercially available AgNPs of 30–50 nm dimensions were tested against HIV-1 isolate panels, where the infections were measured using luciferase-based assay and found inhibiting all the exposed strains (M-tropic, T-tropic, resistant isolate, and dual-tropic) [253]. There was 50% inhibition against infectivity in case of 0.44 to 0. 91 mg/ml AgNP concentrations [253]. Similar effects regarding the inhibition against HIV infection were found by other researches too [254, 255].

Besides HIV-1 viruses, AgNPs also show potential antiviral actions against the Hepatitis B virus, Norovirus, and influenza viruses too [256]. Previously, AgNP was also reported to kill the SARS-COV-2 viruses [257]. Another report also claimed to have shown inhibiting effects of colloidal silvers having 10 nm size being capped with polyvinylpyrrolidone against the SARS-COV-2 [258]. Typically, the size of NPs is below 100 nm, whereas the sizes of viruses is around 100 nm (HIV-1 is 120 nm, whereas SARS virus is around 100 nm) [250]. Therefore, the smaller AgNPs, sized below 10 nm are considered to be the most effective, compared to the larger NPs, whereas the peak performances are found with 1–7 nm particles [250]. Conversely, NPs having higher diameter are reported to have insignificant interactions with the viruses [259]. Overall, the small size of metallic NP is a vital precondition to get efficient interactions against the viral infections. In the beginning, it was expected that similarly formulated medications could be effective to treat and prevent any respiratory infectious disease like COVID-19. However, in case of bacterial infections half dosages were prescribed, especially for the patients in ICU compared to antibacterial cases [259]. Besides, there are also notable concerns about the toxicity of AgNPs. However, greenly synthesized AgNPs, having smaller diameters less than 10 nm could easily be eliminated by the hair pores and during urine discharge [260]. Nevertheless, the harmful effects of AgNPs are still not well known. Furthermore, antibacterial coatings developed from biocompatible polymers could also provide contact killing, release killing, and anti-adhesion (a schematic representation is shown in Figure 20). Science still needs to go a long way to ensure safe and effective use of AgNPs to treat different viral infections.

Biosensors have become a powerful tool for the analysis and detection in the fields of healthcare, biomedical, environmental, battlefield, homeland security, food preservation, and pharmaceuticals monitoring [261]. Metallic NPs like Ag gained significant attention for constructing biosensors due to the unique physico-chemical properties, which can be used in places where accurate, quick, cheap, and online-based detection is necessary. Rashid et al. developed a synthesis protocol of AgNPs to determine the presence of vitamin C in the produce sold at the market of Bangladesh [246]. Moreover, in case of photovoltaic and catalytic applications, the implementation of AgNPs also gained significant attention. In some cases, AgNPs were also reported for their potential to modify other NPs like TiO_2 for better functionalization effects on cellulosic cotton substrates [262]. The homogeneous AgNPs with controlled shape, size, function, and morphology could be considered as building blocks for emerging dental materials [212]. Moreover, AgNPs could be reinforced with different acrylic or polymeric resins to fabricate for removing dentures in the treatment of prosthetic, direct restoration by composite resin, adhesive material in case of orthodontic treatments, guided tissue regeneration membrane periodontal treatment, obturation material for endodontic treatments, and so on [212]. AgNPs have further applications in food and packaging, where the resistance against bacterial attack/degradation may prove useful.

Textile products are also functionalized using AgNPs in terms of antibacterial, UV-protection, thermal, mechanical, coloration, and so on. Hygiene textiles are becoming increasingly popular due to busy lifestyles of consumers who seek to reduce the maintenance of their clothing, hence the interest toward antibacterial products is increasing. Antibacterial

