Fabrication of anti-bacterial cotton bandage using biologically synthesized nanoparticles for medical applications

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Abstract
Recently the use of plant-derived extracts for the green synthesis of nanoparticles has drawn considerable attention. In the present study silver and copper nanoparticles were synthesized using extracts of Andrographis paniculata which is found to possess various pharmacological properties. The synthesized nanoparticles were characterized using UV spectroscopy, SEM with EDS, XRD, TEM and DLS. Furthermore, an attempt is made to impregnate these nanoparticles onto cotton bandages. The structure and morphology of silver nanoparticles impregnated onto the cotton bandages were confirmed by SEM. The anti-bacterial activity of cotton bandages loaded with silver and copper nanoparticles was tested against Escherichia coli, Bacillus cereus, and Staphylococcus aureus using a modified disc diffusion assay. The results indicate that the cotton bandages biofabricated with nanoparticles exhibited anti-bacterial activity in terms of zone of inhibition of growth of tested bacteria suggesting their usage as medical textiles in various biomedical applications for the prevention of infections. Hence, the nanoparticles impregnated cotton fibers can be applied for the development of masks, aprons, etc. to protect against bacterial penetration and as well to counteract the present situation of the world.

Keywords Metal nanoparticles · Andrographis paniculata · Green synthesis · Anti-bacterial activity · Medical textiles

Introduction
The development of anti-microbial and antibiotic-resistant pathogens makes the treatment of bacterial infections complicated leading to the exploration of novel approaches for circumventing this problem. Metal nanoparticles are acknowledged to possess strong inhibitory and anti-bacterial effects (Khodadadi et al. 2021; Urnukhsaikhan et al. 2021). These metal nanoparticles can be synthesized using physical, chemical and biological methods (Rónavári et al. 2021). However, physical and chemical methods involve high energy constraints and the use of toxic reagents for synthesis. This issue can be overcome by employing biological agents, such as bacteria, fungi, algae, actinomycetes, and plants for the synthesis of metal nanoparticles (John et al. 2021; Koul et al. 2021; Chugh et al. 2021; Rai et al. 2021; Dikshit et al. 2021). Recently, the use of plant extracts for nanoparticle synthesis has received much attention due to the rich diversity of phytochemicals, availability in bulk quantities, and simplicity (Balciunaitiene et al. 2021; Amjad et al. 2021; Gaddam et al. 2021; Aboyewa et al. 2021; Selvakasan and Franklin 2021; Sawalha et al. 2021; Rajagopal et al. 2021).

Andrographis paniculata Nees (commonly known as the king of bitters) is a medicinal plant that belongs to the Acanthaceae family (Jayakumar et al. 2013; Niranjan et al. 2010). The plant is native to India and Srilanka and is distributed in northern parts of India, Java, Malaysia, Indonesia, West Indies, Hong Kong, Thailand, and Singapore (Jayakumar et al. 2013; Niranjan et al. 2010; Nugroho et al. 2013). The plant is used to treat common cold and fever and is found to exhibit pharmacological activities, such as immunostimulatory, anti-viral and anti-bacterial activities (Jayakumar et al. 2013). Major active phytoconstituents of the plant are andrographolide, neoandrographolide and dehydroandrographolide. Andrographolide exhibits a broad range of biological activities, such as anti-inflammatory, anti-bacterial, anti-tumor, anti-diabetic, anti-malarial, anti-snake venom,
and hepatoprotective (Jayakumar et al. 2013; Niranjan et al. 2010). Anti-SARS-CoV-2 activity of *A. paniculata* was reported recently (Sa-Ngiamsuntorn et al. 2021).

Cotton fabrics such as the lab, surgical coats, and masks are more prone to microbial attack (Ravindra et al. 2010). Few reports have highlighted the use of nanoparticles in the production of anti-microbial fabrics. Vigneshwaran et al. (2007) reported a novel in situ synthesis protocol for the incorporation of silver nanoparticles onto cotton fabrics. El-Shishawy et al. (2011) have employed silver nanoparticles coating on cotton fabrics. Khan et al. (2019) developed an anti-bacterial, UV-protected and self-cleaning surgical gown coating on cotton fabrics. El-Shishawy et al. (2011) have employed silver nanoparticles incorporation of silver nanoparticles onto cotton fabrics. Tania and Ali (2021) applied copper nanoparticles. Further antimicrobial surgical cotton was developed using iron nanoparticles coating. Román et al. (2020) developed anti-bacterial cotton fabrics through functionalization with copper oxide nanoparticles. Tania and Ali (2021) applied zinc nanoparticles onto cotton fabrics using the mechanical thermo-fixation technique.

In the present study, an attempt was made to synthesize silver and copper nanoparticles using an aqueous extract of flowers and roots of *A. paniculata*. The biologically synthesized nanoparticles were characterized using various methods, such as UV spectral studies, SEM with EDS, XRD, TEM, and DLS. Furthermore, the work also attempted to impregnate the synthesized nanoparticles onto the cotton bandage and to evaluate its anti-bacterial potential. Hence this study will be helpful for the development of novel anti-bacterial medical textiles and wound dressing materials.

