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Phytosynthesized-Silver Nanoparticles for Functionalization of Cotton Fabric: A Systematic Literature Review

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Abstract. Coating cotton fabrics with silver nanoparticles (AgNPs) will produce a multifunctional fabric. Additional functions such as antibacterial, antifungal, UV protector, sensor, and wound dressing can be improved by adding AgNPs to the cotton fabric. The functionalization can be performed by various techniques, such as pad-drying, dip-drying, or sonochemical, where the AgNPs were produced by phytosynthesis or utilizing plant extracts as a reducing agent, and this has been reported by many researchers in the past. This review systematically extracts and critically discusses the available published information on the functionalization of cotton fabrics with phytosynthesized-AgNPs from the Scopus database. Future challenges in fabricating multifunctional cotton with AgNPs were also discussed, including obtaining stable and permanent AgNPs immobilization on cotton fabric and developing additional or new functions.

Keywords: AgNPs; Bibliometric analysis; Functionalization of cotton; Phytosynthesis; VOSviewer

1. Introduction

Textile materials, in some cases, are produced with additional functionalities to meet the end-use requirement apart from their basic purpose, which has attracted many researchers. These materials are termed multifunctional textiles or advanced textiles. Some examples of these functionalities include electrical properties, UV protection, water and oil repellent, and antibacterial activity. These functional textiles have various applications such as for personal protection, medical, hygiene, sport and leisure, and military. Nanotechnology has become one of the fields studied in textile functionalization (Elmaaty *et al.,* 2022; Reningtyas *et al.,* 2022).

Silver nanoparticles (AgNPs) have been widely explored because of their exceptional properties, such as optical and antimicrobial activity (Singh *et al.,* 2023; Yin *et al.,* 2020; Duval, Gouyau, and Lamouroux, 2019). Consequently, various textiles like cotton, polyester, polyamide, wool, and silk have been investigated for the production of textiles treated with AgNPs. These nanoparticles can be synthesized using different methods, such as microwave-assisted, chemical vapor deposition, chemical reduction, sonochemistry, and

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photochemistry (Tarannum, Divya, and Gautam, 2019).

In the chemical reduction process, a reducing agent such as borohydride, trisodium citrate, hydrazine, and ascorbic acid reduces Ag^+ from precursor materials such as silver nitrate, silver acetate, and silver citrate to Ag^0 (Avissa and Alauhdin, 2022; Sadalage *et al.,* 2020; Mavani and Shah, 2013).

This synthesis method is termed biosynthesis, green synthesis, or phytosynthesis. Such a method offers considerable benefits in terms of environmental friendliness through biomass valorization, limiting the use of harmful chemical reagents, hence reducing the costs and toxicity (Lite *et al.,* 2022).

The incorporation of nanoparticles into cotton fabrics is a way to apply nanotechnology in the functionalization of textiles. Several ways have been developed to incorporate AgNPs into cotton, such as immersion or dip-coating, pad-dry-cure, sonication, printing, etc (Zayed *et al.,* 2022; Arshad *et al.,* 2022; Hassabo *et al.,* 2020; Verma *et al.,* 2021; Elmaaty *et al.,* 2018; Anbazhagan *et al.,* 2017; Velmurugan *et al.,* 2014). The growing interest in green technology concepts in various utilities fuels the development of environmentally beneficial materials. Consequently, there is a growing interest among researchers in the utilization of natural-based materials, particularly in the development of functional textiles. The functionalization of cotton with biosynthesized AgNPs emerges as an eco-friendly alternative in the pursuit of sustainable, functional textiles.

Based on searches from the Scopus database using related keywords, there are only a few review articles on the functionalization of cotton fabrics with silver nanoparticles in the 2013-2022 period. One of the articles discusses the application of AgNPs for fabric functionalization, not specifically for cotton fabrics (Syafiuddin, 2019). Meanwhile, another article discusses the functionalization of cotton fabrics using nanotechnology, including the use of Ag, TiO_2, SiO_2, ZnO, Cu or CuO, and Au nanoparticles (Elmaaty *et al.,* 2022). The nanoparticles were synthesized using various methods, including chemical, physical, and biological methods. There are also reviews on the influence of several types of nanoparticles, including AgNPs, on the physical properties of modified cotton fabrics for conductive textiles (Alamer and Beyari, 2022) and for medical applications (Ahmed, Ogulata, and Bozok, 2022). Meanwhile, this systematic review attempts to discuss more comprehensively the functionalization of cotton fabric with silver nanoparticles using plant extracts as bio-reductors.

