Environmental Science and Pollution Research (2024) 31:32637–32648
https://doi.org/10.1007/s11356-024-33373-z

RESEARCH ARTICLE

Clean synthesis of silver nanoparticles (AgNPs) on polyamide fabrics by *Verbascum thapsus* L. *(mullein)* extract: characterization, colorimetric, antibacterial, and colorfastness studies

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Received: 31 December 2023 / Accepted: 13 April 2024 / Published online: 24 April 2024

Abstract
The production of antibacterial colored textiles using nanomaterials (NMs) has become an ideal goal from both a research and industrial perspective. In this study, the clean synthesis and characterization of silver nanoparticles (AgNPs) on polyamide fabrics were performed using *mullein* extract for the first time. Natural dyes were extracted from *mullein* leaves using an ultrasonic method, with an optimal amount of 15 g/L. The synthesized AgNPs in different ratios of *mullein* extract and Ag ions were analyzed (using UV–visible spectroscopy) and dynamic light scattering (DLS). It was found that AgNPs synthesized with a ratio of 1:4 of *mullein* extract: to Ag ions had a diameter of 85 nm. The active site groups of the synthesized AgNPs were characterized using Fourier transform infrared spectroscopy (FT-IR). Nylon fabrics dyed with different ratios of *mullein* extract and Ag ions exhibited acceptable color strength values (K/S) of 3.36. Furthermore, the reduction in bacterial growth for dyed fabrics improved with an increase in the ratio of Ag ions, with a 100% reduction observed for a sample dyed with *mullein* extract: Ag ions at a ratio of 1:4. Overall, this method offers a simple, low-cost, and compatible process with environment without the consumption of any chemicals to producing nylon with acceptable antibacterial and dyeing properties.

Keywords Antibacterial · *Mullein* extract · Natural dye · Nylon fabric · Silver nanoparticles

Introduction

Wet treatments in the textile industry such as scouring, bleaching, dyeing, and finishing produce hazardous environmental pollutants due to the large amount of waste chemicals and dyes produced. These chemical substances are released into the water and the environment, causing toxic and harmful effects on people's health. In response to these issues, researchers and industrialists are increasingly turning towards using natural crops and products. Different parts of most plants, insects, and microorganisms have a high potential for producing natural dyes. One effective solution to reduce the harmful impact of chemicals and synthetic dyes in textile dyeing is the application of natural dyes. These natural dyes offer advantages such as being eco-friendly, biocompatible, and biodegradable. Additionally, many natural dyes possess unique properties such as being antioxidant, anti-allergenic, antibacterial, and even having medicinal properties (Gokiladevi et al. 2023; Verma et al. 2021).

Today, natural dyes are also being used for dyeing nylon, attracting the attention of researchers and producers. Many natural dyes can not only be used as a colorant for dyeing nylon fibers, but can also provide antibacterial and antioxidant properties (Benson and He 2024; Surana et al. 2024; Sadeghi-Kiakhani et al. 2023). This approach allows the dyeing and finishing process to be completed in one step, using less energy, time, water, and chemicals. To enhance the antibacterial finishing of textiles, various metal salts such as silver nitrates, copper, and zinc oxides are employed (Thakur and Raposo 2023; Rather et al. 2020). Most metal salts can be reduced by natural colorants and transformed into nanoparticles. Currently, one of the most environmentally friendly, efficient, simple, and low-cost techniques for producing nanoparticles on textiles is the use

Responsible Editor: George Z. Kyzas

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of natural colorants (El-Molla and El-Ghorab 2022; Ortega et al. 2022).

Metal ions are reduced by plant ingredients, leading to the synthesis of NMs with diverse shapes, morphologies, and sizes. Phytochemicals from different parts of plants serve as effective reducing agents for addressing environmental concerns associated with the chemical production of NPs (Liu et al. 2020; Huang et al. 2020). Several reports have documented the synthesis of various NMs using plant extracts (Nasrollahzadeh and Mohammad Sajadi 2016; Chinnathambi et al. 2021), which reduce metal ions and stabilize NPs for dyeing of textiles such as cotton (Zayed et al. 2022), wool (Manhita et al. 2011), polyester (Elnagar et al. 2014), and more (Alsaiari et al. 2023). AgNP synthesis employs various techniques, with green methods being extensively researched for their environmental compatibility. Deposition of silver on textile surfaces, through these green methods results in the production of goods with desirable characteristics, including antibacterial properties, self-cleaning, capabilities, flame resistance, hydrophobic conductive coating, and more (Arshad et al. 2023). Additionally, the localized surface plasmon resonance (LSPR) characteristic of NMs on textiles in the presence of natural compounds contributes to the production of dyed textiles with unique properties (Tran et al. 2021; Mahmud et al. 2020). AgNPs have been synthesized using natural dyes in many reports. Demibras et al. successfully used red cabbage extract for the production of AgNPs with high antioxidant activity (Dai et al. 2024; İlhan et al. 2024). Eellike et al. described an ecological synthesis of AgNPs by *mullein*. The existence of bioactive groups in *mullein* extract was confirmed by FT-IR spectroscopy, and the synthesized NPs were stabilized by the extract (Elemike et al. 2016). Additionally, AgNPs were produced using the leaf extract of *Verbascum thapsus*. It was observed that the color change of the extract solution occurred by mixing with silver nitrate, and the resulting AgNPs displayed high potential photocatalytic activity and significant antibacterial properties (Alvarenga et al. 2024; Shree Roy et al. 2024; Badola and Negi 2017). Furthermore, the clean production of AgNPs was performed using the leaf of *Verbascum thapsus*, and the inhibition of bacterial growth of the produced AgNPs exhibited the highest inhibition rate of 81.29% (Gonca et al. 2021).