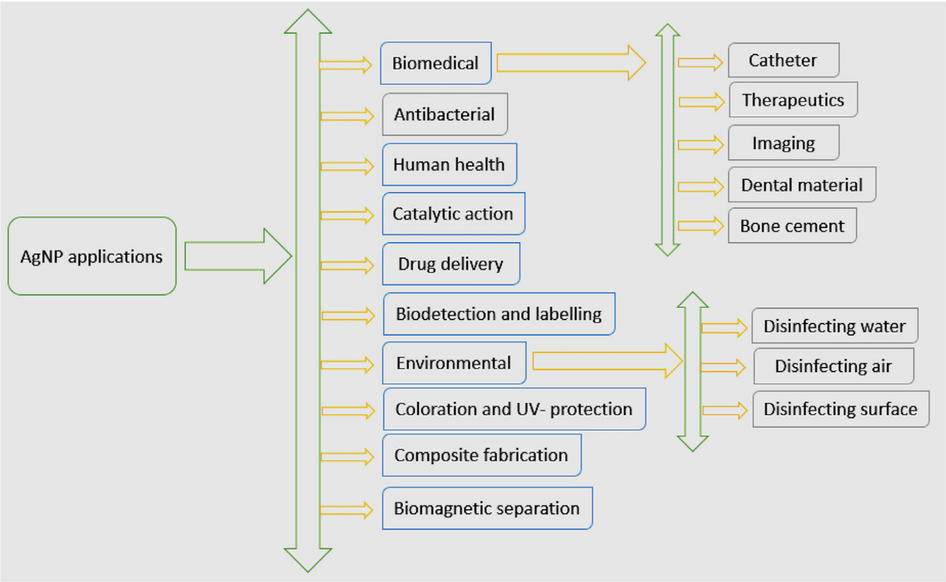


Figure 19. Potential applications of AgNPs.

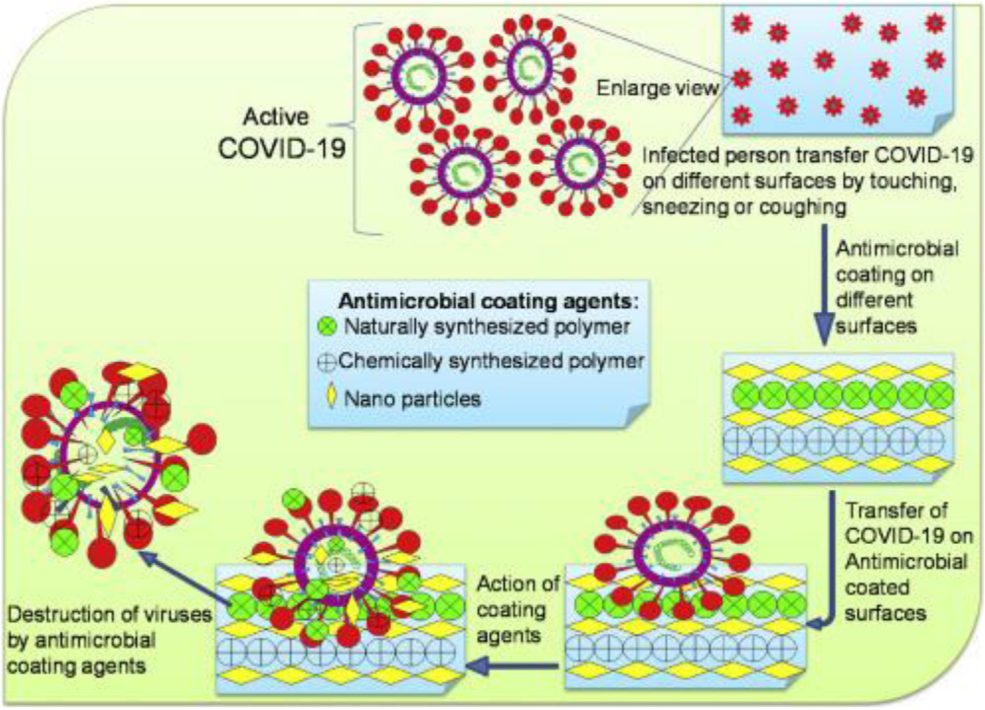


Figure 20. A hypothetical tackling mechanism against COVID-19 in terms of antibacterial coating. Adapted with permission from Elsevier [249]. Copyright, Elsevier 2020.

finishes could facilitate the removal of odor/diseases through resisting the microorganism development [263]. Fabrics are extensively made of fibers, and cotton fiber is the most frequently used sustainable material having hydroxyl groups in their polymeric structure, facilitating the formation of bonds between the AgNPs and alcoholic elements present in the cellulosic fiber [196]. However, synthetic materials, another important candidate for textile fabrics production, also attained significant consideration for functionalization by AgNP [264, 265]. Furthermore, PET, a widely used synthetic fiber is also biocompatible and possess minimum inflammation response, and gas superior metal binding capability, thus providing significant antibacterial, coloration, and thermal properties [134, 265]. Moreover, due to the LSPR characteristics, AgNPs provide excellent coloration effects to the fabrics too. The AgNP treated woven/non-woven fabrics also show versatile potential towards the production of nanobiocomposites with improved mechanical performances [239]. The fabrics used for shower curtains, carpets, upholstery, covering of mattresses, sails, ropes, and tents are in need of antibacterial finishes, which will provide not only bright coloration effects, but also significant resistance against microbial growth, as otherwise they cause not only hygiene issues but also rot, mildew or mold development [263, 266]. AgNP treatments may also improve the biocidal properties of school dresses, sportswear, uniform, military dresses, and so on.

