Electroless deposition of silver on aminated graphene oxide coated cotton fabric to develop high-performance electromagnetic interference shielding

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Abstract

Endowing conductive textiles for electromagnetic interference (EMI) shielding with dominant absorption mechanism is highly demanding. In this study, we propose a facile method of silver electroless plating on aminated graphene oxide (NH$_2$-GO) and reduced graphene oxide (rGO) based cotton fabric for remarkable EMI shielding performance. The successful formation of silver-plated fabrics was confirmed by scanning electron microscopy (SEM), Fourier transform infrared spectroscopy (FTIR) and X-ray diffraction (XRD). EMI shielding performance and surface resistance were studied by vector network analyzer (VNA) and four-probe digital multimeter respectively. Antibacterial activity and hydrophobicity of modified fabrics were also evaluated. Our results showed that all fabrics have good antibacterial activity, and the highest antibacterial activity was shown by silver/rGO fabric about 99.99%. Silver-plated aminated GO-based fabric exhibits low surface resistance and its EMI shielding effectiveness (EMI SE) reaches 49 dB at 7 GHz with 1.2 mm thickness as amination of GO provides more functional groups for silver electroless plating. Moreover, these modified fabrics have higher SE$_A$ rather than SE$_R$ that verifying the absorption characteristic of material. Thus, the remarkable EMI shielding performance of silver-plated NH$_2$-GO fabrics tends to make significant progress in eliminating electromagnetic radiations pollution from our environment.

1 Introduction

Everyday life of people is improving with the invention of different modern electronic devices, however, a type of pollution is emerged known as ‘Electromagnetic Interference (EMI) or Electromagnetic Radiation (EMR) pollution’. It is known well that exposure/contact to acute or long-term electromagnetic radiations can impose dangerous effects upon human tissue, moreover, they also interfere with various electronic biodevices i.e. pacemakers with effect on people’s lives (Periyasamy et al. 2020). Therefore, such issues if remained unchecked can result in adverse impacts to sophisticated electronics, communication systems or even human bodies (Lin et al. 2019). For EMI shielding, the material exhibiting high conductivity usually has electromagnetic wave reflection coefficient exceeding 90%, meaning that a major part of incident waves is reflected into the space that results in secondary EMR pollution. Thus, obtaining an efficient and better performing EMI shielding material exhibiting low EMR reflection coefficient is yet challenging (Shen et al. 2022). Among different materials for EMI shielding, conductive textiles having adjustable components and textures are known to be ideal for fabricating and designing EMI shielding materials with cost-effectiveness (Ghosh et al. 2018).

The development of electrically conductive textiles having remarkable characteristics such as electromagnetic interference shielding, flexibility, radio frequency interference protection, electrical conductivity and electrostatic discharge has gained huge attention (Sankaran et al. 2018). Conductive textile-based shielding materials exhibits great potential to replace the rigid shielding materials because they are flexible, lightweight and have tunable structure. In the present research progress, all the efforts have been credited to a combination of textiles with inorganic carbon-based materials, graphene (Raagulan et al. 2018), metallic nanoparticles (Ag nanowire, (Yuan et al. 2018) Iron NPs) (Luo et al. 2020), conductive polymers (polyaniline (Saini et al. 2012), polypyrrole) (Zhao et al. 2016) and so on for achieving the best
EMI shielding. Generally, different methods have been used to impart conductivity to textiles such as spray coating, metallic nanoparticles, polymer and carbon-based deposition, dip coating, vapor coating and sputtering method.