One of the most important species in the Scrophulariaceae group is *Verbascum thapsus* L. (VTL). This common type of *mullein* genus is widely cultivated in the southwest of Iran (Calabrese et al. 2021). The leaves and flowers of this plant have the medicinal applications due to the existence of various chemical compounds such as saponins, flavonoids, vitamin C, and minerals in VTL (Hashemi et al. 2022). Therefore, VTL extract can be utilized to treat allergies, cough, asthma, and fever diseases, with antibacterial and anti-inflammatory effects. The antibacterial properties of CuO NPs synthesized by VTL extract and its potential for the removal of methylene blue dye were also reported. It was found that copper NPs significantly inhibited the growth of bacteria (Weldegebrieal 2020). The literature reviews revealed that there is no existing research on the clean production of AgNPs on nylon fibers by VTL extract with both dyeing and antibacterial properties. Hence, this study aimed to explore the phyto-synthesis of AgNPs using VTL extract on nylon fabric for the first time. The characteristics of the formed AgNPs in the solution were analyzed using DLS, FT-IR, and UV–visible spectroscopies. Moreover, the presence of AgNPs on the nylon fabric was examined through FE-SEM–EDX and FT-IR spectroscopy. The antibacterial activity, color coordinates, and colorfastness of dyed samples with VTL extract and Ag ions at various ratios were assessed using quantitative antibacterial tests following AATCC100 method, reflectance spectrophotometer, and ISO standard, respectively.

Experimental

Materials

The leaves of VTL were prepared from a traditional store in Tehran, Iran, and were carefully washed and dried at 40 °C before being milled into a fine powder using an electric semi-industrial mill. Silver nitrate with a purity of > 99% was purchased from Merck, Germany. Knitted nylon 6 (100 g/m^2) was selected for the study and provided by Alyaf Co., Iran. Analytical grade ethanol and other solvents (from Dr. Mojallali Co) were used. Common bacteria strains, *Staphylococcus aureus* (*S. aureus*) and *Escherichia coli* (*E. coli*) were obtained from the Iranian Science and Technology Research Organization (ISTRO) for the antibacterial tests. These bacteria were cultured in Muller-Hinton broth (from HiMedia, India).

Equipment

An ultrasonic bath Sonorex Digitech DT 1028H (Bandelin, UK) was used for the extraction of VTL. The absorbance behavior of synthesized AgNPs by VTL extract was measured using a double-beam UV–visible spectrometer, Cecil 9200, from England. The Nicolet Nexus 670 Fourier Transform Infrared was used to characterize the active groups of the synthesized samples and fabrics. Field emission scanning electron microscopy-energy dispersive spectroscopy (FE-SEM–EDS) was employed to visualize the surface structure of the dyed samples and identify their elemental components. The diameter of synthesized AgNPs by VTL extract in nanometers was measured by dynamic light scattering (DLS) (HORIBA, Japan). A reflectance spectrophotometer

7000A, from X-rite using a standard CIE D65 illuminant, and a standard CIE 10 °C observer were used to measure the dyeing behavior and colorimetric data for dyed samples.

Extraction of natural ingredients from VTL and synthesis of Ag NPs

The ultrasonic technique was used to extract natural ingredients from VTL. To maximize the extraction yield (maximum absorption), the extraction process was performed using different solvents (50 ml) like water, ethanol, methanol, and acetone, and at varying extraction times (5–45 min). Subsequently, the absorbance intensity and maximum absorbance wavelength (λ_{max}) of the extracts are measured using a UV–visible spectrophotometer. A solution of silver nitrate (2 mM) was then prepared and added to the extract solution at different ratios (1:1, 2:1, 1:2, 4:1, and 1:4). The reducing of Ag ions by VTL extract and formation of AgNPs were assessed using the UV–visible spectrophotometer. The solutions were boiled for 5 min, and the measurements were repeated to investigate the impact of the ratio of Ag ions to VTL extract on the absorption of the solution (Fig. 1).

Dyeing of nylon fabric

The dyeing of nylon fabric (1 g) was conducted using VTL extract and Ag ions at different ratios at boiling temperature for 60 min with a liquid ratio of 50:1. Subsequently, fabrics were rinsed and dried at ambient temperature. The measurements were assessed in the CIEL*a*b* system. The Kubelka–Munk relationship (Eq. 1) was used to determine the reflectance value and the color strength (K/S) of the dyed sample.

$$\frac{K}{S} = \frac{(1-R)^2}{2R} \tag{1}$$

where K and S are the absorption coefficient and the emission coefficient of dyed fabrics, respectively.

The wash fastness of dyed samples was assessed using the ISO 105-C06 test. The washing was conducted with SDC soap at a concentration of 5 g/L with a L.R ratio of 50:1 at 50 °C for 45 min. Subsequently, the adjacent fabrics were evaluated using a gray scale, with ratings from 1 to 5 indicating poor to excellent colorfastness. The fastness to light of dyed samples was measured using the ISO 105-B02 test. A blue scale was utilized to assess the light fastness, with grades ranging from 1 to 8 indicating poor to excellent colorfastness.

The percentage reduction in bacteria growth at different ratios of VTL extract: Ag ions was measured by the AATCC100 procedure. *S. aureus* (Gram-positive, MTCC 902), and *E. coli* (Gram-negative, MTCC 443) bacteria with a final concentration of 10^7–10^8 CFU/ml, were selected as antimicrobial test strains due to their recognition as