2. Methods

2.1. Literature Search

This systematic review referred to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework. The literature search was conducted using the Scopus database for the last 10 years (2013-2022). A combination of keywords, [textile OR fabrics AND cotton AND "silver nanoparticles"], was used in the search command to find the relevant literature. The search is based on the occurrence of the keyword combination in the title, abstract, and keyword of articles. Only original research papers written in English were included. Only original research papers written in English were considered, excluding books, book chapters, conference proceedings, and theses. Following these criteria, 424 papers were retrieved from the Scopus database.

2.2. Selection of Papers

The results of the literature search were further refined by reading through the abstracts to check whether the study applied bioreductors for preparing AgNPs. Further screening was conducted to include only papers that applied plant extract as a bioreductor for the synthesis. The screening resulted in the exclusion of 349 papers, which means 75 papers remained to be analyzed. Afterward, any relevant studies were evaluated from the reference lists of the 75 papers, which resulted in six additional texts. Thus, the final selection comprised 81 papers to be reviewed.

2.3. Bibliometric keyword analysis

A bibliometric study is intended to understand the relationships between journal citations and to summarize the current state of a given or emerging research area (Donthu *et al.,* 2021). The bibliometric mapping software program VOSviewer was used to analyze and visualize the keywords co-occurrence of the studied papers (n = 424). VOSviewer was created by Van-Eck and Waltman (2010) and has been utilized effectively in numerous studies (Indriati and Nandiyanto, 2023; Su *et al.,* 2021; Kamdem *et al.,* 2019).

The analysis employed "full counting" as the technique of counting, and the next steps included a selection of the "all keywords" option and lowering the threshold for keyword occurrence to 10, where 146 out of 3565 total keywords found were included. The resulting keyword selection was then subjected to further manual adjustments, including the elimination of redundant terms like "textile" and "textiles," as well as outlier and generic keywords unrelated to the research on the functionalization of cotton with AgNPs. Examples of the excluded keywords include "article," "controlled study," "nonhuman," "priority journal," and "color."

3. Results and Discussion

3.1. Number and categorization of research articles

Search results from the Scopus databases generated 424 articles that studied the functionalization of cotton with AgNPs. Figure 1 shows the distribution of 424 articles over the period of 2013-2022. In general, the number of publications has increased, especially from 2019 onward. This data showed that the topic is attractive to the researchers. Furthermore, 424 papers were screened with inclusion criteria for AgNP synthesis using plant extract bioreductor. The use of other bioreductors, such as fungi, biopolymers, starch, and sugar-based reductors was excluded. This screening resulted in 75 articles that were considered in the systematic review study.

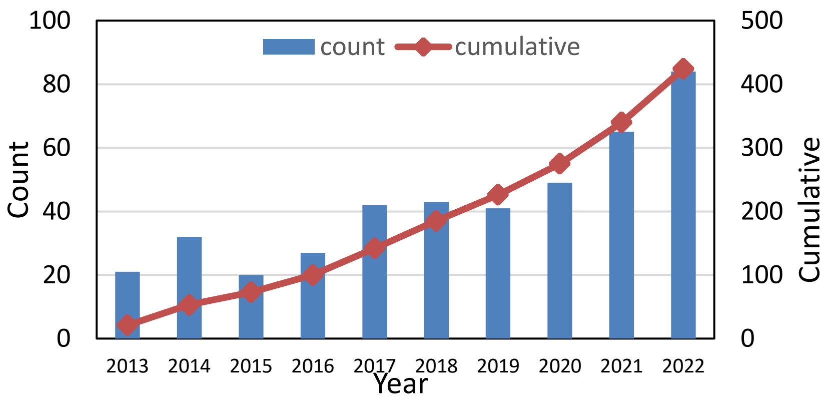

Figure 1 Trend in the number of research publications on the topic of functionalization of cotton fabric with AgNPs from 2013-2022 in the Scopus database

This review also includes six more publications in an effort to incorporate any papers that might have been overlooked throughout the literature search which are El Guerraf *et al.* (2023), Afroj *et al.* (2020), Hong *et al.* (2016), Yun *et al.* (2013), Zeng *et al.* (2013) and Prabhu and Poulose (2012) by going through the reference list of related articles and from the studies within the emerging additional textile functions topic.

