Cellulose Nanofibers Coated with Silver Nanoparticles as a SERS Platform for Detection of Pesticides in Apples

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Abstract

A nanocomposite based on cellulose nanofibers (CNFs) coated with silver nanoparticles (AgNPs) was developed in this study as a flexible and effective substrate for use in surface-enhanced Raman spectroscopy (SERS) analysis. An effective Raman indicator molecule, 4-aminothiophenol (pATP), was used to characterize AgNPs impregnated on CNFs. The CNF-AgNP films were used in SERS analysis to detect thiabendazole (TBZ) pesticides in apples. The influence of pH on the SERS spectra of TBZ was investigated because TBZ is a neutral molecule that has a low affinity for AgNPs. The pH of TBZ solution was decreased to below the TBZ's pK_a , thus enabling the electrostatic attraction between TBZ and AgNPs. CNFs can prevent the uncontrolled aggregation of AgNPs in low pH environment and serve as an effective AgNP/nanocellulose platform for SERS analysis. Results of this study demonstrate that CNF-AgNP nanocomposites can be used to rapidly detect TBZ pesticides in various food products.

Keywords: SERS; cellulose nanofiber; thiabendazole; pesticides; silver nanoparticles

1. Introduction

Nanocellulose has gained much attention recently for its potential applications in material science, biomedicine, agriculture, and food packaging. Nanocellulose is a natural and unique material composed of nanosized cellulose fibrils with a high aspect ratio (length to width) and can self-assemble into well-defined architectures at the nano- or macro-scale. Nanocellulose is one of the most abundant and sustainable nanobiomaterials in nature (Habibi, Lucia, & Rojas, 2010; Hubbe, Rojas, Lucia, & Sain, 2008; Moon, Martini, Nairn, Simonsen, & Youngblood, 2011). In particular, cellulose nanofibers (CNFs) are made from wood-derived fibers, hence they have a low environmental impact for their production and disposal (Seo et al., 2015).

Surface-enhanced Raman Spectroscopy (SERS) is a novel and sensitive technique that can enhance Raman signals of analyte molecules deposited on a roughened metal surface or nanostructure (Zhong Zhang, Yu, Li, Mustapha, & Lin, 2015; Z. Zhang, Zhang, & Lin, 2014). SERS can acquire distinctive spectral features based on different vibrational modes of analyte molecules (Shi, Wang, & Zhan, 2016). The enhancement of SERS signals is based on two mechanisms: electromagnetic enhancement and chemical enhancement. Electromagnetic enhancement is dependent on the excitation of localized surface plasmon on a metal substrate surface with a roughness feature. On the other hand, chemical enhancement is due to the charge transfer between substrate and analyte (Haynes, McFarland, & Duyne, 2005). The commonly used SERS substrates include gold nanosubstrates, acid-etching silver foils, laser-ablated silver plates, and other conventional SERS substrates based on silicon, glass, and porous alumina (Marques, Nogueira, Pinto, Neto, & Trindade, 2008). However, these SERS substrates are rigid, brittle, expensive, and not environmentally friendly. Therefore, there remains a need to develop novel, flexible, cost-effective, and biocompatible substrates for SERS analyses.

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50 The objective of this study is to develop a nanocomposite using CNFs impregnated with silver
51 nanoparticles (AgNPs). These CNF-AgNP nanocomposites are lightweight and strong, and can
52 be used as an effective SERS platform (Group, 2013). In addition, CNFs have a large surface
53 area and 3D nanofiber network (Gardner, Oporto, Mills, & Samir, 2008; Li, Yao, Wang, Cai, &
54 Wang, 2014), which can increase the potential number of molecules that can react with AgNPs
55 and also enhance the roughness of the substrate's surface to increase SERS signal intensity. An
56 effective Raman indicator molecule, 4-aminothiophenol (pATP), was used to characterize
57 AgNPs on CNFs (Meng, Lai, Jiang, Zhao, & Zhan, 2013). The performance of CNF-AgNP
58 nanocomposites was evaluated by measuring thiabendazole (TBZ) in different concentrations.