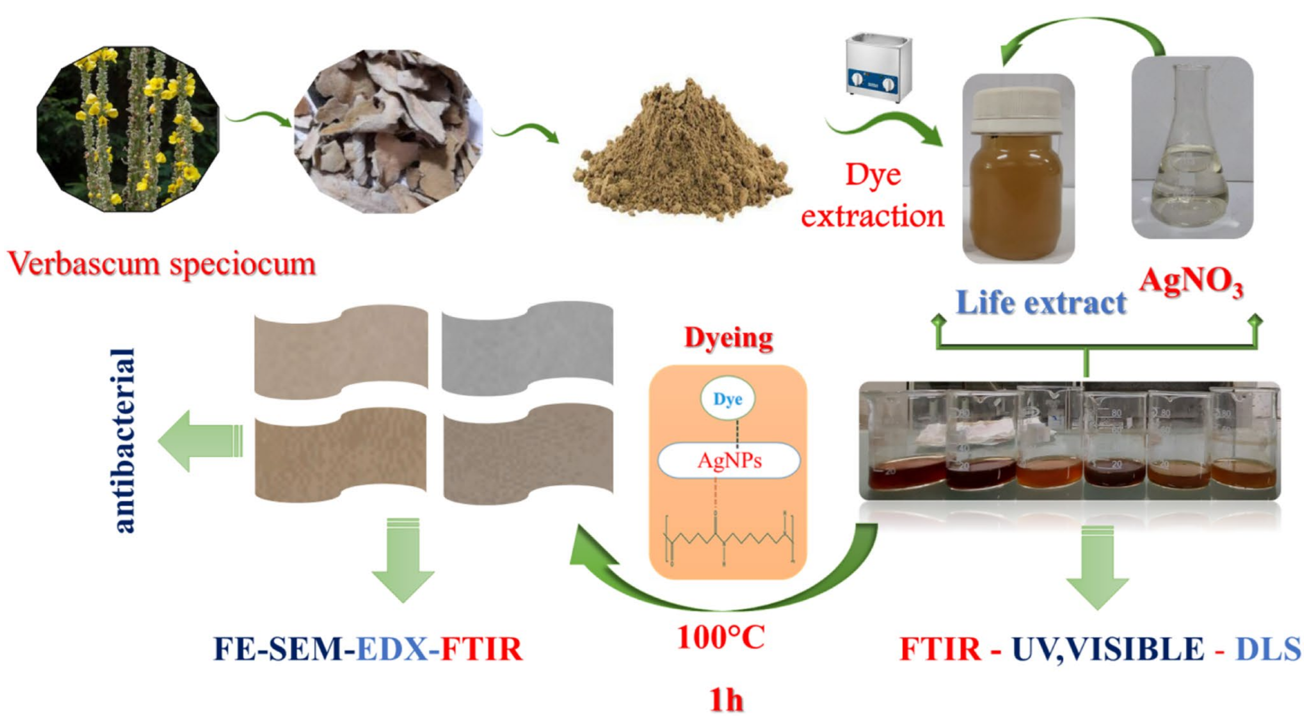


Fig. 1 Phyto-synthesis process of AgNPs by VTL extract on the nylon fabric

infectious organisms. Initially, Mueller–Hinton Broth was prepared as instructed and then added to falcon tubes (10 ml), which were sterilized at 120 °C for 20 min in an autoclave. Subsequently, each sample was incubated at 37 °C for 24 h with 10 μl of bacteria solution. The reduction in bacteria growth was then calculated using Eq. (2):

$$\text{Bacteria reduction}(\%) = \frac{B - T}{B} \times 100 \quad (2)$$

B and *T* represent the number of bacteria (CFU/ml) for samples without extract and samples containing extract, as well as for raw and dyed fabric samples, respectively.

Results and discussion

Ultrasound extraction of VTL

One of the most common techniques used to isolate natural products is solid/liquid extraction. In this method, the solvent's choice and its polarity significantly impact the extraction efficiency of natural dyes. The dissolving strength of the solvents used influences the absorption values of the extracted solutions. The surface tension of ethanol is lower than that of water, which allows for better dissolution of organic ingredients in ethanol. Consequently, the migration of colorants from the VTL towards the liquid phase increases (Singh et al. 2021). The extraction efficiency of natural dyes from biosources can be determined using UV–visible spectroscopy, which is a fast, simple, and low-cost technique. The VTL was extracted using different solvents, and UV–visible spectra are provided in Fig. S1. The data indicated that among the solvents tested, water is more effective than ethanol for extracting natural color from VTL. Generally, it is recommended that phenolic compounds be extracted using alcoholic solvents such as ethanol (Fig. S1). Phenolic compounds are common in plants and can absorb light in the UV area. Additionally, some phenolic compounds act as colorants and have absorbance in the visible region. Therefore, UV–visible spectroscopy is a suitable technique for detecting phenolic compounds. Moreover, an increase in temperature results in better penetration of the solvent into the VTL, leading to increased extraction efficiency of natural dyes (Mirnezhad et al. 2023). Ultrasound is an efficient, simple, low-cost, and eco-friendly method for extracting effective ingredients from plants. Compared to conventional methods, ultrasound extraction is completed in less time and at lower temperatures. Many compounds in plants are sensitive to high temperatures and may be destroyed with prolonged boiling. These compounds can be extracted effectively using ultrasound. The optimal conditions for extracting ingredients from VTL were found to be 15 g/L of VTL powder, a solvent water:ethanol 1:1, a 5 min extraction time, and a temperature of 30 °C (Fig. S1).

Analyses of synthesized AgNPs by VTL extract

Various compounds such as glycosides, flavonoids, terpenoids, saponins, apigetrin, luteolin, kaempferol, quercetin, cynaroside, and rutin have been identified in the VTL extract (Prem et al. 2024). These ingredients in the VTL extract provide a λ_{max} of 400 nm with low intensity, resulting in a light yellow color of the solution. The alteration in color of the extract solution to dark brown can serve as a criterion for the formation of AgNPs by the VTL extract. The size, shape, and morphology of the produced AgNPs are influenced by the surface plasmon resonance (SPR) property of NPs. Typically, the SPR absorbance of AgNPs is observed at 400–500 nm after combining the extract solution and the Ag ion solution in different ratios. An increase in temperature can expedite the formation of AgNPs by the VTL extract, leading to a color change towards dark brown (Fig. 2). Generally, among the synthesis parameters of AgNPs, temperature significantly affects the formation, shape, and particle size of AgNPs. Also, the efficiency of phyto-synthesis of AgNPs depends on the ratio and type of the metal ions used and natural dye extract (Sharifi-Rad et al. 2024). A broad absorption band at λ_{max} of 425 nm was observed for the synthesized AgNPs by the VTL extract (Prem et al. 2024). According to the size and shape of AgNPs, the SPR shifts to a λ_{max} in the range of 430 to 450 nm (Sharifi-Rad et al. 2024). The absorption intensity also increases with the rising concentration of natural dyes as a bio-reducing agent. As a result, more active bio-reducing molecules can further reduce Ag ions to AgNPs (Sadjadi et al. 2020). The data also indicated that a darker color change occurred with an increase in the ratio of Ag ions, likely due to a higher number of synthesized AgNPs. In this study, the ratio of VTL extract:Ag ions of 1:4 was preferred as the optimized condition for the production of AgNPs. It was noted that no chemical-reducing agents were utilized to reduce silver ions; instead, the VTL extract served as the sole stabilizing and reducing agent (Fig. 3).