3.2. Bibliometric analysis

Three cluster research fields connected to the functionalization of cotton with AgNPs were visually shown by the keyword co-occurrence network analysis using VOSviewer (Figure 2). The blue cluster is related to research on the properties of AgNPs-coated cotton; the red cluster is depicted as a research field on the synthesis and characterization of AgNPs-coated cotton, while the green cluster is related to the application of AgNPs-coated cotton in textiles. The node size and keyword labels correspond to the frequency of the keywords, while the space between the circles denotes how closely related the keywords are. The distance between the circles will be smaller the more often a keyword occurs in the studied articles. Two keywords are linked together by curved lines, and the thickness of the lines reflects how frequently the two keywords occur together in articles.

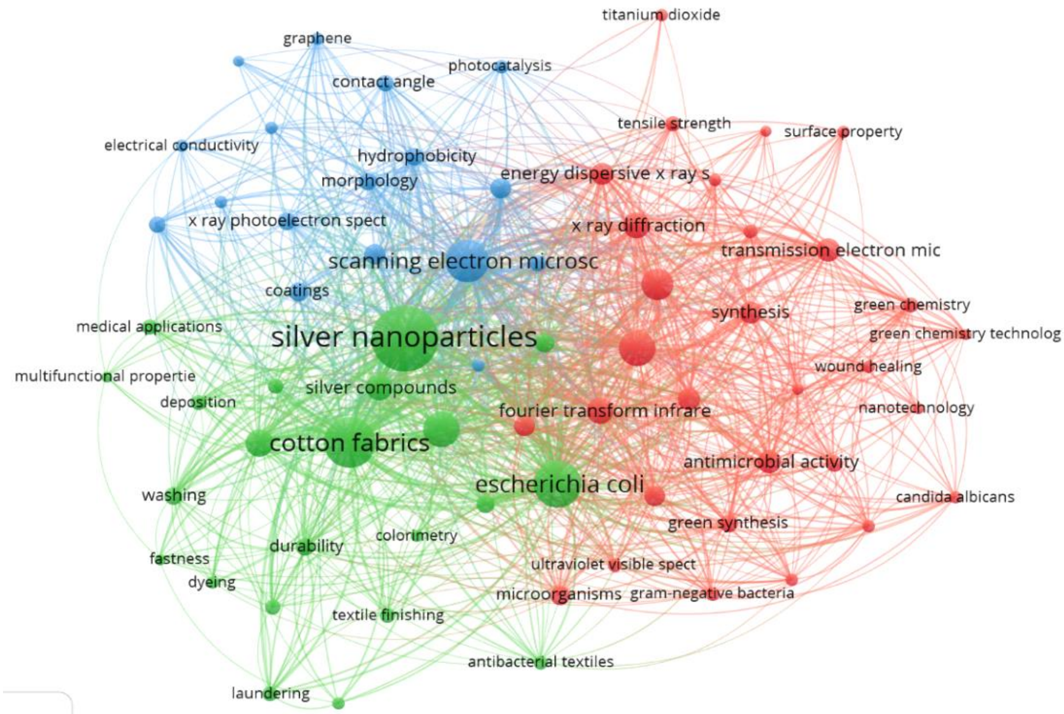

Figure 2 Keywords co-occurrence network of screened research articles from the Scopus database showing three clusters: red, green, and blue clusters.

Overlay visualization (Figure 3) shows keyword-related trends across the study period (2013-2022). The study period is indicated by the colors of the keyword nodes, from blue (old period) to yellow (new period). According to the analysis, research areas related to the green synthesis of AgNPs-coated cotton are still interesting to study at this time. This is in line with the increasing awareness of green chemistry and green technology. Applications of AgNPs-coated cotton as conductive fabrics and their combination with other materials, such as graphene, have also started to appear recently, as indicated by the yellow nodes in Figure 3.

3.3. Phytosynthesis and loading of AgNPs

The AgNPs loading into fabrics are mainly classified into *ex-situ* and *in-situ* methods. In the ex-situ method, synthesis and loading are performed consecutively, while in the in-situ method, both are performed simultaneously in one pot. Nearly half of the reviewed articles used the *in-situ* method (36 studies), which revealed AgNP coating with good wash-durability and color fastness. Moreover, it consumes less time, chemicals, and energy (Jain *et al.,* 2022; Yu *et al.,* 2020). The *in-situ* synthesis resulted in higher entanglement of nanoparticles because they grow within the fibroids of cellulose (Tania, Ali, and Azam

2019). Meanwhile, the *ex-situ* method is mostly done through pad-drying or dip-drying, some of which are followed by curing. This method was chosen because it is more applicable to current industrial applications (Naebe *et al.*, 2022).