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60 TBZ is a pesticide and fungicide that has been widely used post-harvest on fruits and vegetables
61 (USEPA, 2002). Apple is one of the produce that can be contaminated with TBZ (USDA, 2014).
62 Although TBZ has low acute toxicity compared to other pesticides, it has been classified as
63 likely to be carcinogenic at doses high enough to cause disturbance of the thyroid hormone
64 balance (USEPA, 2002). However, TBZ is a hydrophobic molecule that has a low affinity for
65 AgNPs (Alvarez-Puebla & Liz-Marzan, 2012; Guerrini, Garcia-Ramos, Domingo, & Sanchez-
66 Cortes, 2009; Nergiz et al., 2013; Stella et al., 2000). This issue can be overcome by controlling
67 the electrostatic force, either altering the surface coating of nanoparticles or changing the
68 solution pH to enhance the affinity of target molecules and nanoparticle surface (Alvarez-Puebla,
69 Arceo, Goulet, Garrido, & Aroca, 2005). In this study, we chose the method of adjusting the
70 solution pH to below TBZ's pK_a ($pH = 4.65$) to enhance the SERS signals. To our knowledge,
71 this is the first study to use SERS coupled with CNF-AgNP films for detecting TBZ pesticides in
72 apples.

2. Materials & Methods:

2.1 Materials and chemicals

4-aminothiophenol (pATP), ethanol (95%), AgNO₃, thiabendazole (TBZ), 99% hydrolyzed polyvinyl alcohol (PVA), glycerol, sodium borohydride (NaBH₄) were all purchased from Sigma-Aldrich (St. Louis, MO). Acetone was purchased from Fisher Scientific (Pittsburgh, PA, USA). Cellulose nanofibers (CNFs) were purchased from the University of Maine.

2.2 Synthesis of CNF films

Five grams of PVA were dissolved in 50 g water (10%) by autoclaving for 30 min. At the same time in another glass flask, 5 g CNFs were dissolved in 50 g water (10%), 5 g of glycerol were added and mixed for 30 min. Then, the two solutions were mixed, heated and stirred at 90°C for 2 h. Lastly, the solution was poured into square plastic petri plates and stored at room temperature for 24 h to form a film.

2.3 Impregnation of AgNPs into CNF films

AgNPs were impregnated into the CNF films by immersing the film into 0.001 M AgNO₃ solution for 1 h at room temperature. CNF films were then rinsed by ethanol to wash out the chemicals. The silver ion-saturated CNF films were placed in 0.001, 0.01, and 0.1 M NaBH₄ solution for 10 min in an ice bath, and the color of the films gradually changed from bright yellow to brown yellow as the molar ratio of NaBH₄ increased. The CNF-AgNP nanocomposites were rinsed with Milli-Q water to remove the excessive chemicals on the films.

2.4 Preparation of pATP solution

pATP powders were mixed with 95% ethanol to make a series of concentrations of pATP solutions (1, 5, and 10 ppm). A small amount of pATP solution was added onto the CNF-AgNP nanocomposites. pATP was used as a Raman reporter to conjugate with AgNPs to enhance Raman signals. The film samples were then measured by SERS to collect the signals of AgNPs-pATP complexes.

2.5 UV-vis spectroscopy for detection of AgNPs prepared with different concentration of NaBH₄

A volume of 30 mL of 0.001, 0.01, and 0.1 M of NaBH₄ was prepared in Erlenmeyer flasks. The solutions were then stirred and cooled in an ice bath for 20 min. Then, 0.001 M of AgNO₃ was then added at a rate of 1 drop per second into different concentrations of NaBH₄ solution. The solution was stirred continually until the last drop of AgNO₃ was added. This step was carefully controlled because if stirring was continued after all the AgNO₃ was added, the AgNPs would aggregate and the color of the solution would become gray. Finally, the three yellow AgNP solutions were obtained using different molar ratios of NaBH₄:AgNO₃ and the solutions were tested by UV-vis spectroscopy. CNF-AgNP nanocomposites were then used as a SERS substrate to test the performance of this substrate. The pATP molecules were chosen as the target analyte in the measurement.

2.6 Preparation of different concentrations of TBZ pesticide at different pH values

TBZ was another analyte for SERS analysis. In this study, we synthesized 1, 5, 10, and 100 ppm of TBZ by dissolving TBZ powders in acetone solution. Each sample was then measured at different pH values (4, 6, and 7). The pH 4 is below TBZ's pK_a value of 4.65. Then, a volume of 200 μ L of different concentrations and different pH values of TBZ solutions were added into 2 cm² CNF-AgNPs film for 1 min before SERS detection.