Textile surface metallization among all the methods has gained much attention because of its uniqueness for providing multi-functional performance related to antibacterial properties, EMI shielding and electrical conductivity. Traditionally, silver due to its highest electrical conductivity is known as excellent shielding material amongst different conductive materials (Zhang et al. 2019). Various methods like sputter coating, arc and flame spraying, vacuum deposition and in situ deposition of metallic particles have been reported but with restriction of metals oxidation, stiffness, high weight and non-uniformity properties. Currently, the electroless plating method appeared as excellent method for metallization of textile surface owing to improved performance relative to its durability, conductivity, coherent metallic deposition, and application for materials having complex shape. Electroless plating is a non-electrolytic method of deposition of metals from the solution and simple in handling that can be used to deposit uniform and continuous metal coating on textile or substrate (Xu et al. 2015).

Recently, graphene has been attracted by various research groups owing to its surface area, high conductivity, amazing stability and flexibility towards thermal and chemical environment. GO can be easily functionalized with different derivatives such as sulfonated, fluorinated, hydrogenated and aminated are emerged as a new class of materials. The introduction of these functional groups into graphene oxide structure improves the properties such as solubility and reactions with different materials such as polymers, organic and biological compounds (Zahid et al. 2021). Additionally, aminated graphene has ability to enhance the electrical conductivity of a substrate. To the best of our knowledge no study has been reported on amination of GO in textiles for EMI shielding. Gosh et al fabricated rGO/Ag composite based conductive cotton fabric for EMI shielding and antibacterial applications. Their results revealed that these coated textile fabrics showed EMI shielding effectiveness about 27.36 dB in X-band having range of frequency about 8.2–12.4 GHz with absorbance dominant mechanism but the value of EMI SE was not so high (Ghosh et al. 2019). In another study, Wang et al. fabricated Ag/rGO based cotton fabric for EMI shielding performance having frequency range from 1–18 GHz and their results showed 40 dB EMI shielding effectiveness, but absorption and reflection were not measured in this study (Wang et al. 2017). So, there is a need to develop more new material that not only enhanced the EMI shielding performance but also shows EMI shielding through dominant absorption.

To address the above issue, we have fabricated novel silver-plated aminated graphene oxide (NH$_2$-GO) based conductive textiles for high-performance EMI shielding properties. Silver electroless plating was performed on reduce and aminated graphene oxide based cotton fabric and to confirm the successful formation of these modified fabrics, surface morphology, composition and crystal structure were studied via SEM, FTIR and XRD respectively. Hydrophobicity and antibacterial activity was also checked of modified fabrics. Moreover, surface resistance and EMI shielding performance was measured by four-probe digital multimeter and vector network analyzer in the wide range of frequency from 100 MHz to 13.6 GHz respectively.
2 Materials

Plain woven cotton fabric (GSM-270) was purchased from a local mill. Graphite powder (99%) potassium permanganate (KMnO₄), H₂SO₄ (98wt %), sodium nitrate (NaNO₃), hydrogen peroxide (H₂O₂), ascorbic acid (99%) and silver nitrate (AgNO₃), glucose (99%), urea and ammonium Hydroxide (28%) were purchased from Sigma Aldrich. All chemicals were of analytical grade and used without further purification.

3 Methods

3.1 Synthesis of graphene oxide

Graphene oxide was synthesized by Hammer’s method as in our previous study. Briefly, 5g graphite powder, 2.5g NaNO₃ was put in 300ml H₂SO₄ in a flask with continuous mechanical stirring at 5°C. Then 30g KMnO₄ was added slowly into the flask with stirring and the color of the mixture turned green due to KMnO₄. Then, the mixture was stirred at 40°C for 1 day until the color of the mixture turned light brown. After that, 200ml distilled water was added into the mixture and raised the temperature up to 98°C for 25 minutes. After cooling, 20ml hydrogen peroxide was added to the solution to stop the reaction and the color of the mixture turned bright yellow. After the completion of reaction, centrifugation of graphitic oxide was done at 10,000 rpm for 20 minutes and washed the filtrate with distilled water until the pH was neutral. After that, the sonication was done to separate the different layers of graphene oxide for 20 minutes followed by the drying at 60 °C in oven for 24 h.