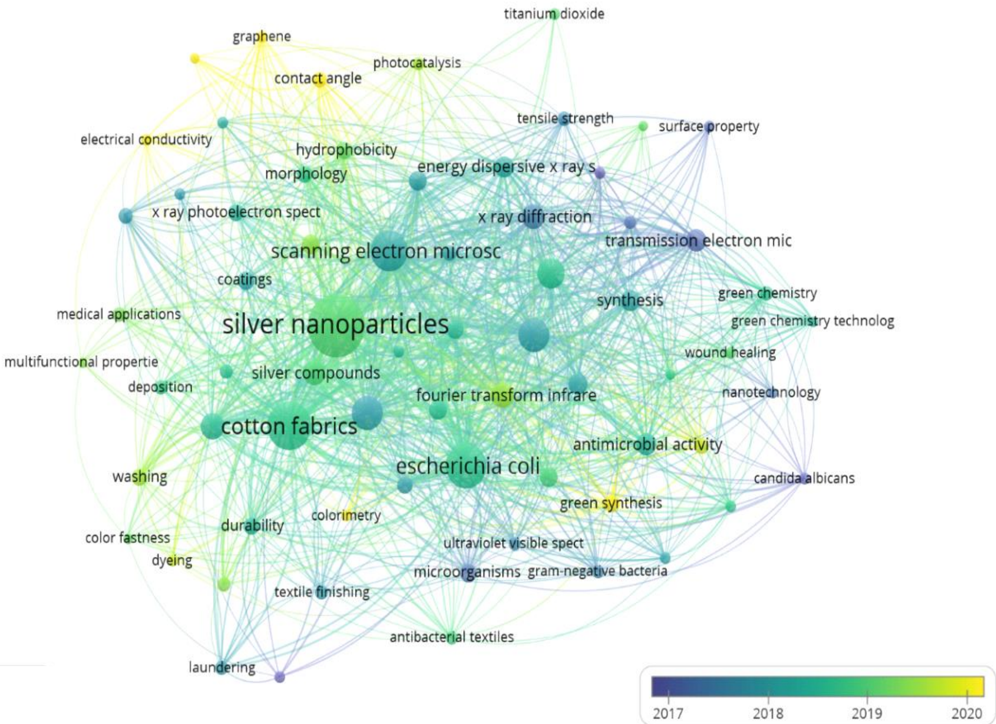

Figure 3 Overlay visualization of keyword co-occurrence of screened research articles from the Scopus database

Various types of plant extracts have been used to synthesize AgNPs, where the plant extracts act as a reductant to convert Ag^+ to Ag^0. The plant extracts also function as a stabilizer (El-Zawahry *et al.*, 2022; Rather *et al.*, 2022) or colorant (El-Zawahry *et al.*, 2022; Jiang *et al.*, 2022; Rehan *et al.*, 2022; Sadeghi-Kiakhani *et al.*, 2022a; Yu *et al.*, 2020). Table 1 summarizes the phytosynthesized-AgNPs that have been utilized to impart multifunctional properties to cotton fabric.

Several studies discussed the role of compounds in plant extracts in the process of reducing Ag^+ to Ag^0. Generally, various authors have reported that phenolic compounds play an important role in the reduction process (El-Zawahry *et al.*, 2022; Shahid-ul-Islam *et al.*, 2020). As the reducing agent, the phenol content in the extract was consumed during phytosynthesis. For example, Lite *et al.* (2022) observed a 5% reduction in the phenolic content of Primula officinalis extract after the phytosynthesis of AgNPs. In addition, the consumption of the phenolic compounds during the formation of AgNPs was also observed when *Hibiscus* flower extract was used simultaneously as a dye and reductant in an *in-situ* synthesis of AgNPs (Rehan *et al.*, 2022). The antioxidant activity of the extract of *Hibiscus* flowers was mainly produced by phenolic, flavonoid, and volatile compounds. Since phenolic compounds serve as reductants in the synthesis of AgNPs, their quantity decreases, consequently reducing the overall antioxidant activity.

The proposed mechanism of the phytosynthesis of AgNPs is described below in Figure 4 (El-Zawahry *et al.*, 2022; Rehan *et al.*, 2022; Shahid-ul-Islam *et al.*, 2020; Rehan *et al.*, 2017) in which:

- The Ag^+ ions form an intermediary complex with the nearby hydroxyl (-OH) groups of the phenolic compounds.

- The hydroxyl groups are subsequently used to donate electrons to the Ag^+ ions, reducing them to AgNPs and changing phenolic compounds into their quinone form.
- The quinone form is then adsorbed onto the formed AgNPs surface and stabilized by the nanoparticles.