The VTL extract and synthesized AgNPs were analyzed by FT-IR spectroscopy, and the following absorption features were detected (Fig. 4). The –OH stretching vibration of flavonoids/tannins and a stretching C-H bond specifically related to methyl groups provide the absorption band at 3420 cm^{-1} and 2930 cm^{-1}, respectively. The absorption band at 1644 cm^{-1} is related to the C = O and C = C groups of the aromatic rings (Ejaz et al. 2024). The absorption band around 740–900 cm^{-1} belongs to the single bonds C–OH and C-O of flavonoids. So, FT-IR spectroscopy confirmed the existence of active groups (–OH, –C-H, –C = C–, –C = O–, and = C-H) in the VTL extract (Ejaz et al. 2024). Moreover, the synthesized AgNPs by using VTL extract exhibited remarkable differences in the value of the wavenumber 1730 cm^{-1} and 650–900 cm^{-1}. These changes were marked in Fig. 4, and this can verify the phenolic groups of VTL extract can reduce

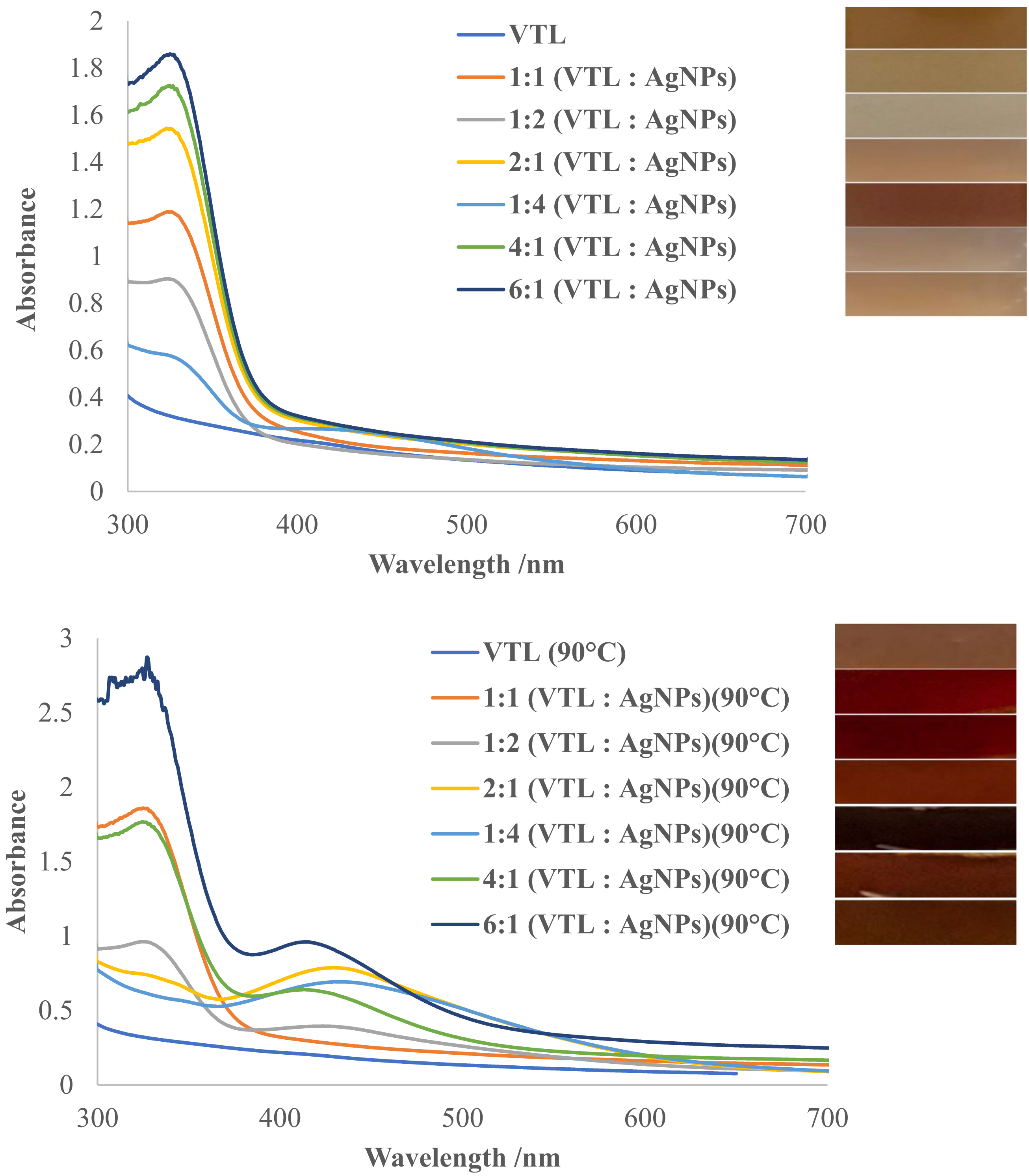


Fig. 2 UV–visible analysis of synthesized AgNPs at various ratios of the VTL extract and Ag ions

the Ag ions, and consequently, the production of AgNPs is completed successfully by VTL extract.

DLS is used to analyze the dynamic factors of nanoparticles, such as particle size and diffusion coefficient. Hence, the size range of synthesized AgNPs using the VTL extract was measured by DLS, and they were approximately 85 nm at a ratio of VTL extract: to Ag ions of 1:4 (Fig. 5). This size falls within the specified