3.2 Fabrication of graphene oxide, reduced graphene oxide and aminated graphene oxide fabric

3g GO was dispersed in 500ml distilled water via sonication for 3 hours. The suspension of GO was applied on cotton fabric via dip and dry method. The reduction of GO based fabric was done via L-ascorbic acid to obtain rGO based fabric. Firstly, 35g ascorbic acid was dissolved in 500ml distilled water by stirring and raised the temperature of solution to 90 °C followed by the immersion of GO based fabric. The solution was kept at 90°C for 1h with continuous stirring and the color of GO based turned black that confirms the successful reduction of GO fabric. Then, rGO fabric was washed with distilled water to remove the excess ascorbic acid.

The amination of GO based fabric was done via solvothermal reaction. Firstly, 8g urea was added into the 100ml distilled water and stirred for 20 minutes for mixing. After that solution was transferred to teflon based autoclave reactor followed by the addition of GO fabric and 2ml ammonia. Then, after putting autoclave in oven, the temperature was maintained at 100 °C for 12h. When the reaction was completed, the autoclave was cooled at room temperature and the color of GO fabric was turned black and wash the fabric with distilled water to remove the impurities as shown in Fig. 1(a).

3.3 Silver electroless plating on rGO and AGO cotton fabric
Silver electroless plating was done on simple cotton, rGO and AGO fabric. The solution was prepared by adding 40g/L AgNO₃ as source of silver in distilled water followed by the addition of 40ml/L ammonia and the color of the solution turned brown and stirring was continued until the solution became clear. After that the cotton/ rGO/AGO fabric was immersed into the solution separately and 80g/L glucose was added into the solution as reducing agent that initiates the silver electroless plating. The color of the fabric changed which confirms the successful coating of silver on fabrics as shown in Fig. 1(b). Then fabric was rinsed and dried at 60°C for further application. The composition of different samples is shown in Table 1.

<table>
<thead>
<tr>
<th>Sr.No</th>
<th>Name of sample</th>
<th>Fabric</th>
<th>Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>S-0</td>
<td>100% Cotton</td>
<td>rGO</td>
</tr>
<tr>
<td>2</td>
<td>S-1</td>
<td>100% Cotton</td>
<td>NH₂-GO</td>
</tr>
<tr>
<td>3</td>
<td>S-2</td>
<td>100% Cotton</td>
<td>Ag</td>
</tr>
<tr>
<td>4</td>
<td>S-3</td>
<td>100% Cotton</td>
<td>Ag-rGO</td>
</tr>
<tr>
<td>5</td>
<td>S-4</td>
<td>100% Cotton</td>
<td>Ag-NH₂</td>
</tr>
</tbody>
</table>

**4 Characterization**

FTIR spectroscopy (Bruker Tensor 27, Bruker Optik, Ettlingen, Germany) with attenuated total reflectance (ATR) mode having range 4000 – 600 cm⁻¹ was used to analyze the functional groups and chemical composition of modified and unmodified cotton fabrics. Surface morphology of modified fabrics was evaluated by SEM (FEI Nova NanoSEM 450, Hillsboro, OR, USA) at an accelerating voltage of 15 kV. Sputter coating of sample was done with very thin layer of Au for one minute to acquire clear SEM images.

X-ray diffraction (XRD) pattern was used to determine the crystal phase structure of all unmodified and modified fabrics by using Cu Kα radiations and range of 2 theta angle is 10° to 80°. To determine the hydrophobicity of fabrics the contact angle was measured by optical tensiometer using the sessile drop method.

The surface resistance of modified fabrics was determined by using four-probe digital multimeter (MODEL RM3000 + by JANDEL). Each sample was measured three times and the average values of results were calculated.