Figure 4 The proposed mechanism of biosynthesis of AgNPs (Ag^0)

In the presence of cotton, the hydroxyl groups of the cellulose bind and fix the formed AgNPs on the cotton surface (Figure 5). In situ synthesis, when cotton fabric was immersed in $AgNO_3$ solution, the silver ions were absorbed and dispersed across the cotton surface, allowing for electrostatic interactions with the negatively charged hydroxyl groups in the cellulose chain of cotton (Rehan *et al.*, 2015). Then, the reduction of Ag^+ ions was promoted by the phenolic groups or other bioactive molecules of the plant extract or the cotton (Jain *et al.*, 2022). In addition, alkaline pretreatment of the cotton has been reported to increase AgNPs loading. Here, the hydroxyl group of the alkali activates the cotton fabrics and makes more AgNPs attachments (Ahmed, Ogulata, and Bozok, 2022).

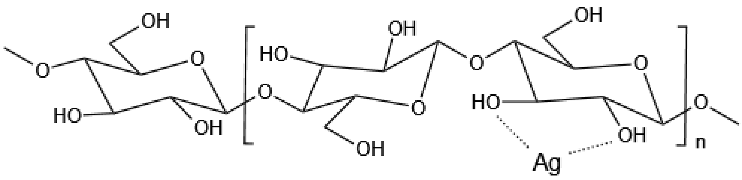

Figure 5 The hydroxyl groups of the cellulose bind the formed AgNPs on the cotton surface

The successful incorporation of AgNPs into cotton fibers can be verified using electron microscopic techniques. For example, the in-situ insertion of AgNPs within the fiber was verified by cross-sectional imaging of the cotton fibers with a FIB-FESEM. The particles have a Gaussian distribution with an average diameter of 28.2 ± 8.0 nm. Meanwhile, the SAED measurement reveals the typical lattice spacing for metallic Ag, (1 1 1), (2 0 0), (2 2 0), and (3 1 1) planes of the face-centered cubic (fcc) structure of elemental Ag (Nam *et al.*, 2022).

3.4. Application of AgNPs-loaded cotton

In the applications of AgNPs-modified cotton, the predominant function is as an antibacterial and antimicrobial agent. Almost all reviewed studies have focused on examining the antibacterial properties of the resulting textiles. Indeed, AgNPs are well known to have good antibacterial properties (Shreyash *et al.*, 2021, Alsultani, 2017). Another functionality that has also been widely studied, although not as much as an antibacterial, is as a UV protector. It is also common that the researchers examined more than one functionality of the AgNPs-loaded cotton. Examples of other functionalities of AgNPs cotton are milk freshness sensor, colorant, anti-inflammatory, wound dressing, and packaging. Table 1 below summarizes the various applications of AgNPs-loaded cotton.

Table 1 Summary of the functionalization of cotton fabrics with phytosynthesized-AgNPs, extracted from the Scopus database during 2013-2020