**Materials and methods**

**Chemicals**

Fresh flowers and roots of *A. paniculata* were collected from the Kalasalingam Academy of Research and Education Campus. All the chemicals used in the study were obtained from Himedia Laboratories, Mumbai.

**Preparation of aqueous extracts of flowers and root of *A. paniculata***

Fresh flowers and roots were washed thoroughly in tap water, followed by distilled water. Dried flowers and roots were cut into minor pieces and 5 g of cut flowers and roots were boiled for 10 min in 100 mL distilled water and filtered through Whatman No. 1 filter paper (Padalia et al. 2015). The filtered extracts were used for the synthesis of silver and copper nanoparticles.

**Synthesis of silver nanoparticles**

1 mM aqueous solution of silver nitrate (AgNO₃) was used for the synthesis of silver nanoparticles. 3 mL of flower and root extracts was added into 20 mL of AgNO₃ solution, and incubated in dark at room temperature for 40 and 50 min, respectively. This causes the reduction of Ag⁺ ions into Ag nanoparticles (AgNPs). Purification of AgNPs was carried out by repeated centrifugation at 10,000 rpm for 10 min and air-dried. The purified AgNPs were then stored at 4°C and used for the rest of the analysis (Padalia et al. 2015).

**Synthesis of copper nanoparticles**

To 20 mL of copper sulphate, 3 mL of flower and of root extracts were added separately in different flasks. The reaction mixture was incubated at room temperature for 60 and 40 min, respectively. This causes the reduction of Cu²⁺ ions into copper nanoparticles (CuNPs). Purification of nanoparticles was done by repeated centrifugation at 10,000 rpm for 10 min. The nanoparticle pellet was stored at 4°C for further analysis (Padalia et al. 2015).

**Characterization of synthesized silver and copper nanoparticles**

The nanoparticles were dispersed in distilled water and UV–Vis spectra of the synthesized AgNPs and CuNPs were acquired using a spectrophotometer (Shimadzu) in the range of 400–700 nm. The FTIR spectra were recorded in the range of 400–4000 cm⁻¹ using Fourier transform infrared spectroscopy (Shimadzu). The surface morphology of the nanoparticles was imaged using scanning electron microscopy (Carl Zeiss) at an accelerating voltage of 15 kV. Elemental analysis was performed using EDS (Bruker). XRD pattern was used to study the crystalline nature of the nanoparticles by a Bruker, ECO D8 Advance X-ray diffractometer operating at a voltage of 40 kV, and a current of 20 mA using CuKα radiation. Scherrer formula \( D = 0.94 k / \beta \cos \theta \) was used to calculate the crystallite domain size from the width of the XRD peaks, where \( D \) is the average crystallite domain size perpendicular to the reflecting planes, \( k \) is the X-ray wavelength (1.5406), \( \beta \) is the full width at half maximum (FWHM), and \( \theta \) is the diffraction angle (Dinesh et al. 2012). The shape and size of the synthesized nanoparticles were studied through transmission electron microscopy (Jeol/JEM 2100) operating at 200 kV voltage. The size distribution of AgNPs and CuNPs was analyzed using a particle size analyzer (Horiba) through light scattering.
Impregnation of silver and copper nanoparticles onto cotton bandages

The surgical cotton bandage was cut into small pieces and pre-weighed pieces (2.5 g) of cotton bandage were immersed in 250 mL of 1 mM silver nitrate. To this mixture, 50 mL of extracts of *A. paniculata* was added and kept on an orbital shaker at 100 rpm at room temperature in dark for 24 h. Phytochemicals present in flower and root extracts result in the reduction of silver ions into silver, which nucleates into AgNPs on the cotton bandages. After 24 h, the pieces of cotton bandages were recovered from the mixture. The AgNP impregnated cotton bandage was washed with deionized water and oven-dried at 55 °C (Vivekanandhan et al. 2012). The same procedure was repeated for impregnating CuNPs on the cotton bandages.

Confirmation of nanoparticle impregnation using SEM

The surface morphology of AgNPs and CuNPs impregnated cotton bandages were analyzed using a scanning electron microscope (Carl Zeiss SEM) at an accelerating voltage of 15 kV. The normal cotton bandage was used as a control.

Anti-bacterial activity of nanoparticle impregnated cotton bandage

Dried pieces of AgNPs and CuNPs impregnated cotton bandages were evaluated for anti-bacterial activity against the test microorganisms, *Escherichia coli*, *Bacillus cereus* and *Staphylococcus aureus*. The overnight cultures prepared using nutrient broth were used for swabbing. The anti-bacterial susceptibility testing was studied similar to disc diffusion assay by placing the pieces of AgNPs and CuNPs impregnated cotton bandages in the form of discs in bacteria swabbed Mueller Hinton agar plates. The plates were inspected for the inhibition zones developed against the tested bacteria after incubation at 37 °C for 1 day. A cotton bandage disc without nanoparticles was used as a control.