The EMI shielding effectiveness of modified fabrics was calculated by measuring Scattering (S) parameters by vector network analyzer (Rhode & Schwarz ZVL13) has frequency ranges from 1KHz to 13.6GHz. Modified fabric for VNA was cut into disc shape keeping outer diameter of 7mm while inner diameter of 3mm with 1.2 mm thickness and calibration was done in frequency range from 100 MHz to 13.6 GHz. The coaxial cable method was used to measure EMI shielding by VNA.
Quantitative analysis was performed to check antibacterial activity of modified fabrics by following 20743:2013 Transfer Method. Antibacterial activity was checked against both gram-negative and gram-positive bacteria *E. coli* and *S. aureus* respectively. Samples were put on agar plates that had been inoculated with 1ml of bacterial culture and samples were pressed down for 60 seconds using a 200 g cylindrical weight. After 60 seconds samples were removed from the agar surface and put inverted on an empty petri plate for 18 hours at 37 °C. After 24 hours, incubated samples were placed in a 20 ml saline solution and vortex them for 1 minute before being serially diluted to 10^4. After the preparation of agar plates, 60 µl of each dilution was distributed on the surface of agar, followed by incubation of all plates. At zero hour, same method was repeated but incubation was not done once the bacteria was attached to the fabric. The number of survived bacterial colonies for all samples was taken at 0h and after 24 h. following equations were employed for the calculation of antibacterial activity (A) and percentage reduction.

\[
\% \text{Age Reduction}= \left[\frac{\log Ct - \log Tt}{\log Ct}\right] \times 100 \quad (1)
\]

\[
A = F - G \quad (2)
\]

### 5 Result And Discussion

#### 5.1 Surface morphology

Morphology plays an important role in EMI shielding performance of a material. Scanning electron microscopy (SEM) and optical images were used to study the surface morphology of the pure cotton and modified fabrics for EMI shielding performance. Figure 2 (a,b) showed SEM and optical images of pristine cotton having smooth surface that confirms the no deposition of any material on the surface of fabric. The SEM image of rGO and aminated GO fabric showed that the crystalline structure of the fabric was not disturbed but there is deposition of some material on the surface of fabrics indicating the compatible interaction between cellulose fibers and rGO and aminated GO (c, d and e, f). Additionally, Fig. 2 (g,h) shows that the Ag nanoparticles are present on cotton fabric which confirmed the successful coating of silver on the fabric and conductive path was generated on the surface of the fabric which helps in EMI shielding performance of the fabric. Figure 2 (i, j) and (k, l) shows the surface characteristics of silver plated rGO and aminated GO based fabrics and it clearly shows the complete and uniform coating of silver on the surface of fabrics that helps in the better performance of these conductive fabrics.

#### 5.2 FTIR

FTIR spectroscopy was used to evaluate the functional groups present in modified and unmodified fabrics and Fig. 3(a) represents the FTIR spectra of all fabrics. Cotton fabric showed peaks at 3308, 2900, 1445 and 902 cm\(^{-1}\) due to the presence of O-H group, C-H stretching, C-H bending and C-H stretching respectively (Zhou et al. 2020). All modified fabrics showed peaks of cotton fabric and in spectrum of GO based fabric the lower peak intensity was observed in the range of 600-1500 cm\(^{-1}\) wavelength due to the presence of more oxygen-containing groups and it exhibited the characteristic peaks at 1028, 1176, 1626 and 3310 cm\(^{-1}\) which attributed to the presence of alkoxy C-O stretching, epoxy C-O stretching, aromatic C
= C and O-H stretching vibrations (Xu et al. 2015). S0, spectrum showed low intensity peaks which is credited to the removal of oxygen functional moieties, however, there was strong intense peak at 1626 cm$^{-1}$ owing to enhanced aromaticity that confirmed the successful reduction of GO. All spectra showed broad peak of -OH group but S1 sample has lower intensity due to the presence of amine group. Moreover, S1 has additional peak at 1542 cm$^{-1}$ that might be due to the presence of N-H bond (Mohammadi et al. 2017). Thus, it validates the successful formation of aminated GO on fabric. The FTIR spectra of S2, S3 and S4 sample is shown in Fig. 3 (b) and the intensity of all peaks was very weak due to the successful coating of silver on all fabrics.