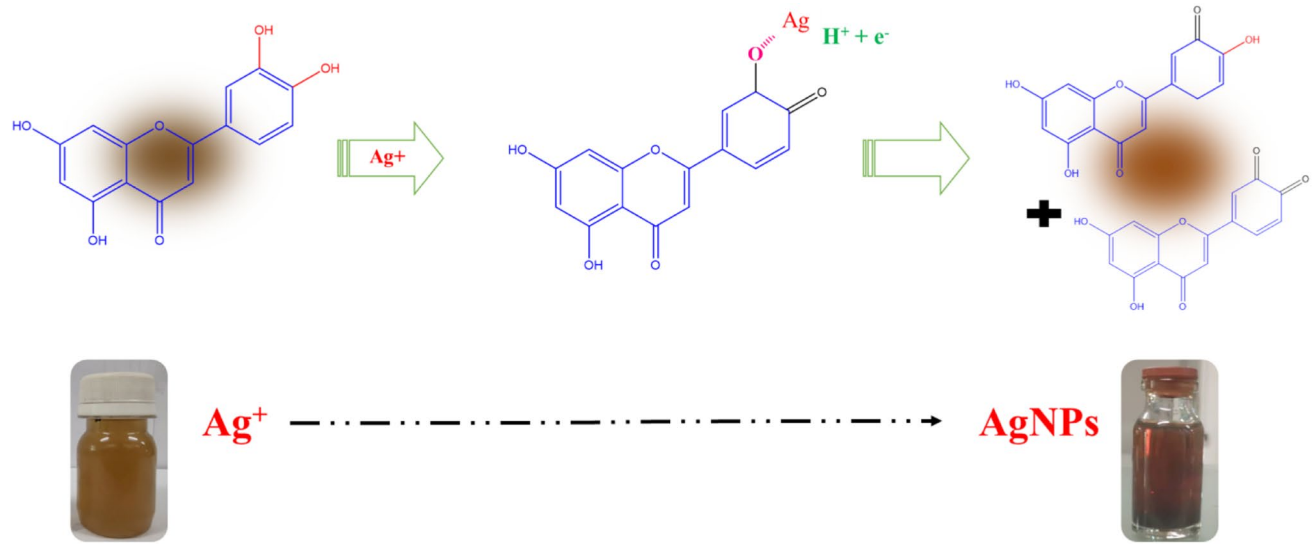
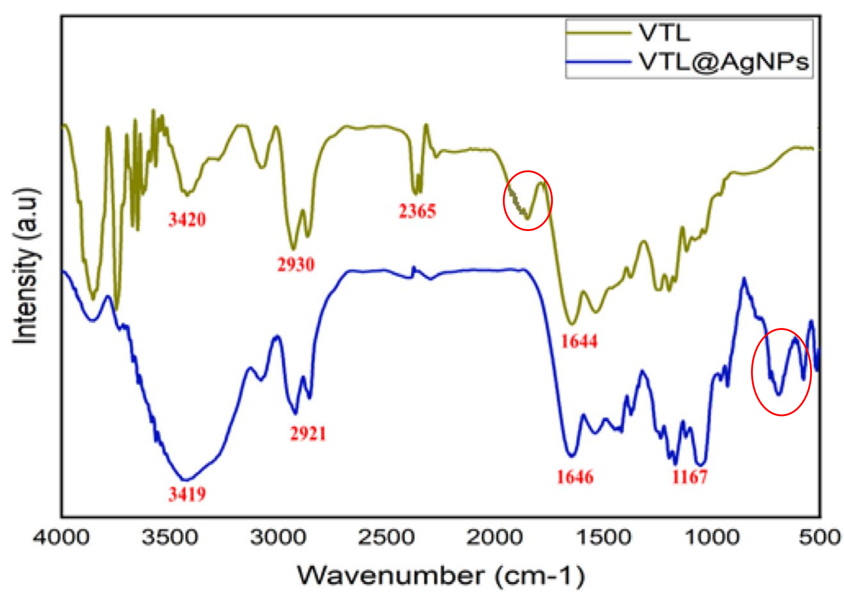


Fig. 3 Schematic presentation of reduction of Ag ions by the VTL extract

Fig. 4 The FT-IR analysis of the VTL extract and biosynthesized AgNPs at VTL extract:Ag ions ratio 1:4



range (less than 100 nm) for NMs. The results showed that as the ratio of Ag ions to the extract increases, the size range of AgNPs decreases (Table 1). The smallest size of AgNPs was achieved at the ratio of VTL extract to Ag ions of 1:4, which is considered the optimal condition for the production of AgNPs.

Characterization of nylon fabric dyed by VTL extract:Ag ions

The mechanism of synthesizing AgNPs by the VTL extract on nylon fabrics is illustrated in Fig. 6. The hydroxyl (–OH) groups in the VTL extract can both form a complex with Ag ions and reduce them, leading to the deposition of AgNPs on the nylon substrate. Additionally, these groups can bind to hydroxyl and amine groups in the nylon fiber, creating a complex between the VTL extract/fiber system, and stabilizing the AgNPs on the nylon surface (Mondal et al. 2023).

FT-IR analysis of nylon fabrics dyed with VTL extract and VTL extract and Ag ions at a ratio of 1:4 are presented in Fig. 7. In nylon samples dyed with VTL extract, characteristic bands are observed at the position of 3411 cm^{-1}, which belong to –NH and –OH stretching bonds, and the bands at the position of 2924 cm^{-1}, which are related to the aliphatic stretching characteristics of C-H groups. The peaks 1742 cm^{-1} and 1637 cm^{-1} belong to the carbonyl amide, and these bands are related to polyamide chains of nylon, which contain the one amide linkage (–CONH–) (Huang et al.

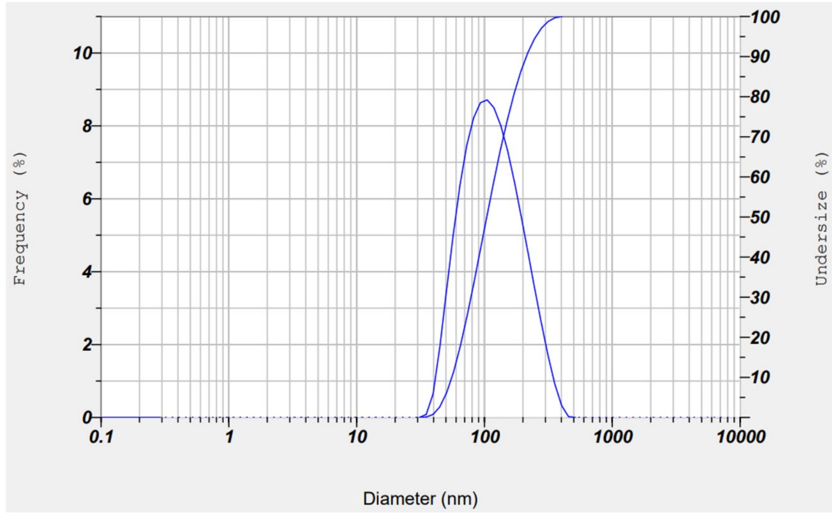


Fig. 5 DLS analysis of the synthesized AgNPs by VTL extract:Ag ions at ratio 1:4

Table 1 The diameter of the synthesized AgNPs by VTL extract at different ratios

Sample (VTL extract:Ag ions ratio)	**6:1**	**4:1**	**2:1**	**1:1**	**1:2**	**1:4**	**1:6**
Diameter (nm)	1102.5	903.2	487.6	214.1	95.7	85.1	84.9

Nanomaterials are defined as particles less than 100 nm, which were obtained in ratios of 1:2, 1:4, and 1:6 extract: Ag ions