Results and discussion

Visual observation

With the addition of root and flower extract to the colorless silver nitrate solution, the color changed into reddish brown in the former and dark brown in the latter mixtures, due to the reduction of silver ions to silver nanoparticles as evidenced from Fig. 1a, b. The intensity of color was directly proportional to the formation of AgNPs (Padalia et al. 2015). Similarly, the addition of root and flower extract to copper sulphate results in the color change of the reaction mixture into light green and pale green, respectively, leading to the formation of CuNPs (Gopinath et al. 2014) as visualized from Fig. 1c, d.

UV–visible spectroscopy

The UV spectrum (Fig. 2a) of the AgNPs synthesized using the root extract displayed a peak at 416 nm by a “surface plasmon resonance” (Sudhakar et al. 2014). Similarly, the AgNPs prepared from the flower extract exhibited an absorption peak at 429 nm. The UV spectrum of biosynthesized CuNPs from the root extract showed a peak at 251 nm (Fig. 2b) and CuNPs prepared from the flower extract revealed a peak at 308 nm by the surface plasmon resonance (Shobha et al. 2014).

FTIR spectral analysis

FTIR analysis was used to recognize the possible reducing biomolecules in the root and flower extracts. Figure 3a–d shows the FTIR spectra of aqueous AgNPs and CuNPs prepared from root and flower extracts of *A. paniculata*, respectively. The functional groups and their corresponding signal assignment are provided in Tables 1, 2, 3 and 4. The reducing agents promote the development of metallic nanoparticles from the respective ionic compounds. The reduction is mediated by plant biomolecules, such as sugars, proteins, organic compounds and numerous functional groups, such as C=C (alkenyl), C=N (amide), O=H (phenolic and alcohol), N–H (amine), C–H and COO– (carboxylic group) that are responsible for the synthesis of nanoparticles (Awwad et al. 2013). These metabolites are acknowledged as significant sources for controlling various acute diseases (Kuppusamy et al. 2016).

SEM and EDS analysis

The SEM images of AgNPs synthesized with the root and flower extracts and CuNPs with the root and flower extracts of *A. paniculata* are shown in Figs. 4a, b and 5a, b, respectively. The EDS graphs of AgNPs and CuNPs synthesized using *A. paniculata* are depicted in Figs. 4c and 5c, respectively.

Figure 4a, b shows that AgNPs are in spherical aggregated form and the corresponding EDS (Fig. 4c) confirms the presence of AgNPs with a broad peak at 3 keV (Oluwaniyi et al. 2016). Figure 5a shows that the shape of CuNPs synthesized using root extract is
Fig. 1 Silver (a, b) and copper nanoparticles (c, d) synthesis using root extract and flower extract of *Andrographis paniculata*, respectively.
cuboidal, while the CuNPs synthesized using flower extract of *A. paniculata* is in spherical and aggregated (Fig. 5b). The corresponding EDS graph (Fig. 5c) shows a peak at 8 keV, which is characteristic of the absorption of metallic copper nanoparticles (Caroling et al. 2015).

**XRD analysis**

Figure 6a shows distinct peaks at 38° and 77° indexed as (111), (311), 27.5° and 32° (111), 38° (200), 46° (220), 55° (311) and 57.5° (222) lattice planes of face-centered cubic (fcc) structure of metallic silver of AgNPs synthesized from flower extract (Ponvel et al. 2015). Similarly, Fig. 6b shows distinct peaks at 38° and 77° which are indexed as (111), (311), 28° and 33° (111), 38° (200), 46.5° (220), 55° (311) and 57.5° (222) lattice planes of face-centered cubic (fcc) structure of metallic silver of AgNPs synthesized from root extract.

Figure 6c, d shows the XRD pattern of the CuNPs synthesized from the flower and root extracts of *A. paniculata*. The orientation and crystalline nature of the nanoparticles were revealed through the XRD patterns. Peak position at 32° (Fig. 6c) is characteristic of face-centered cubic of copper lines indexed at (210), (111), (210) and (220) and peak position at 28°, 32°, 38°, 46° (Fig. 6d) are characteristic of face-centered cubic of copper lines indexed at (210), (111), (210) and (220), respectively (Awwad et al. 2013). The crystallite size of AgNPs and CuNPs synthesized using root and flower extract.

| Nanoparticles                      | Wavenumber (cm⁻¹) | Functional group                                                                 |
|-----------------------------------|-------------------|----------------------------------------------------------------------------------|
| Silver nanoparticles (root extract) | 1074.35, 1031.92  | Bending vibration of C–OH groups and anti-symmetric stretching bend of C–O–C groups of polysaccharide (Mollick et al. 2019) |
|                                    | 1382.96           | Asymmetrical stretching for nitro compounds (Rajeshkumar et al. 2014)            |
|                                    | 1606.60           | C=O stretching modes due to the free carboxylic group (Vijayan et al. 2014)       |
|                                    | 2885.51           | CH stretching modes of alkanes (Dinesh et al. 2012)                              |
Table 2  FTIR bands corresponding to the functional groups of silver nanoparticles synthesized from flower extract of A. paniculata

| Nanoparticles                              | Wavenumber (cm⁻¹) | Functional groups                                                                 |
|--------------------------------------------|-------------------|-----------------------------------------------------------------------------------|
| Silver nanoparticles (flower extract)      | 1109.07           | C–OH vibrations of primary alcohols (Caroling et al. 2015)                        |
|                                            | 1625.99           | Amide I group of proteins (Hegazy et al. 2015)                                    |
|                                            | 2376.30           | The tertiary amine of NH⁺ stretching (Ponvel et al. 2015)                         |