5.3 XRD

X-ray diffraction (XRD) pattern of modified and unmodified cotton fabrics was measured to evaluate the crystal structure of S samples having range of theta angle from 10 to 80°. In Fig. 4(a) XRD pattern of pristine cotton fabric showed characteristic peaks at 2 theta of 15.1, 17.2, 22.9 and 34.8° that can be attributed to (110), (110), (200) and (040) diffraction planes respectively (Wanwong et al. 2019). Generally, rGO and NH$_2$-GO showed XRD peak at 23° and in S0 and S1 the diffraction pattern of cellulose merged the major peaks of rGO and NH$_2$-GO indicating that during their coating the crystal structure of fabric was unaffected by ascorbic acid and urea respectively as mentioned in previous literature (Karami et al. 2021b) and SEM images also confirmed this. However, in samples S2, S3 and S4 (Fig. 4b) new characteristics peaks were observed at 2 theta of 38.6, 44.9, 64.9 and 77.9° corresponded to the (111), (200), (220) and (311) diffraction planes of face centered cubic silver and diffraction peaks of cotton has been disappeared which confirmed the uniform and successful coating on cotton, rGO and NH$_2$-GO based fabrics and it also indicates the absence of impurities. Thus, it provides the significant information about the crystal structure of the modified fabrics that is alternately related to the performance of these fabrics.

5.4 Mechanism

The reaction mechanism for the bonding of aminated graphene oxide and cotton fabric is shown in Fig. 5 and then silver attach on NH$_2$-GO based fabric by silver electroless plating. It is noted that, the hydroxyl groups of fabric have ability to make covalent and hydrogen bonds with the amine and hydroxyl groups of aminated graphene oxide.

During silver electroless plating, silver nitrate adsorbed on the fabric surface due to presence of different functional groups and it is confirmed from our SEM and XRD results that the crystalline structure of the fabric is not disturbed with the coating of rGO and NH$_2$-GO and all reactions of silver electroless plating occurs on the surface of fabric. Additionally, the amine groups on NH$_2$-GO based fabric provides more functional groups to deposit the silver on its surface and the equations for the silver electroless deposition reaction on all fabrics are following

$$AgNO_3 + NH_3 \cdot H_2O \rightarrow Ag_2O + 2NH_4NO_3 + H_2O$$
\[
Ag_2O + 2NH_3 \cdot H_2O + 2NH_4NO_3 \rightarrow 2\left[Ag(NH_3)\right]^{2+} \cdot NO_3 + 3H_2O
\]

The amine complex is relatively stable in the solution. However, when glucose was added into the solution the redox reaction initiated can be explained by following equation:

\[
2\left[Ag(NH_3)\right]^{2+} \cdot NO_3 + C_5H_{11}O_5 \cdot CHO + H_2O \rightarrow 2Ag^0 + C_5H_{11}O_5 \cdot COOH + 4NH_4NO_3 + H_2O
\]

In this reaction, glucose was served as the source of aldehyde group and when reaction is completed the aldehyde group oxidizes into carboxylic group and reducing agent convert Ag\(^+\) into Ag metal. Therefore, it can be expected that the Ag nanoparticles deposit on the fabric by this mechanism (Chen et al. 2017).

### 5.5 Contact Angle

The wearable materials possessing EMI shielding are usually exposed to external contamination. Once polluted, their EMI shielding performance may be considerably decreased. For that reason, it is of great practical significance to produce hydrophobic EMI shielding materials with multi-functional properties for long term and safest use of system (Mei et al. 2020). Figure 6 shows the surface wettability of pure cotton and modified cotton fabrics and our results revealed that cotton has hydrophilic nature because large number of hydroxyl groups are present in its structure. The rGO based fabric showed higher contact angle about 102° due to the absence of polar functional groups while NH\(_2\)-GO based fabric possesses lower contact angle owing to the hydrophilic nature of amine group. With the silver electroless plating the contact angle increased and sample S3 showed highest contact angle 117° because Ag nanoparticles completely coated on the surface of cotton prevents the contact of water with the fibers of fabric. Moreover, Ag coating makes the surface of fabric rougher than that of cotton which ultimately enhances the hydrophobicity of the fabrics (Karami et al. 2021a). However, Ag coated NH\(_2\)-GO fabric possesses contact angle lower than Ag coated rGO fabric owing to the presence of amine group. Our results proved the hydrophobicity of all modified cotton fabrics.