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122 *2.7 Detection of TBZ in apple*

123 Apple samples were cut into small pieces and spiked with different concentrations of TBZ. TBZ
124 was extracted from the apple by mixing the spiked apple (0.5 g) with 50% of acetonitrile-water
125 solution (0.5 mL). Then, the mixture was shaken for 10 min and centrifuged at 3354 G-force for
126 10 min. A drop of supernatant was then placed on the CNF-AgNPs substrate for SERS analysis.

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128 *2.8 SERS measurement to detect pATP and TBZ*

129 **Droplets of TBZ samples** were deposited on the CNF-AgNP substrate before SERS measurement.
130 SERS was conducted by a Raman spectrometer (Renishaw 1000, Renishaw Inc., Gloucestershire,
131 UK) equipped with a 785 nm laser and 50× objective. The laser beam (25 mW) was focused
132 directly on the gold slide. OMNIC software was used to collect the Raman signals from ten
133 randomly selected spots for each droplet.

134

135 *2.9 Data analysis*

136 Delight software (D-Squared Development Inc., LaGrande, OR, USA) was used to analyze the
137 SERS spectra from different treatments. First, the collected spectra from 10 different locations of
138 different samples were averaged to a final spectrum. Second, the spectra were smoothed to
139 reduce the noises. The SERS spectra of pATP were acquired in the wavenumber range between
140 300 to 1800 cm^{-1} , and the SERS spectra of TBZ were acquired in the wavenumber range
141 between 700 to 1600 cm^{-1} .

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143 **3. Results & Discussions**

144 *3.1 Characterization of AgNPs in CNFs by UV-vis spectroscopy and TEM*

UV-vis spectroscopy was used to characterize AgNPs generated in the mixtures of 0.001 M AgNO₃ solution with 0.001, 0.01, and 0.1 M reducing agent, NaBH₄ solution. Due to the surface plasmon resonance (SPR) of conducting electron on the surface of AgNPs, the synthesized AgNPs display one absorption feature as shown in Figure 1. This is in accord with previous studies that AgNPs showed a characteristic optical absorption peak at ~400 nm (Bhui et al., 2009; Martinez-Castanon, Nino-Martinez, Martinez-Gutierrez, Martinez-Mendoza, & Ruiz, 2008).

Figure 1. Absorption spectra of silver nanoparticles prepared with different NaBH₄ : AgNO₃ molar ratios: 100:1 (a); 10:1 (b); 1:1 (c).

In Figure 1, the NaBH₄:AgNO₃ molar ratio of 100:1 showed a narrow peak at 390 nm. However, when the concentration of NaBH₄ decreased, the absorption band became broader. The peak was located at 392 nm when the NaBH₄:AgNO₃ molar ratio was 10:1; and the sample with NaBH₄:AgNO₃ molar ratio of 1:1 even exhibited a much broadened peak at 393 nm. The red-shift and the bandwidth of the absorption spectra indicated the increased size of AgNPs and a decrease in the reaction efficiency as the concentration of NaBH₄ is reduced. Therefore, it is speculated that the NaBH₄:AgNO₃ molar ratio of 1:1 formed the largest sized AgNPs among the

three molar ratios. The possible reason is that there was a small amount of reducing agent, NaBH_4 , to reduce the ionic silver, so the excessive silver atoms aggregated together. In contrast, the $\text{NaBH}_4\text{:AgNO}_3$ molar ratio of 100:1 formed the smallest size of AgNPs, which was due to more free electron generated from NaBH_4 to prevent the aggregation of silver (Maneerung, Tokura, & Rujiravanit, 2008).

Figure 2. TEM images of AgNPs impregnated CNFs prepared with different $\text{NaBH}_4\text{:AgNO}_3$ molar ratios: 1:1 with average size: 20.05 ± 8.28 (a); 10:1 with average size: 9.44 ± 4.73 (b); 100:1 with average size: 4.71 ± 4.40 (c).