6. Marketing prospects and future potential

Nowadays, metallic NPs are considered as the most attractive area of research for versatile applications. Hence, new technologies, methods and innovative routes are getting explored continuously to make them convenient, sustainable, cheaper, and feasible for the consumers. The striking and bright colorful noble metallic AgNPs have attracted considerable interest as a novel platform in the field of nanoscience and nanobiotechnology. The continuous demand on sustainable, low-cost, and multifunctional products offers bright prospects for biosynthesized AgNPs. In 2015, there was a market volume of AgNP by $1 billion USD, showing a significant demand of this material. As the consumption increases, it is expected to reach a market value of nearly $2.45 billion by 2022 [267] and $3 billion USD by 2024 [268]. The healthcare industry is the biggest consumer of AgNPs (including antibacterial, antifungal applications, and so on, see Figure 21), whereas textile, electronics, electrical, food and beverages use significant amounts as well [269]. The reason behind the growth of AgNP consumption in the electronics and electrical sector is the high performance capability, stability, conductivity, and feasible processing routes. Textile-related applications for coloration, UV-protection, and other functionalities are important in terms of military clothing, sportswear, underwear, medical items like bandages, wound dressing, face masks, and so on. AgNPs also play a great role for food processing and storage. The utilization of metallic silver is also increasing in this sector, as the foods can be kept safe and fresh without any microorganism attack. The green synthesis route of AgNPs is one of the most recent innovation by the scientific community. However, much

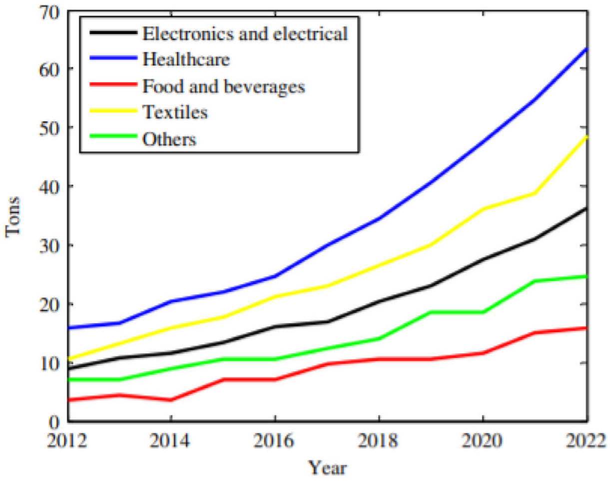
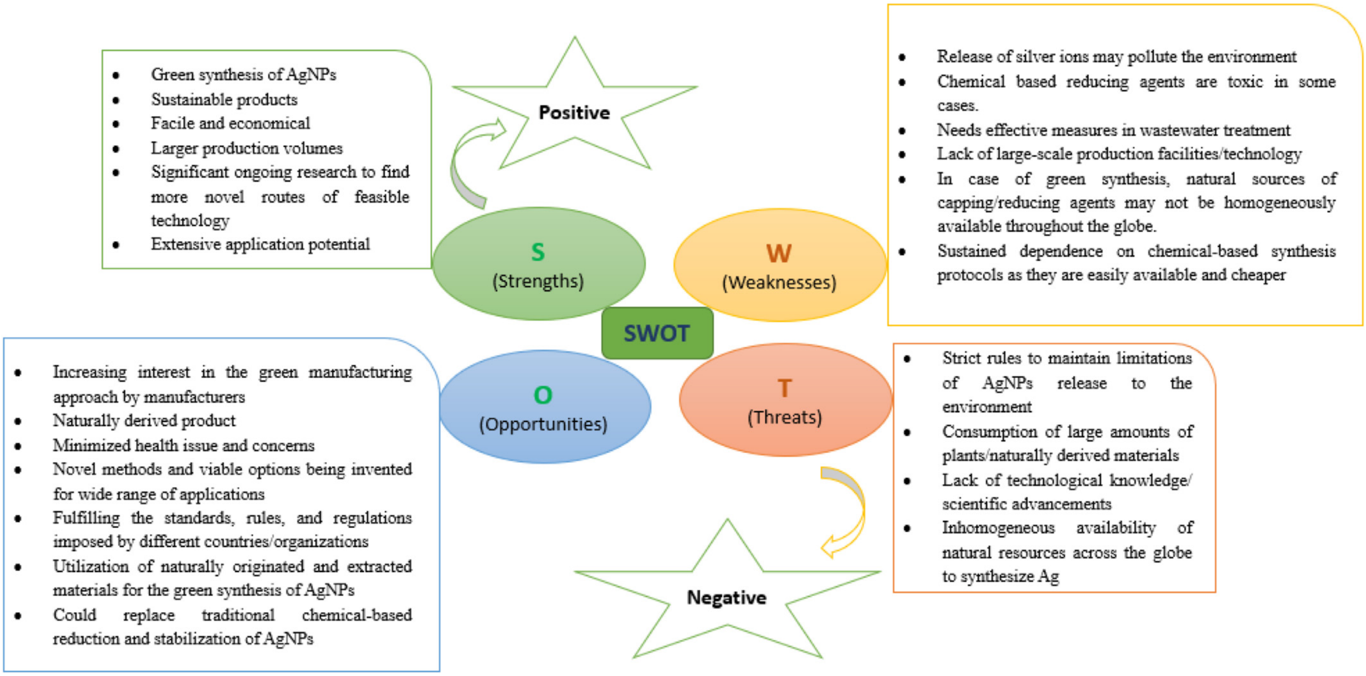