Plant	AgNPs properties	Deposition method	Function	Reference
Hibiscus flowers	Size: 90±11 nm (SEM)	*in situ* synthesis	AM, AO, UVP	(Rehan *et al.*, 2022)
Cineraria maritima	Size: 21.57 - 39.16 nm	dip dry method	AB	(Duraisamy *et al.*, 2022)
Alternanthera sessilis leaf	Spherical structures with a size range of 15–40 nm (HRTEM)	dip dry method	AB	(Kabeerdass *et al.*, 2022)
Cuphea carthagenensis	Spherical shape with a particle size of 10.65±0.1 nm	dip dry and *in situ* synthesis	AB	(Rather *et al.*, 2022)
Azadirachta indica leaf	Zeta potential: −60.9 mV	*in situ* synthesis	AB, UVP	(Jain *et al.*, 2022)
Psidium guajava leave	Size range: 5-120 nm (depend on pH)	pad-dry technique	AB, AO, UVP	(Zayed *et al.*, 2022b)
Andrographis paniculate	Size: 19-279 nm (means: 75.8 nm by DLS)	*in situ* impregnation	AB	(Kannan *et al.*, 2022)
Aloe vera	fcc structure. particle size: 60 nm	pad-dry-cure	AB	(Liu *et al.*, 2022)
Lepidium meyenii polyphenol extract	Spherical shape, particle size: 49.19±0.82 nm	pad-dry process	sensor	(Karakuş *et al.*, 2022)
Gardeniae fructus seeds	Spherical shape with nanometer size.	*in situ* synthesis	AB, UVP, C	(Jiang *et al.*, 2022)
Citrus Sinensis peel (orange peel)	Size: 7-220 nm depend on pH	pad-dry technique	MR, AB	(Zayed *et al.*, 2022a)
Malva sylvestris	Size: 50-80 nm	*in situ* synthesis	AB	(Sadeghi-Kiakhani *et al.*, 2022b)
Sweet Orange Peel extract	Spherical-shaped	dip dry	AB, UVP	(Roy *et al.*, 2022)
Azadirachta indica leaf	Size: 10-100 nm	*in situ* synthesis	AB, AF	(Pawar *et al.*, 2022)
Aloe vera	Spherical shape, size: 30–80 nm	Immersion	AB, AF	(Arshad *et al.*, 2022)
Bark extract of *Acacia nilotica*	Size: 125 nm	Dispersion	AM	(Abd El-Baset *et al.*, 2021)
European larch (*Larix decidua*)	EDS peak 2.96 keV	*in situ* synthesis	C	(Hasan *et al.*, 2021)
Biper nigrum seed extract	spherical shapes, size: 15 - 38 nm	dip-coating technique	AB	(Kanniah *et al.*, 2021)
Tulsi (*Ocimum tenuiflorum*) extract	Size: 23 ± 3 nm. zeta potential: −23.3 mV (alkaline) and −10.3 mV (neutral)	pad-dry-cure method	AM, UVP	(Mia *et al.*, 2021)
Aloe vera	Spherical. Size: 5-20 nm	dip-coating	AB	(Verma *et al.*, 2021)
Scutellaria barbata extract	Spherical shape. Size: 20 to 40 nm	Soaking and sonication	AB	(Veeraraghavan *et al.*, 2021)
Honeysucklee extract	Size average 10.59 nm (TEM) and 35.76 nm (DLS), zeta pot -42.9 mV	dip and dry	AB	(Zhu *et al.*, 2021)
Azadirachta indica	Cubical structure. average size: 25 nm	pad dry cure technique	AM, UVP	(Anwar *et al.*, 2021)
Black rice (*Oryza sativa* L.)	SPR band: 410 nm	*in situ* synthesis	AM	(Yu *et al.*, 2021)

Table 1 Summary of the functionalization of cotton fabrics with phytosynthesized-AgNPs, extracted from the Scopus database during 2013-2020 (cont.)

Plant	AgNPs properties	Deposition method	Function	Reference
Cassia alata	spherical shape in the size range of 20 - 119 nm	*in situ* synthesis	AB	(Sivaranjana *et al.*, 2021)
Beta vulgaris (beetroot)	size: 50.0 ± 12.4 nm, zeta pot. -30 mV	impregnation	AB, AF	(dos Santos *et al.*, 2021)
Senna auriculata	spherical in shape with a mean size of 100 nm	*in situ* synthesis	AB	(Akepogu *et al.*, 2021)
Moringa oleifera	Spherical shape, size: 20 nm (TEM)	pad-dry-cure	AM, UVP	(Hassabo *et al.*, 2020)
Curcuma longa L.	spherical shape, size: 15-40 nm	*in situ* ultra-sonication	AM, WH	(Maghimaa and Alharbi, 2020)
Black rice (*Oryza sativa* L.) extract	size 60-90 nm (depend on pH)	*in situ* synthesis	AB	(Yu *et al.*, 2020)
Aegle marmelos fruit pulp extract	Mostly spherical with sizes ranging from 10 to 75 nm	*in situ* synthesis	AB	(Velmurugan *et al.*, 2020)
Pomegranate peel extract	Spherical shape. Size around 20 nm (TEM)	*in situ* synthesis	AO, AM	(Shahid-ul-Islam *et al.*, 2019)
Pterocarpus santalinus (Red sanders)	spherical shape with a size range of 71–90 nm	*In situ* synthesis	AB	(Rao *et al.*, 2018)
Padina gymnospora (brown seaweed)	spherical shape with a size range of 2-20 nm	Pad-dry-cure	AM, UVP	(Rajaboopathi and Thambidurai, 2018)
Allium cepa L.	size: 36 - 98 nm (DLS), Zeta potential -12 ± 1.5 mV to -26 ± 1.2 mV	*in situ* synthesis	AM	(Sharma *et al.*, 2018)
Pluchea dioscoridis	size: 15–25 nm (TEM)	printing	AM, UVP, AM	(Elmaaty *et al.*, 2018)
Cunninghamella echinulata	Average size of 20–50 nm (TEM)	immersion - shaking	AB	(Anbazhagan *et al.*, 2017)
P. pterocarpum flowers	86 nm in size with a face-centered cubic crystalline	Dipping-ultrasonication	AB	(Balamurugan *et al.*, 2017)
Terminalia catappa, *T. bellarica*, *T. mellurie*	Mostly spherical with diameters in the range of 10 - 14 nm	Pad-dry technique	AI, AB	(El-Rafie *et al.*, 2017)
Liquidambar orientalis Mill	size: 50-150 nm (TEM)	*in situ* synthesis	AM	(Bilgili *et al.*, 2016)
Moringa oleifera	size: 5-10 nm	Pad-dry technique	AB	(Hashem *et al.*, 2016)
Clerodendron infortunatum	average size: 18 nm with a spherical shape	Dry-pad-cure	AB	(Jha and Prasad, 2016)
Cassia roxburghii DC	spherical shape (10 - 30 nm)	Impregnation	AB	(Balashanmugam and Kalaichelvan, 2015)
Erigeron annuus (L.)	spherical and hexagonal structures. size: 10–20 nm (spherical)	Sonication	AB	(Velmurugan *et al.*, 2014)
Ocimum sanctum Linn	SPR: 421 nm, size: about 150 nm (SEM)	Pad-dry-cure method	AM	(Rifaya and Meyyappan, 2014)
Amaranthus dubius	SPR: 425 nm, size: 179 nm (PSA), zeta potential: -25 mV	Dipping-sonication method	AB	(Firdhouse and Lalitha, 2013)