TEM images were obtained in this study for the CNFs impregnated with AgNPs that were prepared by three different $\text{NaBH}_4\text{:AgNO}_3$ molar ratios (Figure 2). The images show 3D nanofiber network and nano-sized structure of cellulose fibers with high length to width ratio and a large surface area that can load AgNPs. Moderate amounts of AgNPs are loaded and they are evenly distributed on the surface of CNFs. The average size of AgNPs made with the $\text{NaBH}_4\text{:AgNO}_3$ molar ratio of 1:1 was estimated to be 20.05 nm (Figure 2a). When the $\text{NaBH}_4\text{:AgNO}_3$ molar ratio increased to 10:1, the average size of AgNPs became smaller at 9.44 nm (Figure 2b). AgNPs made with the $\text{NaBH}_4\text{:AgNO}_3$ molar ratio of 100:1 had the smallest particle size of 4.71 nm (Figure 2c). The size distribution of AgNPs on CNF with different $\text{NaBH}_4\text{:AgNO}_3$ molar ratios is shown in Figure 3.

Figure 3. The size distribution of AgNPs on CNF with NaBH₄:AgNO₃ molar ratio of: (a) 1:1; (b) 10:1; and (c) 100:1.

The size and size distribution of nanoparticles influence the properties and the enhancement of SERS activities (Agnihotri, Mukherji, & Mukherji, 2014; Israelsen, Hanson, & Vargis, 2015). The intensities of SERS measurement from AgNPs from high to low was in accord with the NaBH₄:AgNO₃ molar ratio of 10:1 > 1:1 > 100:1 (Figure 4). The AgNPs made with the NaBH₄:AgNO₃ molar ratio of 10:1 had the strongest SERS intensity compared to the other two ratios. This is because different molar ratio of NaBH₄:AgNO₃ resulted in the formation of different sizes of AgNPs, which affect the intensity of Raman signals. For the NaBH₄:AgNO₃ molar ratio of 1:1, the amount of reducing agent (NaBH₄) is too low. Therefore, AgNPs aggregated together and affected the SERS detection. Due to their small size and low mass, once NPs bind together it is often difficult to separate them. On the other hand, the NaBH₄:AgNO₃ molar ratio of 100:1 had the weakest SERS intensity due to the smallest particle size of AgNPs.

Hence, the $\text{NaBH}_4\text{:AgNO}_3$ molar ratio of 10:1 was chosen to be used as the CNF-AgNPs substrate due to the highest SERS signals among the three types of substrates made with different concentrations of $\text{NaBH}_4\text{:AgNO}_3$ molar ratio solutions.

Figure 4. SERS spectra of pATP-AgNPs complexes prepared with different $\text{NaBH}_4\text{:AgNO}_3$ molar ratio of: (a) 1:1; (b) 10:1; and (c) 100:1.

3.2 Characterization of AgNPs in CNFs film using a Raman indicator pATP

pATP was used in SERS measurement to bind with AgNPs, they can generate the vibrational signals under SERS measurement. Figure 4 shows five significant Raman peaks of pATP-AgNPs complexes at ~ 390 , 1078 , 1143 , 1435 , and 1590 cm^{-1} . The peak located at $\sim 390\text{ cm}^{-1}$ is assigned to the bending mode of the C-S bond (Wu et al., 2011; Zhou, Zhi, Zhao, & Xu, 2010). The bands at ~ 1078 and 1590 cm^{-1} are assigned to the a_1 vibrational modes (in-plane modes). A peak at $\sim 1078\text{ cm}^{-1}$ is attributed the C-S stretching vibration, and C-C stretching vibrations for a peak at $\sim 1590\text{ cm}^{-1}$. Another vibrational mode of pATP-AgNPs complexes is called b_2 modes (in plane mode), which are located at ~ 1143 and 1435 cm^{-1} . The b_2 vibrational modes are based on the charge transfer condition of SERS, which is the charge transfer between the AgNPs and the adsorbed molecules (Premkumar & Geckeler, 2014). These peaks are similar to the SERS spectra of pATP-AgNPs complexes measured in our previous studies, so we extrapolated that AgNPs were successfully impregnated onto the CNF films. In addition, different concentrations of pATP and different concentrations of NaBH_4 can both affect the intensity of SERS signals (Figure 4). SERS is a highly sensitive method that doesn't require a lot of metallic NPs in the substrate, but can still generate very strong Raman signals. As shown in Figure 2, moderate amounts of AgNPs loaded on the surface of CNFs are sufficient to generate strong SERS signals as shown in Figure 4.