Table 3  FTIR bands corresponding to the functional groups of copper nanoparticles synthesized from flower extract of A. paniculata

| Nanoparticles                              | Wavenumber (cm⁻¹) | Functional group                                                                 |
|--------------------------------------------|-------------------|---------------------------------------------------------------------------------|
| Copper nanoparticles (flower extract)      | 619.15            | Vibration of alkyl halides (Rajeshkumar et al. 2014)                            |
|                                            | 1093.64           | Bending vibration of C–OH groups (Mollick et al. 2019)                          |
|                                            | 1400.32           | C–N-stretching vibrations of aliphatic and aromatic amines, alcohols and phenols (Awad et al. 2013) |
|                                            | 1622.13 cm        | Amide I group of proteins (Mollick et al. 2019)                                 |

Table 4  FTIR bands corresponding to the functional groups of copper nanoparticles synthesized from the root extract of A. paniculata

| Nanoparticles                              | Wavenumber (cm⁻¹) | Functional groups                                                                 |
|--------------------------------------------|-------------------|-----------------------------------------------------------------------------------|
| Copper nanoparticles (root extract)        | 1230.58           | C–O groups of polyols, such as hydroxy-flavones (Hegazy et al. 2015)              |
|                                            | 1384.89           | Asymmetric stretching of nitro compounds (Rajeshkumar et al. 2014)                |
|                                            | 2881.65           | CH group of alkanes (Hegazy et al. 2015)                                         |

Fig. 4  SEM image of silver (a, b) nanoparticles synthesized using root and flower extracts of A. paniculata; EDS graph of silver nanoparticles (c) synthesized using A. paniculata, respectively

extracts of A. paniculata are calculated using the Scherrer formula and they are tabulated in Table 5. The crystallite size of nanoparticles ranges between 22 and 42 nm.

**TEM analysis**

The TEM images of silver and copper nanoparticles, synthesized from the root extract, are depicted in Figs. 7 and 8, respectively. The shape of the silver nanoparticles in Fig. 7a–c is triangular, spherical and ellipse with moderate variation in size that is polydisperse. The “selected-area electron diffraction” (SAED) patterns portrayed in Fig. 7d exhibit concentric rings with intermittent bright spots, representing that the nanoparticles are crystalline in nature (Padalia et al. 2015). Figure 8a, b shows that the copper nanoparticles are of irregular shape and in aggregate form. SAED pattern depicted in Fig. 8c exhibits diffuse rings indicating that the nanoparticles are amorphous (Caroling et al., 2015).
Particle size distribution analysis

The particle size distribution of AgNPs and CuNPs is shown in Fig. 9a, b, respectively. AgNPs have a mean size of 75.8 nm with a polydispersity index of 0.559 and the particle size distribution ranges from 19.03 to 279.04 nm. CuNPs have an average size of 144.8 nm with a polydispersity index of 1.505 and the particle size distribution ranges from 118.74 to 171.25 nm.

Confirmation of nanoparticle impregnation using SEM

Figure 10a shows the SEM image and Fig. 10b displays the EDS pattern of the control bandage. Figure 10c, e shows the SEM images of AgNPs (flower extract) impregnated cotton bandage and AgNPs (root extract) impregnated cotton bandage, respectively. The corresponding EDS mapping images are given in Fig. 10d, f. Similarly, Fig. 11a, c shows their respective SEM images of CuNPs (flower extract) impregnated cotton bandage and CuNPs (root extract) impregnated cotton bandage. The EDS mapping images are given in Fig. 11b, d, respectively.

Table 5 Crystallite size of the nanoparticles

| Nanoparticles          | Crystallite size (nm) |
|------------------------|-----------------------|
|                        | Root extract | Flower extract |
| Silver nanoparticles   | 24.73        | 22.098        |
| Copper nanoparticles   | 25.96        | 33.65         |

Figure 5 SEM image of copper (a, b) nanoparticles synthesized using root and flower extracts of A. paniculata; EDS graph (c) copper nanoparticles synthesized using A. paniculata, respectively.

Figure 6 XRD pattern of the silver (a, b) and copper (c, d) nanoparticles synthesized using flower and root extracts of A. paniculata, respectively.

Figure 7 TEM images (a–c) of silver nanoparticles in low and high magnifications, (d) SAED pattern of silver nanoparticles synthesized using root extract of A. paniculata.
From Fig. 10a, it is observed that the cotton bandage is smooth and no peak corresponding to silver and copper is displayed in the EDS pattern (Fig. 10b). Figure 10d, f shows that AgNPs (flower and root extract) have been impregnated in the cotton bandage and a peak at 3 keV confirms it as well. Figure 11b, d shows that CuNPs (flower and root extract) have been impregnated in the cotton bandage and is confirmed by a peak at 8 keV. The hydroxyl groups of polysaccharides present in root and flower extracts reduce the silver nitrate into AgNPs on the cotton bandage.