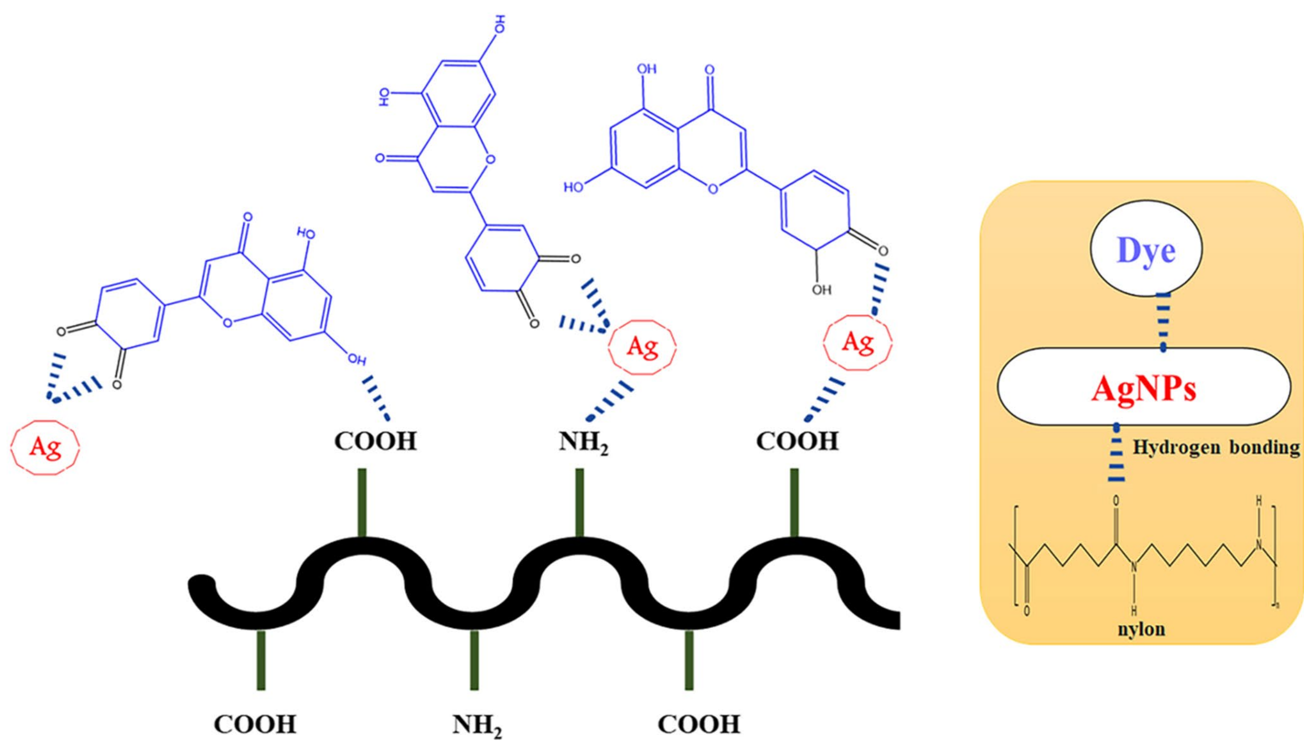
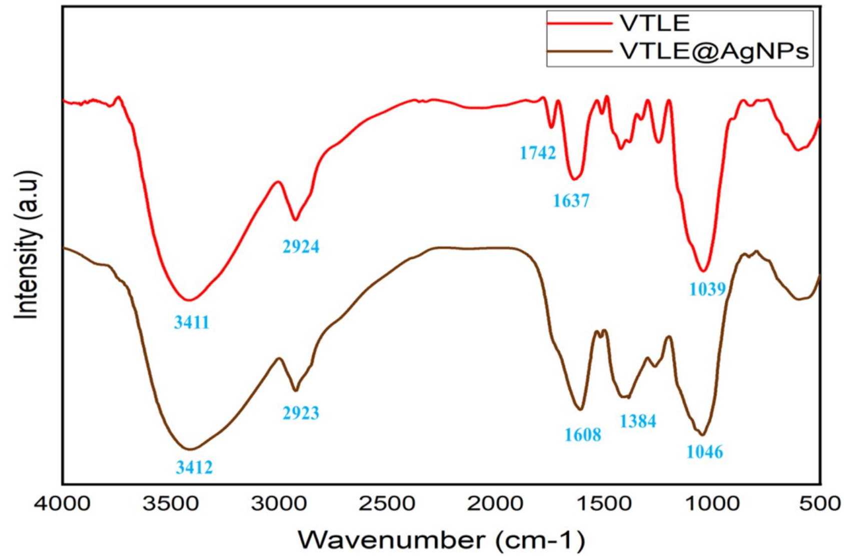


Fig. 6 The reducing mechanism of Ag ions by the VTL extract on the nylon fabrics

2020). However, the mentioned peaks above change vividly with the attachment of AgNPs on the surface of nylon. Also, nylon dyed by VTL extract and Ag ions at a ratio of 1:4 showed remarkable differences in the intensity and location of peak in the range of 1742, 1608, and 1384 cm^{-1}. These changes may be caused by the role of functional groups in

Fig. 7 FT-IR analysis of nylon dyed with the VTL extract, and the VTL extract and Ag ions at a ratio of 1:4