Figure 21. Worldwide consumption of AgNPs. Adapted with permission from Wiley [269]. Copyright, Wiley and 2017.



- Green synthesis of AgNPs
- Sustainable products
- Facile and economical
- Larger production volumes
- Significant ongoing research to find more novel routes of feasible technology
- Extensive application potential

- Release of silver ions may pollute the environment
- Chemical based reducing agents are toxic in some cases.
- Needs effective measures in wastewater treatment
- Lack of large-scale production facilities/technology
- In case of green synthesis, natural sources of capping/reducing agents may not be homogeneously available throughout the globe.
- Sustained dependence on chemical-based synthesis protocols as they are easily available and cheaper

- Increasing interest in the green manufacturing approach by manufacturers
- Naturally derived product
- Minimized health issue and concerns
- Novel methods and viable options being invented for wide range of applications
- Fulfilling the standards, rules, and regulations imposed by different countries/organizations
- Utilization of naturally originated and extracted materials for the green synthesis of AgNPs
- Could replace traditional chemical-based reduction and stabilization of AgNPs

- Strict rules to maintain limitations of AgNPs release to the environment
- Consumption of large amounts of plants/naturally derived materials
- Lack of technological knowledge/ scientific advancements
- Inhomogeneous availability of natural resources across the globe to synthesize Ag

Figure 22. SWOT analysis of greenly synthesized AgNPs.

technological innovation is needed for upscaling the method to meet commercial demands. The biobased synthesis of AgNP has already opened a new scope for using different naturally derived materials as reducing and stabilizing agents. Now, the challenge is to bring the small scale laboratory-based researches to the industrial production, especially in the fields of environment, agriculture, catalysis, biomedical, coloration, and biocomposites. AgNPs are already showing tremendous potential in the biomedical sciences, especially for antibacterial, anti-carcinogenic, anti-tumor treatments, and so on. The exploration of new fields with multifunctionality may be able to satisfy the demands of an increasing global population.

7. SWOT analysis of green AgNPs

The utilization of AgNPs have both advantages and drawbacks. The green synthesis technology and protocols constitute a new route and have good potential for creating sustainable products by the multifaceted applications of AgNPs. The authors developed a SWOT analysis to understand the negatives and prospects of green AgNPs in terms of strengths, weaknesses, opportunities, and threats for attaining certain competitive advantages by the different manufacturing sectors/businesses (Figure 22). However, the idea was taken from a previous study by the same authors for SWOT analysis [270]. Based on the analysis, the positive aspects (strengths and opportunities) of green AgNPs are displaying outweigh the negatives (challenges and threats). The overall review set forth in this current study definitely supports this conclusion.

8. Conclusion

Since ancient times, nature found ingenious and elegant routes to create miniaturized, efficient and functional products. Awareness is rising all over the world to explore green chemistry for implementing safer routes, materials, and technologies to manufacture industrial products in an eco-friendly way. Nanoparticles, like AgNPs, show excellent potential to achieve this objective through creating safer products and reducing waste, to foster healthy communities, environment, and workplaces. Furthermore, utilization of greenly synthesized AgNPs minimizes consumption of synthetic chemical reagents in traditional dyeing processes. Additionally, AgNP fabric treatment is an excellent way to provide diversified functional properties (UV-protection, antibacterial, and mechanical properties), besides imparting the coloration effects. This is why sustainable AgNPs are going to play a significant role in the upcoming decades. However, although massive efforts by the researchers throughout the globe has proved the potential of AgNPs, we still need to explore more feasible routes to make them environment-friendly and cost-effective for industrial utilization. Moreover, there is still a large number of plants and carbohydrate materials available in our environment that are yet to be explored. This could be an area that requires a significant amount of further research to find the most optimal biological agent for this process. If the biomolecules present in naturally derived materials for AgNP extraction are identified properly, a one-step dyeing protocol could be implemented, which would lead to a decline in energy and utilities consumption to create green and efficient technologies.

Declarations

Author contribution statement

All authors listed have significantly contributed to the development and the writing of this article.

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Data availability statement

Data will be made available on request.

Declaration of interests statement

The authors declare no competing interests.

Additional information

No additional information is available for this paper.

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