Cotton is a natural fiber that consists of cellulose with 1,4-D-glucose pyranose as its repeating units. These surface hydroxyl groups present in cotton bandage facilitates the adsorption of AgNPs proficiently onto cotton fibers (Ravindra et al. 2010).

Anti-bacterial activity

Figures 12 and 13 show the anti-bacterial activity of CuNPs and AgNPs impregnated cotton bandage against B. cereus, respectively. Figures 14 and 15 show the anti-bacterial activity of copper and AgNPs impregnated cotton bandage against E. coli, respectively. Figures 16 and 17 show the anti-bacterial activity of CuNPs and AgNPs impregnated cotton bandage against S. aureus, respectively.

Table 6 shows the inhibition zones of exhibited by nanoparticles impregnated cotton bandage against E. coli, B. cereus, S. aureus, respectively. From the table, it can be inferred that the AgNPs impregnated cotton bandages exhibit better anti-bacterial activity against the tested bacteria.

Overall, the fabricated cotton bandages with AgNPs and CuNPs provided a similar inhibition pattern of all the tested bacteria. Though several studies regarding the green synthesis of metal nanoparticles using plant extracts were available, the present study was focused on the green synthesis of AgNPs and CuNPs using extracts of flower and root of A. paniculata which is not addressed in the literature before. To our knowledge, this is the first report highlighting the use of roots and flowers of A. paniculata for AgNPs and CuNPs synthesis. We have also reported the use of roots and flowers of A. paniculata for the synthesis of gallium nanoparticles (Monika et al. 2017).

Synthesis of silver nanoparticles using leaf extract of A. paniculata was reported by Sulochana et al. (2012). Synthesis of silver nanoparticles using A. paniculata leaf extract and its anti-bacterial activity was evaluated by Sinha and
Paul (2015). Devasenan et al., attempted green synthesis of zinc nanoparticles using leaf extract of *A. paniculata* (Devasenan et al. 2016). Rajakumar et al. synthesized zinc oxide nanoparticles by exploiting the reducing and capping potential of *A. paniculata* leaf extract (Rajakumar et al. 2018). Anantharaman et al. used leaf extract of *A. paniculata* for the synthesis of AgNPs and evaluated its antimicrobial properties (Anantharaman et al. 2020). Biological synthesis of titanium dioxide nanoparticles was carried out with leaves extract of *A. paniculata* by Rajeshkumar et al. (2021).

Furthermore, very few studies have reported the development of medical textiles or cotton bandages fabricated with metal nanoparticles synthesized using physical or chemical methods. As the cotton bandages were fabricated with nanoparticles synthesized using herbal extract, it offers an additional advantage in view of the medical applications.

**Conclusions**

Metal nanoparticles synthesized through the green synthesis approach are gaining much attention in recent times. An extensive interest is growing particularly when phytochemicals are employed for the reduction of metal ions to nanoparticles. The present study focussed on a green synthesis strategy for the synthesis of silver and copper nanoparticles using extracts of *A. paniculata*, a medicinal plant used in the treatment of various diseases. The synthesized nanoparticles were characterized using UV spectroscopy, SEM with EDS, XRD, TEM, and DLS analyses. Furthermore, the nanoparticles were impregnated onto the cotton bandages and their anti-bacterial activity was assessed. This study showed that cotton fibres impregnated with nanoparticles through a green synthesis approach can be potentially applied for the development of medical textiles, such as bandages, masks, aprons, etc. for the prevention of infections.
Fig. 11  SEM image and EDS mapping pattern of copper nanoparticles (flower extract—a, b, root extract—c, d, impregnated cotton bandage)

Fig. 12  Anti-bacterial activity of copper nanoparticles (flower and root extract) impregnated cotton bandage against *B. cereus*, respectively

Fig. 13  Anti-bacterial activity of silver nanoparticles (root and flower extract) impregnated cotton bandage against *B. cereus*, respectively
Fig. 14  Anti-bacterial activity of copper nanoparticles (flower and root extract) impregnated cotton bandage against *E. coli*, respectively.

Fig. 15  Anti-bacterial activity of silver nanoparticles (root and flower extract) impregnated cotton bandage against *E. coli*, respectively.

Fig. 16  Anti-bacterial activity of copper nanoparticles (root and flower extract) impregnated cotton bandage against *S. aureus*, respectively.

Fig. 17  Anti-bacterial activity of silver nanoparticles (flower and root extract) impregnated cotton bandage against *S. aureus*, respectively.
### Table 6 Inhibition zone by nanoparticles impregnated cotton bandages

| Nanoparticle impregnated cotton bandage | Inhibition zone (cm) | Escherichia coli | Bacillus cereus | Staphylococcus aureus |
|----------------------------------------|----------------------|----------------|----------------|----------------------|
|                                        |                      |                |                |                      |
| Silver (root)                          | 1.5                  | 1.2            | 1.1            |                      |
| Silver (flower)                        | 1.3                  | 1.5            | 1.3            |                      |
| Copper (root)                          | 1.2                  | 1.1            | 1.2            |                      |
| Copper (flower)                        | 1.4                  | 1.1            | 1.2            |                      |

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### Availability of data and materials

All data generated or analyzed during this study are included in this manuscript.