AM = antimicrobial, AO = antioxidant, AF = antifungal, AB = antibacterial, UVP = UV protection, WH = wound healing, AI = anti-inflammatory, MR = mosquito repellent, C = colorant, SPR = surface plasmon resonance, PSA = particle size analyzer, DLS = dynamic light scattering

The loading of AgNPs on cotton fabrics imparts antibacterial properties to the textiles, making them suitable for various medical applications or textile preservation (Lite *et al.*, 2022; Rehan *et al.*, 2017). The antibacterial efficacy of AgNPs is influenced by several parameters. Among these, the size and shape of the AgNPs are extensively discussed in most studies. Additionally, other crucial factors, including surface accessibility, silver concentration, and the presence of other chemicals, have been reported to affect the antibacterial activity of AgNPs.

Even though the precise mechanism behind the antibacterial activity of AgNPs is still unclear, various researchers have proposed the mechanism of the AgNPs antibacterial action. The death of bacteria may be attributed to the silver nanoparticles' ability to continuously discharge silver ions. Metal nanoparticles, including AgNPs, typically release ions when they come into contact with an organic medium (Ahmed, Ogulata, and Gülnaz, 2022). Silver ions can adhere to the cell wall due to electrostatic attraction and affinity to thiol groups (-SH) of enzymes (Prabhu and Poulose, 2012). This leads to metabolism changes and causes cell death. Various researchers argued that AgNPs' antibacterial properties are primarily influenced by the chemisorbed silver ions (Ag^{+}), not by zero-valent AgNPs (Ahmed, Ogulata, and Gülnaz, 2022; Elmaaty *et al.*, 2018; Liu *et al.*, 2022; Prabhu and Poulose, 2012; Strokova *et al.*, 2020). Following this approach, AgNPs can be categorized as bactericidal agents. On the other hand, the interaction of silver cations with the negatively charged cell walls of the pathogens may also alter their chemical and physical characteristics. This action prevents the cell's ability to reproduce and interferes with the cell membrane's functions and protein activity. In this mechanism, AgNPs act as bacterial inhibitors or bacteriostatic agents (Shahri *et al.*, 2022). *Escherichia coli* and *Staphylococcus aureus* are the most common bacterial species (Shahid-ul-Islam *et al.*, 2020; Yu *et al.*, 2020). The two species are most usually seen in infectious diseases in humans and are known to have high levels of resistance to antibiotics. Depending on the therapeutic applications that one hopes to develop, the choice of the bacterium to be investigated is equally crucial.

Other functionalities, such as UV protection, sensors, and packaging, were also explored in the studied papers. The UV protection properties of AgNPs result from their high refractive index, which leads to more robust UV scattering (El-Zawahry *et al.*, 2022; Rehan *et al.*, 2017). Functionalized cotton with AgNPs could efficiently protect human skin from harmful UV radiation, opening up a wide range of possible medical applications. AgNPs-printed fabrics provide significantly better UV protection than blank fabrics according to the Australian/New Zealand standard (AS/NZS 4399:1996), with UPF values of 33.17 and 1.79, respectively (Elmaaty *et al.*, 2018).