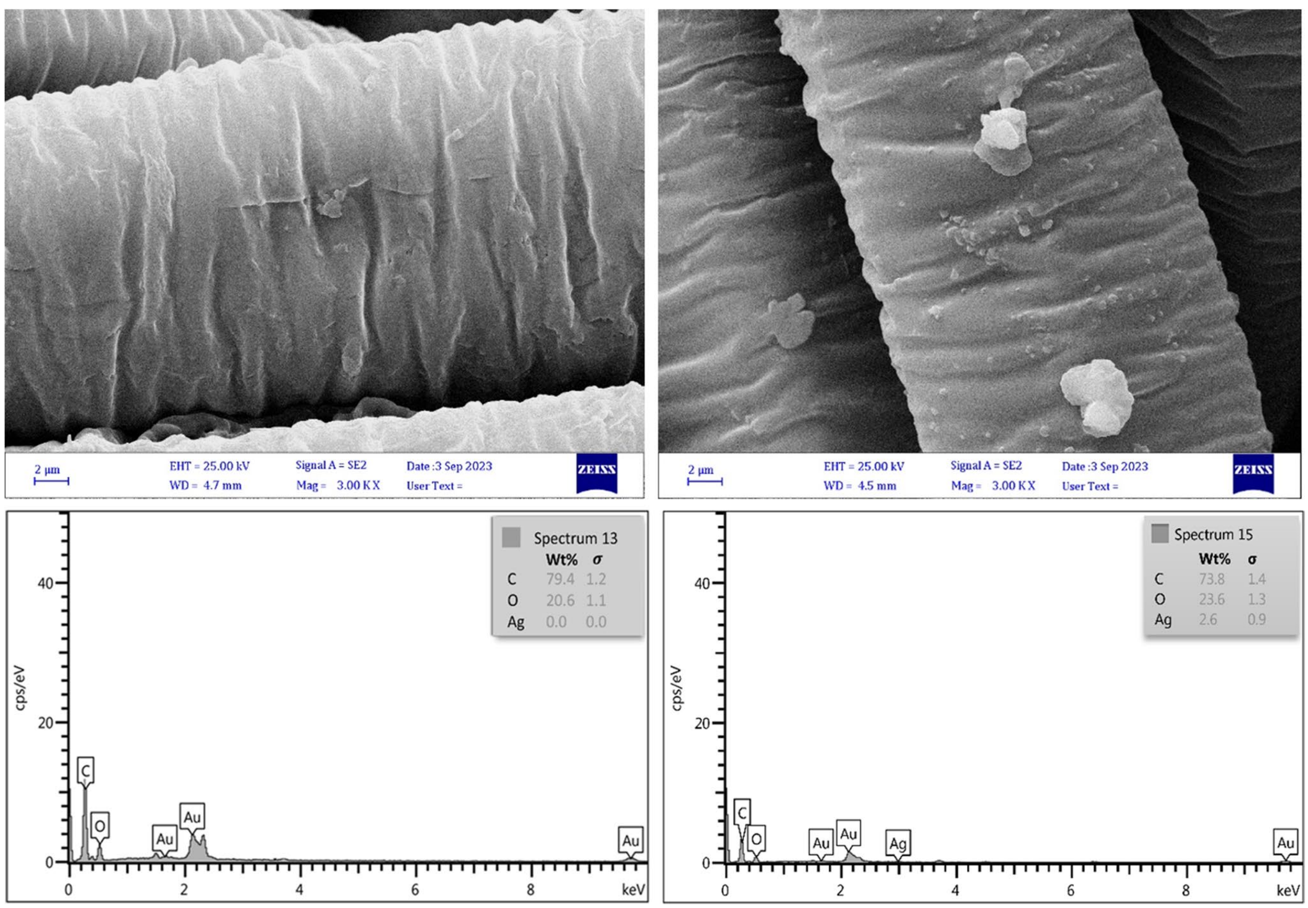


Fig. 8 FE-SEM–EDS micrographs of nylon fabrics dyed by VTL extract, and VTL extract and Ag ions at a ratio of 1:4

nylon fibers and VTL extract as an active redox site, supporting the synthesis process of AgNPs.

FE-SEM micrographs of nylon fabrics dyed with VTL extract and VTL extract and Ag ions at a ratio of 1:4 are shown in Fig. 8. Due to the absorption of VTL extract on the nylon, an uneven texture formed on the surface of the nylon (Singh et al. 2021). The presence of Ag elements signal in the form of NMs was confirmed through linear EDX scanning (Fig. 8). As expected, Ag was not found in the control sample. Conversely, the sample dyed with Ag ions showed 2.6% Ag on the nylon, indicating that Ag was deposited on the surface of the nylon. In the EDX line plot, carbon (C), oxygen (O), and other atoms were also detected, which are existing in the chemical structure of the ingredients of VTL extract and nylon (Liu et al. 2020). The results suggest that the biosynthesis of AgNPs on the nylon fiber was successful, with AgNPs uniformly deposited and distributed on the surface of nylon in a spherical shape.

Colorimetric and colorfastness studies

The color change of VTL extract (light yellow) in the presence of silver ions (dark brown) and nylon dyeing with them indicates that the AgNPs were attached to the nylon. The resulting color change confirms the successful synthesis of AgNPs on the nylon fiber, which can be attributed to the SPR property of AgNPs (Hasan et al. 2019). This property led to the production of bright and attractive multicolored nylon fabrics via phyto-synthesis of AgNPs by VTL extract (Hasan et al. 2019). Colorimetric data and pictures of nylon fabrics after dyeing with VTL extract:Ag ions in different ratios are presented in Table 2. Nylon fabrics dyed with a ratio of VTL extract:Ag ions 1:4 exhibited more K/S value compared to other samples. By changing the ratio of Ag ions, color parameters such as K/S, brightness (L*), and color purity (C*) were altered. Most of the color compounds found in plants contain phenolic groups that carry an anionic charge and are absorbed on the substrate in line with the pH of the media. The hydroxyl groups of flavonoid compounds in plants can form metal complexes with various metal ions (Li et al. 2022), producing a darker and deeper color on the fabric (Gutiérrez-Venegas et al. 2019). Nylon has positive and negative surface charges in a weak acidic condition, due to its isoelectric points and active groups of amine and carboxylic acid in its polymer chain (Roy et al. 2016). Usually, the amine groups in nylon fibers are positively charged, reducing ionic attachments and allowing colorant molecules to be absorbed on the fiber via hydrogen and physical bonds. The phenolic compounds in VTL extract contain numerous hydroxyl and carbonyl groups, supporting the creation of complexes with Ag ions for absorption on the nylon. The results showed that producing AgNPs on the nylon surface can enhance the absorption of natural dyes. Moreover, the highest K/S and color change were observed in the ratio of VTL extract:Ag ions 4:1. Additionally, the K/S values decreased and samples took on a lighter yellow shade with an increase in the ratio of VTL extract.