### Declarations

#### Conflict of interest

The authors declare that there is no conflict of interest.

#### Ethics approval

Not applicable.

#### Consent to participate

Not applicable.

#### Consent for publication

The authors give the consent for publication.

### References

Aboyeja JA, Sibuyi N, Meyer M, Oguntibeju OO (2021) Green synthesis of metallic nanoparticles using some selected medicinal plants from Southern Africa and their biological applications. Plants 10:1929. https://doi.org/10.3390/plants10091929

Amjad R, Mubeen B, Ali SS, Imam SS, Alshehri S, Ghoneim MM, Alzarea SI, Rasool R, Ullah I, Nadeem MS, Kazmi I (2021) Green synthesis and characterization of copper nanoparticles using Funtunella marginata leaves. Polymers 13:4364. https://doi.org/10.3390/polym13244364

Anantharamanan S, Rego R, Muthakka M, Anttes T, Krishna H (2020) Andrographis paniculata-mediated synthesis of silver nanoparticles: antimicrobial properties and computational studies. SN Appl Sci 2:1–14. https://doi.org/10.1007/s42452-020-03394-7

Awad AM, Salem NM, Abdeen AO (2013) Green synthesis of silver nanoparticles using carob leaf extract and its anti-bacterial activity. Int J Ind Chem 4:1–6. https://doi.org/10.1186/2228-5547-4-29

Balcuniaiuteiene A, Viskelis P, Viskelis J, Streimikyte P, Laidauskas M, Bartkiene E, Zavitanavicute P, Zokaityte E, Starkute V, Ruzauskas M, Lele V (2021) Green synthesis of silver nanoparticles using extract of Artemisia absinthium L., Humulus lupulus L. and Thymus vulgaris L., physico-chemical characterization, antimicrobial and antioxidant activity. Processes 9:1304. https://doi.org/10.3390/pr9081304

Caroling G, Priyadharshini MN, Vinodhini E, Ranjitham AM, Shanthi P (2015) Biosynthesis of copper nanoparticles using aqueous guava extract-characterization and study of anti-bacterial effects. Int J Pharm Biol Sci 5:25–43

Chugh D, Viswamalya VS, Das B (2021) Green synthesis of silver nanoparticles with algae and the importance of capping agents in the process. J Genet Eng Biotechnol 19:1–21. https://doi.org/10.1186/s43141-021-00228-w

Devasenan S, Beevi NH, Jayanith SS (2016) Green synthesis and characterization of zinc nanoparticle using Andrographis paniculata leaf extract. Int J Pharm Sci Res 39:243–247

Dikshit PK, Kumar J, Das AK, Sadha S, Sharma S, Singh S, Gupta PK, Kim BS (2021) Green synthesis of metallic nanoparticles: applications and limitations. Catalysts 11:902. https://doi.org/10.3390/catal11080902

Dinesh S, Karthikeyan S, Arumugam P (2012) Biosynthesis of silver nanoparticles from Glicyr rhiza glabra root extract. Arch Appl Sci Res 4:178–187

El-Shishtawy RM, Asiri AM, Abdelwahed NM, Al-Otaibi MM (2011) In situ production of silver nanoparticles on cotton fabric and its antimicrobial evaluation. Cellulose 18:75–82. https://doi.org/10.1007/s10570-010-9455-1

Gaddam SA, Kotakadi VS, Subramanyam GK, Penchalenani J, Challagundla VN, DVRPasupuleti SGVR (2021) Multifaceted phytotherapeutic silver nanoparticles by an insectivorous plant Drosera spatulata Labill var. bakoensis and its potential therapeutic applications. Sci Rep 11:1–17. https://doi.org/10.1038/s41598-021-01281-8

Gopinath M, Subbaya R, Selvam MM, Suresh D (2014) Synthesis of copper nanoparticles from Nerium oleander leaf aqueous extract and its anti-bacterial activity. Int J Curr Microbiol Appl Sci 3:814–818

Hegazy HS, Shabaan LD, Rabie GH, Raie DS (2015) Biosynthesis of silver nanoparticles using cell free callus exudates of Medicago sativa L. Pak J Bot 47:1825–1829

Jayakumar T, Hsieh CY, Lee JJ, Sheu JR (2013) Experimental and clinical pharmacology of Andrographis paniculata and its major bioactive phytoconstituent andrographolide. Evid Based Complement Altern Med 2013:846740. https://doi.org/10.1155/2013/846740

John MS, Nagoth JA, Zannotti M, Giovanni R, Mancini A, Ramasamy KP, Misceli C, Pucciarelli S (2021) Biogenic synthesis of copper nanoparticles using bacterial strains isolated from an Antarctic consortium associated to a psychrophilic marine ciliate: characterization and potential application as antimicrobial agents. Marine Drugs 19:263. https://doi.org/10.3390/md19050263

