VNU Journal of Science: Mathematics - Physics

Journal homepage: https://js.vnu.edu.vn/MaP

Original Article

Fabrication of SERS Substrates Using Ag/SiO_2 Nanocomposite for Dectecting Sub-ppm Glucose Concentration

Bui Hong Van*, Nguyen Thi Huong Giang

VNU University of Science, 334 Nguyen Trai, Thanh Xuan, Hanoi, Vietnam

Received 30th September 2025
Revised 20th November 2025; Accepted 02nd March 2026

Abstract: This work presents the fabrication of an Ag/SiO_2nanocomposite (NC) using the Stöber method coupled with chemical reduction, which serves as an effective SERS platform for the ultrasensitive detection of glucose at sub-ppm concentrations. SEM analysis revealed that the SiO_2 is in the form of nanospheres (NSs) with an average diameter of 159 nm, while TEM images showed Ag nanoparticles (NPs) with an average diameter of approximately 17 nm, uniformly distributed on the SiO_2surface. Such a well-defined nanostructure optimizes the SERS performance by providing distinct Raman signals corresponding to the functional groups in glucose molecules. In this study, glucose was successfully detected in the concentration range from 20 ppm down to 1 ppm, with a characteristic Raman peak observed at 1334 cm^{-1}.

Keywords: Ag/SiO_2, Nanocomposite, SERS, D-Glucose.

1. Introduction

Nanomaterials have become a prominent focus of contemporary research owing to their exceptional versatility. A key challenge in this field is the development of devices capable of sustaining stable plasmonic fields, particularly through stimulated emission [1]. Plasmons represent collective oscillations of electrons at the metal-dielectric interface, excited by incident electromagnetic radiation. Upon resonant light excitation, coherent electron oscillations give rise to localized surface plasmon resonance (LSPR), which concentrates electromagnetic energy into nanoscale “hot spots” surrounding metallic nanostructures. These hot spots are essential for the pronounced signal amplification characteristic of surface-enhanced Raman spectroscopy (SERS) [2].

Core-shell structures, consisting of a metallic core encapsulated by a dielectric shell, offer notable advantages in terms of structural stability and tunable size [3]. This configuration not only enhances

* Corresponding author.
E-mail address: buihongvan@hus.edu.vn

https//doi.org/10.25073/2588-1124/vnumap.5083

the stability of metallic nanoparticles but also enables precise control over plasmon resonance, thereby improving Raman signal enhancement. Recent studies have demonstrated that Ag/SiO_2 nanocomposites (NCs) significantly reinforce "hotspot" formation at the metal-dielectric interface, resulting in increased sensitivity for trace molecular detection [3]. Due to the complementary properties of silver and silica, Ag/SiO_2 NC exhibit broad potential for applications in biomedicine, food safety, environmental monitoring, and advanced materials,… [4].

Within this context, glucose detection has emerged as a particularly critical application. Glucose functions as a fundamental biomarker in diabetes diagnosis - a disease currently affecting more than 350 million individuals worldwide and contributing to over 3.2 million deaths annually [5]. Conventional electrochemical sensors employing enzymes such as glucose oxidase or glucose dehydrogenase are widely used but rarely on invasive blood sampling, which reduces patient compliance [5]. To overcome these limitations, non-invasive approaches, notably SERS, have been explored as promising alternatives [5, 6]. Nevertheless, the inherently weak Raman scattering cross-section of glucose and its limited interaction with metallic substrates present substantial challenges for low-concentration detection [5, 6]. Accordingly, this study aims to establish a facile yet highly sensitive SERS substrates for glucose detection, thereby advancing its practical utility in diabetes diagnostics.

2. Experimental Procedure

Tetraethoxysilane (TEOS) $Si(OC_2H_5)_4$ (99,98%), (3-aminopropyl), trimethoxysilane (APTMS) $H_2N(CH_2)_3Si(OCH_3)_3$ (99,96%), silver nitrate $AgNO_3$ (99,99%), sodium borohydride ($NaBH_4$), ammoniac NH_3 (25 wt%), D–glucose $C_6H_{12}O_6$ (99.6%), absolute ethanol C_2H_5OH (99.5%) were purchased from Sigma Aldrich, China. All used chemicals were analytical grade. Deionized (DI) water was used in all experiments.

The synthesis of SiO_2NSs were synthesized by the Stöber method, in which TEOS served as the silica source, ammoniac served as the catalyst, and absolute ethanol was used as the solvent. The Stöber method is a technique that uses common precursors, simple and easily applicable procedure, and good reproducibility. The process of synthesis Ag/SiO_2 NC as folows: 0.2 g of SiO_2NSs were dispersed in ethanol and modified with APTMS, under magnetic stirring. After centrifugation and washing, a white precipitate was obtained. In a separate step, 0.1 g of silver nitrate was dissolved in 10 ml of water, followed by the addition of 3 ml of NH_3. The above mixture of $SiO_2$was then introduced into above solution, followed by the addition of 0.01 g $NaBH_4$ dissolved in 10 ml of deionized water. The mixture was further stirred to promote the reduction of silver ions. The Ag/SiO_2precipitation was obtained by centrifugation and then dried at 80 °C for 10 hours to obtain a powder form.