3.3 Detection of TBZ using CNF-AgNPs nanocomposites as SERS substrate

Figure 5 shows a Raman spectrum of TBZ powders (99%) and a SERS spectrum of TBZ solutions measured by CNF-AgNP nanocomposites. The powder form and the solution of TBZ exhibit similar Raman peaks at ~ 785 , 1280 , and 1580 cm^{-1} . However, SERS spectra of the TBZ solution displayed more visible peaks than the normal Raman spectra of TBZ powders. Figure 5

shows the SERS spectra of different concentrations (1, 10, 50, and 100 ppm) of TBZ measured by the CNF-AgNP substrate. Only when the pH level is below TBZ's pK_a , were strong SERS signals obtained. Because TBZ is a neutral and hydrophobic molecule, it has a low affinity for the negatively charged AgNP surface due to the lack of electrostatic attractions. TBZ molecule contains secondary amine groups, which can be protonated at pH values below their respective pK_a values (Wei & Vikesland, 2015). Therefore, 0.1 M HCL was added to reduce the pH of the TBZ solution to ~ 4 to induce electrostatic attraction between the amine groups of TBZ and the borohydride ions (BH_4^-) of AgNPs (Figure 7). However, nanoparticles can aggregate when they are in a low pH environment, which will affect SERS measurement (Alvarez-Puebla & Aroca, 2009). Nanocellulose is acid resistant, chemically stable, and in a 3D rigid scaffold structure (Wei & Vikesland, 2015). Our results demonstrate that this new SERS substrate is uniform and very stable because AgNPs are highly uniform and firmly adhered to the CNFs. Cellulose nanofibers have unique properties of porous structure and active hydroxyl groups on their surface, which can function as a substrate for AgNPs. The hydroxyl groups can act as electron donors to aid in the formation of AgNPs (Lin & Tang, 2015). This CNF-AgNP platform can prevent the uncontrolled aggregation of AgNPs in low pH environments.

Figure 5. A Raman spectrum of TBZ powders and a SERS spectrum of TBZ solutions that were measured using CNF-AgNP films.

250
251 Different concentrations of TBZ solutions (1, 10, 50, and 100 ppm) were measured by the CNF-
252 AgNP SERS substrate and the spectra (Figure 6) exhibited four prominent peaks at 785, 1010,
253 1280, and 1580 cm^{-1} . The assignments to these peaks were out of plane bending of C-H, out of
254 plane bending of C-C-C, ring stretching, and C=N stretching, respectively (Kim, Kim, Lee, Jung,
255 & Lee, 2009). In addition, TBZ in real food samples (apples) was also detected in this study.
256 TBZ solutions (1, 10, 50, 100 ppm) were applied onto apples and then extracted from the apples
257 for SERS analysis. Figure 8 shows that the SERS spectra of TBZ extracted from the apple have
258 similar peaks with that of pure TBZ solutions (Figure 6), but the intensity of SERS signals were
259 not as strong as that of pure TBZ solutions. Moreover, the limit of detection of 5 ppm for TBZ
260 were obtained, which is lower than the current tolerance ppm for apple and other citrus fruits (10
261 ppm) (EPA, 2002).

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Figure 6. SERS spectra of different concentrations of TBZ measured by CNF-AgNP substrate: (a) 100 ppm TBZ; (b) 50 ppm TBZ; (c) 10 ppm TBZ; (d) 1 ppm TBZ.

Figure 8. SERS spectra of different concentrations of TBZ extracted from apples.

4. Conclusions

In this study, CNF-AgNP nanocomposite substrates were developed. They are flexible and environmentally friendly compared to the traditional SERS substrates. This novel SERS substrate was evaluated by measuring pATP and TBZ pesticide. The AgNPs-pATP complexes exhibit characteristic SERS peaks at ~390, 1078, 1143, 1435, and 1590 cm^{-1} . On other hand, the SERS spectra of TBZ show prominent peaks at ~785, 1010, 1280, and 1580 cm^{-1} . TBZ is a neutral and hydrophobic molecule that has a low affinity for the surface of negatively charged AgNPs. Therefore, TBZ only exhibited strong SERS signals when the pH is below the TBZ's pK_a value ($\text{pH} = 4.65$) based on the electrostatic attractions between AgNPs and TBZ. This method is simple, rapid, sensitive, and can be extended to rapid detection of other neutral molecules and pesticides in various food products.

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