Khan MQ, Kharghani D, Nisha N, Shahzad A, Hussain T, Khatri Z, Zhu C, Kim IS (2019) Preparation and characterizations of multifunctional PVA/ZnO nanofibers composite membranes for surgical gawn application. J Mater Res Technol 8:1328–1334. https://doi.org/10.1007/s10570-018-08013

Khoddadi S, Mahdinezhad N, Fazeli-Nasab B, Heidari MJ, Fakheri B, Miri A (2021) Investigating the possibility of green synthesis of silver nanoparticles using Vaccinium arctostaphylos extract and evaluating its antibacterial properties. Biomed Res Int 2021:1–13. https://doi.org/10.1155/2021/5572252

Koul B, Poonia AK, Yadav D, Jin JO (2021) Microbe-mediated biosynthesis of nanoparticles: applications and future prospects. Biomolecules 11:886. https://doi.org/10.3390/biom11060886

Kuppusamy P, Yusoff MM, Maniam GP, Govindan N (2016) Biosynthesis of metallic nanoparticles using plant derivatives and their new avenues in pharmacological applications. Saudi Pharm J 24:473–484. https://doi.org/10.1016/j.jsps.2014.11.013

Mollick MR, Rana D, Dash SK, Chattopadhyay S, Bhowmick B, Maity D, Mondal D, Pattanayak S, Roy S, Chakraborty M,
Chattopadhyay D (2019) Studies on green synthesized silver nanoparticles using Abelmosschus esculentus (L.) pulp extract having anti-cancer (in vitro) and anti-microbial applications. Arab J Chem 12:2572–2584. https://doi.org/10.1016/j.arabjc.2015.04.033

Monika S, Ponlakshmi SH, Sundar K, Vanavil B (2017) Biological synthesis of gallium nanoparticles using extracts of Andrographis paniculata. Int J Eng Sci, Adv Comp Biotech 8:208–222

Niranjan A, Tewari SK, Lehri A (2010) Biological activities of Kalmegh (Andrographis paniculata) Nees) and its active principles. Ind J Nat Prod Resour 1:125–135

Nugroho AE, Lindawati NY, Herlyanti K, Widyasturi L, Paramona S (2015) Anti-diabetic effect of a combination of andrographolide-enriched extract of Andrographis paniculata (Burm. f) Nees and asiaticoside-enriched extract of Centella asiatica L. in high fructose-fat fed rats. Indian J Exp Biol 51:1101–1108

Oluwaniyi OO, Adegoke HI, Adesuji ET, Alabi AB, Bodede SO, Labose-fat fed rats. Indian J Exp Biol 51:1101–1108

Rajagopal G, Nivetha A, Sundar M, Panneerselvam T, Murugesan S, Ravindra S, Mohan YM, Reddy NN, Raju KM (2010) Fabrication of Rajeshkumar S, Malarkodi C, Kumar KP, Vanaja M, Gnanajobitha G, Rajakumar G, Thiruvengadam M, Mydhili G, Gomathi T, Chung IM Rai M, Bonde S, Golinska P, Trzcińska-Wencel J, Gade A, Abd-Padalia H, Moteriya P, Chanda S (2015) Green synthesis of silver nanoparticles using aqueous leaf extract of Thevetia peruviana Juss and its antimicrobial activities. Appl Nanosci 6:903–912. https://doi.org/10.1007/s13204-015-0505-8

Padalia H, Moteriya P, Chanda S (2015) Green synthesis of silver nanoparticles from marigold flower and its synergistic antimicrobial potential. Arab J Chem 8:732–741. https://doi.org/10.1016/j.arbje.2014.11.015

Prabakaran J (2015) Biosynthesis of silver nanoparticles using root extract of the medicinal plant Justicia adhatoda: characterization, electrochemical behavior and applications. Int J Nano Dimens 6:339–349. https://doi.org/10.1155/2015/4.002

Rai M, Bonde S, Golinska P, Trzcińska-Wencel J, Gade A, Abd-Elsalam KA, Shende S, Gaikwad S, Ingle AP (2021) Functional finishing of cotton fabrics using textile with enhanced mechanical properties. Polymers 13:2701. https://doi.org/10.3390/polym13162701

Rajagopal G, Nivetha A, Sundar M, Panneerselvam T, Murugesan S, Parasuraman S, Kumar S, Kunjippan IS, S, (2021) Mixed phytochemicals mediated synthesis of copper nanoparticles for anti-cancer and larvicidal activities. Heliyon 7:e07360. https://doi.org/10.1016/j.heliyon.2021.e07360

Rajakumar G, Thiruvengadam M, Mydhili G, Gomathi T, Chung IM (2018) Green approach for synthesis of zinc oxide nanoparticles from Andrographis paniculata leaf extract and evaluation of their antioxidant, anti-diabetic, and anti-inflammatory activities. Bioprocess Biosyst Eng 41:21–30. https://doi.org/10.1007/s00449-017-1840-9

Rajeshkumar S, Mallarodi C, Kumar KP, Vanaja M, Gnanajobitha G, Annadurai G (2014) Algae mediated green fabrication of silver nanoparticles and examination of its antifungal activity against clinical pathogens. Int J Met 2014:1–10. https://doi.org/10.1155/2014/692643