### 5.6 Surface Resistance

Electrical conductivity is one of the major parameters to obtain high EMI shielding performance of any material. Thus, surface resistance of modified fabrics was measured by four probe multimeter and the obtained results are shown in Fig. 7. Since pure cotton and GO based fabric are insulator so, they showed very high surface resistance. But on the reduction of graphene oxide this fabric exhibits resistance about 10 KΩ while, fabric based on NH\(_2\)-GO has lower surface resistance about 1 KΩ due to the n-doping in GO structure that results in more conductivity (Rabchinskii et al. 2020). Graphene intrinsically exhibits electrically conductivity induced via its 2D planar configuration in couple with network of delocalized π electrons (Islam et al. 2019). By silver electroless deposition on these fabrics, surface resistance dramatically decreases due to the successful, complete and uniform coating of silver. S4 sample exhibits
lowest electrical resistance $0.7\Omega/$square as shown in Fig. 7. Note that, conductive Ag electroless plating on rGO and NH$_2$-GO based fabric proved as an effective conductive agent to generate conductive pathway within the fabric for the transport of electrons which ultimately enhanced the electrical properties and EMI shielding performance.

5.7 EMI SE

Vector network analyzer was used to measure the scattering parameter. There exist three major interaction phenomena like reflectance ($R$), absorbance ($A$) and transmittance ($T$) when the incident electromagnetic wave falls upon material (Siddique et al. 2021). Mathematically, it is expressed as:

$$A + R + T = 1$$

Where, shielding effectiveness (SE) expresses the shielding material performance to attenuate EMI in the unit of decibels (dB). Whereas the term dB represents the opacity of electromagnetic wave at specific frequency band. When EM waves pass through a material, the measurement of SE is done through the proportion of incoming power ($P_i$) and outgoing power ($P_o$) by using following equation:

$$SE = 10\log P_i / P_o$$

If the decibel level is high for EMI shielding effectiveness, then less energy will be transmitted through shielding material (Modak et al. 2016). The material must exhibit dielectric properties for reflectance, whereas permeability and permittivity properties are significant for absorbance. The prime mechanism of EMI shielding is reflection which needs charge such that electrons or holes directly interact with the electromagnetic field for radiation reflection. The secondary mechanism is absorption which needs material's magnetic and electric dipoles for interaction with radiation whereas the absorption of electromagnetic waves might result in heat like conversion of EM energy into thermal energy. Temperature change can affect the extent of absorption and reflection. There is a promotion in the shielding with the absorption enhancement through appropriate increase in temperature (Cao et al. 2018). Internal/multiple reflection is considered to be a third mechanism which arises from the scattering and interfaces centers within the material that results in scattering followed by absorption of electromagnetic signals and there is a requirement of huge surface area within material for such mechanism (Panahi-Sarmad et al. 2020). Based on Schelkunoff’s theory, total shielding effectiveness ($SE_T$) of material is actually an absorption, reflection or multiple reflections which is proportional and dependent to electrical conductivity. In complete SE, the internal/multiple reflections are negligible when the loss in absorption is $\geq 10$ dB. Since because of the absorption, the magnitude of electromagnetic waves ignored when moving at high frequency form one boundary to other. So, the internal/multiple reflections can be safely neglected if material for shielding exhibits high capability of absorption and thickness. Thus, only loss of reflection ($SE_R$) or loss of absorption ($SE_A$) donation to SET (Singh et al. 2018) as:
\[ SE_T = SE_A + SE_R \]