Colorfastness is a crucial property for dyed samples to be successful in commercial marketing. Textiles are regularly exposed to washing, light, and rubbing during use. Those that remain stable and do not show significant color changes demonstrate excellent color fastness. Therefore, the color fastness of samples was evaluated when subjected to light, washing, and rubing. A light fastness rating above 6 indicates "excellent" color fastness to light, meaning that the dyed fabrics do not undergo severe degradation from sunlight exposure. Similarly, a washing

Table 2 Colorimetric analysis of samples dyed with VTL extract and Ag ions at different ratios (SD was ± 0.02)

Samples	L*	a*	b*	C*	h	K/S	Photo
VTL extract	71.15	4.48	18.69	19.22	76.51	1.12	
1:1 (Extract: Ag)	70.84	1.90	18.23	18.33	84.05	1.18	
1:2 (Extract: Ag)	63.96	6.70	25.75	26.60	75.42	2.37	
1:4 (Extract: Ag)	63.40	6.03	30.27	30.86	78.73	3.36	
2:1 (Extract: Ag)	64.83	6.09	22.35	23.17	74.76	1.96	
4:1 (Extract: Ag)	67.14	6.24	20.02	20.97	72.69	1.18	

Table 3 The color fastness ratings of dyed samples with VTL extract and Ag ions at different ratios (SD was ± 0.5 degree)

Sample	Rubbing fastness		Washing fastness			Light fastness
	Wet	Dry	Color change	Staining on nylon	Staining on cotton	
VTL extract	3	4	3	4	4	3
1:1 (Extract:Ag)	4	4–5	3	5	4–5	4
1:2 (Extract:Ag)	4–5	5	3–4	4	4	4–5
2:1 (Extract:Ag)	4	4–5	4	5	5	3–4
1:4 (Extract:Ag)	4–5	5	4	5	4–5	5
4:1 (Extract:Ag)	4	4–5	4	5	5	3–4

and rubbing fastness rating above 4 indicates "excellent" color fastness to laundry. The wash fastness tests, which included staining on adjacent fabrics (nylon and cotton) and color changes, demonstrated the excellent fastness of the dyed samples (4–5) (Table 3). Samples dyed with VTL extract showed poor light fastness (3), but the light fastness improved to 5 when Ag ions were used. The Ag ions stabilize the chromophore and dye structure, increasing photo-stability. The rubbing fastness of dyed fabrics in dry and wet conditions showed moderate to good values. The dyeing and fastness tests were repeated three times and the results were reproducible.

Antibacterial proficiency

The antibacterial activities of different ratios of VTL extract and Ag ions as well as dyed samples with them were specified. VTL extract demonstrated strong antibacterial properties, reducing the quantity of *S. aureus* and *E. coli* bacteria by 64% and 55%, respectively. VTL extract contains various flavonoid compounds with high antibacterial potential. These compounds can attach to the negatively charged cell membrane, disrupting its stability (Nadeem et al. 2021). Additionally, flavonoid compounds can prevent the entry of essential nutrients and proteins into the cells, hindering cell growth. The flavonoid group remains attached to the textile, retaining its antimicrobial properties even during the inactivation of bacterial cells (Gutiérrez-Venegas et al. 2019).

Inhibition of bacterial growth was measured using different ratios of extracts and Ag ions (Anees Ahmad et al. 2020). As shown in Table 4, nylon did not exhibit any antibacterial activity. However, when nylon was dyed with only VTL extract, it reduced the number of *E. coli* and *S. aureus* bacteria by 55% and 49%, respectively. When VTL extract was combined with Ag ions in a 1:4 ratio on nylon, it effectively hindered the growth of bacteria. The introduction of Ag ions into the microorganism system, along with the formation of secondary metabolites containing Ag ions, inhibits the growth and reproduction of microorganisms, providing toxicity to them (Qing et al. 2018). AgNPs can impede cell enzyme activity, growth, and spread of microorganisms, eventually to cause cell destruction and death (Aponte et al. 2020). The biosynthesis of AgNPs with significant antibacterial properties is a simple, cost-effective, biocompatible, and promising technique. This method could result in the production of bioactive fibers with numerous applications in the field of biomedicine (Mouro et al. 2023).

Table 4 Bacterial reduction (%) of different ratios of VTL extract and Ag solution

Sample	Reduction of bacteria (% ± 2)		Inhibition zone (mm ± 0.2)	
	E. coli	*S. aureus*	*E. coli*	*S. aureus*
VTL extract	64	55	2.1	1.8
Extract:Ag; 1:0.5	77	70	3.1	2.6
Extract:Ag; 1:1	97	91	4.3	3.9
Extract:Ag; 1:2	100	100	4.8	4.2
Extract:Ag; 1:4	100	100	4.8	4.2
Nylon—VTL extract	55	49	1.4	1.1
Nylon—Extract:Ag; 1:0.5	72	68	2.4	2.0
Nylon—Extract:Ag; 1:1	93	89	4.0	3.5
Nylon—Extract:Ag; 1:2	99	99	4.1	4.1
Nylon—Extract:Ag; 1:4	100	100	4.3	4.2

Conclusion

The present report described the production of the antibacterial and colored nylon fabric through the synthesized AgNPs using VTL. DLS results showed that VTL extract was operative and suitable in the synthesis of AgNPs with a diameter of 85 nm. In UV–visible experiments, the SPR peak in the range of 430–450 nm was obtained, corresponding to the formation of AgNPs. FT-IR analysis confirmed the role of flavonoids in capping silver ions. The deposition of AgNPs on the nylon fabric was performed successfully, and the distribution of silver on the nylon fibers was confirmed by FE-SEM–EDS. Additionally, grafting of AgNPs on nylon fabric in the presence of VTL extract illustrates their effectiveness with a significant increase in color strength, colorfastness (washing, light, and rubbing), and antibacterial activities.

This study evidently indicates that AgNPs can be synthesized using the VTL extract via a clean, simple, cheap, and efficient method to produce colored nylon fabric with antibacterial activities.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11356-024-33373-z.

Author contribution Mousa Sadeghi-Kiakhani contributed to the study conception and design. Material preparation, data collection, and analysis were performed by Mousa Sadeghi-Kiakhani and Elaheh Hashemi. The first draft of the manuscript was written by Mohammad-Mahdi Norouzi. Mousa Sadeghi-Kiakhani and Elaheh Hashemi commented on previous versions of the manuscript. Mousa Sadeghi-Kiakhani, Mohammad-Mahdi Norouzi. and Elaheh Hashemi read and approved the final manuscript.

Funding This work was supported by "Institute for Color Science and Technology." Mousa Sadeghi-Kiakhani has received research support from Institute for Color Science and Technology.

Data Availability All data generated or analyzed during this study are included in this published article.

Declarations

Ethical approval The authors approved the ethical responsibilities.

Consent to participate The authors willingly participate.

Consent for publication The authors willingly publish.

Competing interests The authors declare no competing interests.

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