Rajeshkumar S, Santhoshkumar J, Jule LT, Ramaswamy K (2021) Synthesis of titanium dioxide nanoparticles using king of bitter Andrographis paniculata and its embryonic toxicity evaluation and biomedical potential. Bioinorg Chem Appl 2021:1–11. https://doi.org/10.1155/2021/6267634

Ravindra S, Mohan YM, Reddy NN, Raju KM (2010) Fabrication of antibacterial cotton fibers loaded with silver nanoparticles via green approach. Colloids Surf A Physicochem Eng Asp 367:31–40. https://doi.org/10.1016/j.colsurfa.2010.06.013

Román LE, Gomez ED, Solís JL, Gómez MM (2020) Antibacterial cotton fabric functionalized with copper oxide nanoparticles. Molecules 25:5802. https://doi.org/10.3390/molecules25245802

Rónavári A, Igaz N, Adamecz DI, Szerencsés B, Molnar C, Kónya Z, Pfeiffer I, Kirisci M (2021) Green silver and gold nanoparticles: biological synthesis approaches and potentials for biomedical applications. Molecules 26:844. https://doi.org/10.3390/molecules2604844

Sa-Ngiamsuntorn K, Sukatsu A, Pewkliang Y, Thongsri P, Kanjanasirirat P, Manopwisijaroen S, Charoensutthivarulak S, Wongtrakoongat P, Pitiporn S, Chaopreecha J, Kongsomros S, Jearawuttanakul K, Wannalo W, Khemawoot P, Chutipongtaneet S, Borwornynio S, ThithiananONT A, Hongeng S (2021) Anti-SARS-CoV-2 Activity of Andrographis paniculata extract and its major component andrographolide in human lung epithelial cells and cytotoxicity evaluation in major organ cell representatives. J Nat Prod 84:1261–1270. https://doi.org/10.1021/acs.jnatprod.ka01324

Sawalha H, Abira R, Sanusi R, Shahraddun NA, Noor A, Ab Shakor NA, Abdul-Hamid H, Ahmad SA (2021) Toward a better understanding of metal nanoparticles, a novel strategy from Eucalyptus plants. Plants 10:1–22. https://doi.org/10.3390/plants10050929

Selvakesavan RK, Frankling G (2021) Prospective application of nanoparticles green synthesized using medicinal plant extracts as novel nanomedicines. Nanotechnol Sci Appl 14:179–195. https://doi.org/10.2147/NSA.S333467

Shobha G, Vinutha M, Ananda S (2014) Biological synthesis of copper nanoparticles and its impact—a review. Int J Pharm Sci Invent 3:6–28

Sinha SN, Paul D (2015) Phytosynthesis of silver nanoparticles using Andrographis paniculata leaf extract and evaluation of their anti-bacterial activities. Spectrosc Lett 48:600–604. https://doi.org/10.1080/00387010.2014.938756

Sudhakar PS, Krishna KBM, Sundar S (2014) Synthesis and characterization of silver nanoparticles using aqueous extract of Andrographis paniculata and their anti-microbial activities. Int J Sci Technol Manag 29:1962–1969

Sulochana S, Krishnamoorthy P, Sivarajanki K (2012) Synthesis of silver nanoparticles using leaf extracts of Andrographis paniculata. J Pharmacol Toxicol 7:251–258

Tania IS, Ali M (2021) Coating of ZnO nanoparticles on cotton fabric to create a functional textile with enhanced mechanical properties. Polymers 13:2701. https://doi.org/10.3390/polym13162701

Turakbia B, Chikkala S, Shah S (2019) Novelty of bioengineered iron nanoparticles in nanocoated surgical cotton: a green chemistry. Adv Pharmcol Sci 2019:1–10. https://doi.org/10.1155/2019/9825969

Urnuksaikhan E, Bold BE, Gunbileg A, Sukhbaatar N, Mishig-Ochir T (2021) Antibacterial activity and characteristics of silver nanoparticles biosynthesized from Carduus crispus. Sci Rep 11:1–12. https://doi.org/10.1038/s41598-021-00520-2

Vigneshwaran K, Kathe AA, Varadarajan PV, Nachane RP, Balasubramanayam RH (2007) Functional finishing of cotton fabrics using silver nanoparticles. J Nanosci Nanotechnol 7:1893–1897. https://doi.org/10.1166/jnn.2007.737

Vijayan SR, Santhiyagu P, Singamuthu M, Ahila NK, Jayaraman R, Ethiraj K (2014) Synthesis and characterization of silver and gold nanoparticles using aqueous extract of seaweed, Turbinaria conoides and their anti-micro fouling activity. Sci World J 2014:1–14. https://doi.org/10.1155/2014/938272

Vivekanandan S, Laura C, Manjusri M, Mohanty AK (2012) Green process for impregnation of silver nanoparticles into microcrystalline cellulose and their anti-microbial bionanocomposite films. J Biomer Nanobiotech 3:371–376. https://doi.org/10.4236/jbnnb.2012.33035

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