S parameters measuring from VNA are used to calculate \( SE_T, SE_A, SE_R \) and expressed as:

\[ SE_T = 10\log_{10}\left(\frac{1}{|S_{12}|^2}\right) = 10\log_{10}\left(\frac{1}{|S_{21}|^2}\right) \]

9

\[ SE_A = 10\log\left(\frac{1-R}{T}\right) = 10\log_{10}(1 - |S_{11}|^2/|S_{12}|^2) \quad (10) \]

\[ SE_R = 10\log\left(\frac{1}{1-R}\right) = 10\log_{10}\left(\frac{1}{1-|S_{11}|^2}\right) \quad (11) \]

These equations were used to evaluate the shielding effectiveness of all modified fabrics.

In general, EMI SE has direct relation with conductivity, if the conductive material has lower resistivity there will be more EMI shielding performance. EMI shielding was measured in a broad range of frequency from 100 MHz to 13.6 GHz and the results of \( SE_T \) are depicted in Fig. 8(a). Cotton fabric and GO based fabric exhibits zero EMI shielding effectiveness due to insulative nature while on the reduction of GO the resistivity of fabric decreases and EMI SE was about 3 dB and aminated GO fabric showed some better results as compared to rGO based fabric due to nitrogen doped structure. Silver electroless plating on simple cotton and rGO fabric exhibits EMI SE about 31.6 dB and 41.2 dB at 8 GHz and 7 GHz respectively. S4 sample showed maximum EMI \( SE_T \) 49 dB at 6 GHz as amine group provide more active sites for the attachment of silver nanoparticles during synthesis. It is worth mentioning that the EMI shielding of all silver coated fabrics meets the requirement for commercial applications i.e greater than 20 dB.

Figure 8 (b) and (c) shows the reflection (\( SE_R \)) and absorption (\( SE_A \)) of S0, S1, S2, S3 and S4 fabrics respectively. With the increase of frequency, \( SE_R \) of all S samples was decreased while the \( SE_A \) increased gradually which indicates the absorption dominant mechanism. The maximum \( SE_R \) was shown by S4 sample about 15 dB at 3 GHz that gradually decreased at higher frequency. Sample S3 and S4 exhibits \( SE_A \) about 34.1 and 41.2 dB respectively which indicates that more radiations are absorbed by fabric rather than scatter into the air. Such significant property will help to reduce the secondary pollution of electromagnetic waves in our surroundings. The absorbance dominant mechanism can be attributed due to the carbon based material as well as the porous structure of fabric that enable them to absorb and attenuate the radiations (Shen et al. 2022). Furthermore, the comparison between \( SE_T, SE_A \) and \( SE_R \) of all samples is represent in Fig. 8 (d) that also showed absorption dominant mechanism rather than reflection inside the material. The EMI shielding mechanism of Ag/NH\(_2\)-GO based fabric is shown in Fig. 9. There are three types of mechanisms namely reflection, absorption and multiple internal reflections that shows the EMI shielding
behavior of Ag/plated NH$_2$-GO based fabric. Moreover, silver nanoparticles firmly attached on aminated GO fabric and play significant role in EMI shielding performance.