AgNPs-coated cotton, where the AgNPs were produced using *Lepidium meyenii* extract, was applied as a colorimetric sensor for detecting milk freshness in real time (Karakuş Baytemir, and Taşaltın, 2022). The freshness of the milk was detected by its hydrogen peroxide (H_2O_2) content and performed by the smartphone RGB image analysis application and the ImageJ software. In the presence of other biomolecules such as urea, ascorbic acid, lactose, and glucose as interference, the colorimetric H_2O_2 sensor exhibited a low limit of detection (LoD) of 3.84 M in a broad concentration range of 0.5-5000 μM. The color changes of the AgNPs-coated cotton biosensor were associated with the oxidation of Ag in the presence of H_2O_2. The color of cotton gradually changed from black to transparent at 4 °C milk for 4 days.

Treated cotton with phytosynthesized-AgNPs can also be applied in various packaging functionalities. The treatment can increase air permeability and water absorbance of the cotton but decreases its tensile strength and elongation at break (Ramadan *et al.,* 2020). As it also resists microbes, the cotton-chitosan-AgNPs composite can be used in packaging processes for seeds, powdered materials, etc.

4. Future Challenges

This section discusses challenges related to the development of multifunctional cotton with AgNPs. The first challenge is related to the loading technique, which is to obtain permanent AgNPs immobilization on cotton. Stable and permanent deposition of AgNPs on the cotton usually requires numerous steps, such as preparation, application, drying, and curing. As a result, these procedures require a lot of time, resources, and energy, especially in high-volume production. Procedures that are simpler, low cost, environmentally friendly, and applicable on an industrial scale are certainly needed. Applying the *in-situ* synthesis method and modifying the reducing and stabilizing agents using bio-based material such as from plants can be a good alternative and solution to current and future problems.

The second challenge is related to the development of functionalities. As technology develops and human needs become increasingly diverse, textiles and garments with additional or new functions will be in demand. One of the functionalities that becomes a challenge is conductive textiles. This conductive property will make textiles usable for electrical functions. For example, smart garments or wearable sensors for personalized healthcare, smart food packaging, or energy conversion and storage (El Guerraf *et al.,* 2023; Afroj *et al.,* 2020; Yun *et al.,* 2013). Some conductive polymers, such as polypyrrole, polyanilines, and polythiophenes, have been applied to fibers to develop phi-conjugated conductive fibers (Zeng *et al.,* 2014). For example, silver-coated polyamide multifilament yarns were fabricated as fabric electrodes. The electrodes can be developed as wearable nanogenerators and applied to convert the mechanical energy of human activity into electricity (Zeng *et al.,* 2013).

The third challenge is related to the aesthetic of textile products. People will normally choose a textile product not only on its functionalities but also on its appearance, for example, the color. Cotton fabrics have been used for thousands of years and are mostly colored. Synthetic dyes, such as azo dyes, are normally used to produce colorful fabrics, which can seriously endanger the environment. Anisotropic AgNPs can also act as a colorant where the color is tailored by changing their size and shape (Wu *et al.,* 2016). However, the range of colors produced is limited. Alternatively, the use of eco-friendly natural dyes can be an option to get more colorful multifunctional textiles.

5. Conclusions

This article systematically reviews the functionalization of cotton with phytosynthesized-AgNPs. The studied papers were extracted from the Scopus database in the 2013-2022 period. Bibliometric analysis exhibited that there are three cluster research fields connected to the functionalization of cotton with AgNPs, i.e., research on the synthesis methods, characterization, and application of the AgNPs-coated cotton. Generally, AgNPs loading can be done by *ex-situ* and *in-situ* methods, but nearly half of the study reviewed used the *in-situ* method as this method produced AgNPs coating with good wash-durability and color fastness. Most often, the AgNPs were used due to their antibacterial and antimicrobial properties. However, other functionalities such as UV protector, sensor, colorant, anti-inflammatory, wound dressing, and packaging have also been studied, and it is expected that these are among the areas where AgNPs-coated cotton or fabric will be applied in the near future. Meanwhile, research challenges related to the development of AgNPs-functionalized cotton will include developing techniques for permanently immobilizing AgNPs on cotton, creating functionalities for advanced applications, and producing aesthetic textile products with functionalities by applying natural dyes.

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