6 Antibacterial Activity

The antibacterial activity of all samples (S0, S1, S2, S3, and S4) has been evaluated against bacterial strains *E. coli* and *S. aureus* and obtained result are expressed in terms of logarithm values of CFU/ml is shown in Fig. 10. This figure shows the growth of bacterial colonies and number of survived bacterial colonies after 24 hrs. as log number for all tested samples. From the graph values, it was seen that in case of samples S0, there is a significant decrease in log values i.e., 5.43 to 2.13 for *S. Aureus* and 6.43 to 2.62 for *E. Coli*. The reduction in number of bacterial colonies was slightly higher for sample S1 (5.44 to 2.01 for *S. Aureus* and 6.43 to 2.23) as compared to the sample S0. This slight increase in activity could be attributed to the presence of aminated GO. The sample S2 has shown highest antibacterial action i.e., log values reduced to 0 from 5.43 (99.99 bacterial growth inhibition) for *S. Aureus* and 6.43 to 0.3 (> 96% activity) for *E. Coli*. This strong antibacterial action could be due to the plating of silver on the surface of fabric. Then, for sample S4, the antibacterial activity decreased slightly when compared to sample S3 (5.43 to 0.47 for *S. Aureus* and 6.44 to 0.6 for *E. Coli*) due to the agglomeration of silver nanoparticles.

Conclusively, all tested samples have shown strong antibacterial action (> 85%) against both test microbes whereas the sample S3 was the most efficacious and sample S1 showed the least antibacterial action. In case of untreated fabric (control fabric), the logarithm values were found to be increased from 5.44 to 5.46 for *S. Aureus* and 6.43 to 6.44 for *E. coli* suggesting that no antibacterial action has been shown by the untreated control fabric. The images in Fig. 11. illustrate the number of inoculated and survived bacteria colonies after a certain incubation period at 0 hr and 24 hr for control and sample S3. It was also observed antibacterial activity of all tested samples was slightly lower for *E. Coli* than *S. Aureus*. This could be due to the fact that gram-negative bacteria (*E. Coli*) have thicker cell walls than gram-positive bacteria (*S. aureus*), which hinders and lowers the penetration of antibacterial agents into bacterial cell membranes resulting in higher concentrations of antibacterial agents required for inhibiting *E. Coli* growth.

7 Conclusion

Based on the unique selection of materials, we demonstrated the fabrication of silver/NH$_2$-GO based cotton fabric for EMI shielding applications with absorption dominant mechanism. Silver electroless plating was done on conductive rGO and NH$_2$-GO fabrics. The uniform and successful coating of material on the fabric surface was confirmed by XRD, SEM and FTIR techniques. Our results showed that these modified fabrics exhibit 99.99% antibacterial activity, low surface resistance 0.7 $\Omega$/square and high EMI shielding performance about 49 dB in wide range of frequency from 100 MHz to 13.6 GHz with higher SE$_A$ that will reduce the secondary pollution of radiations from our environment. Thus, the multiple outstanding properties of Ag/NH$_2$-GO fabric are found to be promising material for EMI shielding applications.

Declarations
Competing Interest

There is no conflict of interest among authors.

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References


oxide. Membranes 11:510


Figures

Figure 1

Schematic representation of the fabrication of Graphene oxide, rGO and NH_2-GO fabrics (a) and Silver electroless plating on fabrics (b).
Figure 2

Optical and SEM images of pure cotton (a, b), S0 (c, d), S1 (e, f), S2 (g, h), S3(i, j) and S4 (k, l).
Figure 3

FTIR spectra of modified and unmodified cotton fabrics.
Figure 4

XRD pattern of pure cotton, S0 and S1 (a) and S2, S3 and S4 (b).

Figure 5

Reaction mechanism between cotton and silver aminated graphene oxide
**Figure 6**

Contact angle of cotton and modified cotton fabric
Figure 7
Surface Resistance of modified fabrics.

Figure 8
EMI shielding performance of modified fabrics. Total EMI SE of modified fabrics (a), EMI shielding through reflection (SE_R) (b), EMI SE through absorption (SE_A) (c) and Comparison of SE_T, SE_A, SE_R of modified fabrics (d).
Figure 9

EMI shielding mechanism of silver/aminated graphene oxide based fabric.
Figure 10

Antibacterial activity of cotton and modified fabrics

![Figure 10](image1.jpg)

Figure 11

Antibacterial images of cotton and S3 samples against *S. Aureus* (a) and *E. Coli* (b) bacteria

Supplementary Files

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