A Si (100) wafer (0.6 × 0.6 cm, double-side polished) was sequentially ultra sonicated in acetone, ethanol, and DI water for 15 min each. To remove the residual metal and the native oxide layer on the substrate surface in order to obtain a clean Si substrate, the wafer was immersed in a mixed solution of 50% $HNO_3$and 6% HF for 15 min, rinsed thoroughly with DI water. For substrate preparation, 0.1 g of Ag/SiO_2 NC were dispersed in 10 mL of DI water and magnetically stirred for 5 min. A 10 μL portion of the suspension was drop-cast onto the wafer surface in three successive steps, with each layer being dried at room temperature before the next deposition [7]. To evaluate SERS performance, 10 μL of a 20 ppm D-Glucose solution was applied onto the $Ag/SiO_2/Si$ substrate and dried at RT. The same procedure was repeated for glucose concentrations ranging from 1 to 20 ppm. The fabrication process of Ag/SiO_2 NCS and the preparation procedure of the SERS substrate are briefly illustrated in Figure 1.

The microstructure of SiO_2 and Ag/SiO_2 NC were investigated by X-ray diffraction (XRD) on a PANalytical Empyrean device using Cu-K_α radiation (λ = 1.54056 Å, 2θ = 15 ÷ 70°). The morphology of the Ag/SiO_2 nanostructures were characterized by field-emission scanning electron microscopy

JMS-7100F (JEOL) and high-resolution transmission electron microscopy JEM-2100. The absorption spectra were recorded on the UV-2450 system. Raman spectra were recorded on a portable μRaman-Ci (Technospex) spectroscopy using a diode laser with technical specifications of power (10 mW), an excitation radiation (785 nm). All spectra were recorded at room temperature.

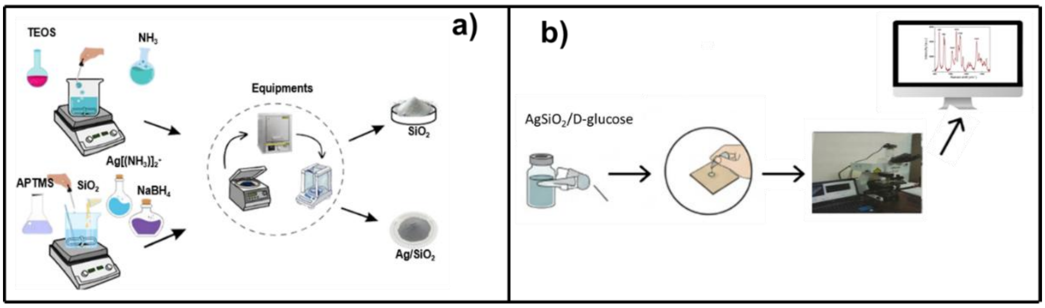

Figure 1. Diagram of Ag/SiO$_2$ synthesis (a) and substrate preparation for SERS investigation (b).

3. Results and Discussion

3.1. Characterization of the Morphology and Crystal Structure of SiO$_2$ and Ag/SiO$_2$ Nanostructures

The morphology and size distribution of SiO$_2$NSs were examined by SEM (Figure 2a), while those of Ag/ SiO$_2$ were further characterized by TEM (Figure 2b).

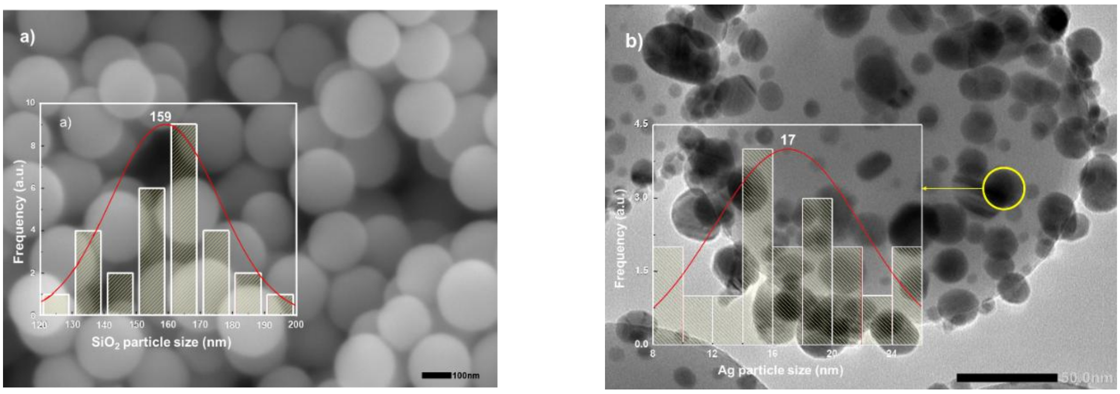

Figure 2. (a) SEM image of SiO$_2$ NSs; (b) Magnified view of Ag NPs on SiO$_2$ NSs, with an inset showing the size distribution histogram of Ag NPs on the SiO$_2$ surface.

Figure 2(a) presents the SEM image of SiO$_2$ NSs synthesized by the Stöber method, showing uniformly spherical shape with smooth surfaces and homogeneous distribution. The particle size distribution indicates an average diameter of about 159 nm, which is consistent with previous reports [7]. This result demonstrates an efficient particle formation process, yielding a monodisperse system [8,9]. At the same time, numerous silver nanoparticles (NPs) are observed to be evenly distributed on the silica surface. TEM analysis (Figure 2b) reveals that the Ag NPs are almost uniformly dispersed, with sizes ranging from 8 to 25 nm and an average diameter of 17 nm. These results confirm that Ag NPs were successfully synthesized on the surface of SiO$_2$nanoparticles with uniform size and high crystallinity. This size range increases the surface-to-volume ratio, resulting in an extended light absorption region. Overall, the results indicate effective dispersion and strong adhesion of Ag onto the SiO_2surface [10].

The X-ray diffraction (XRD) pattern of the Ag/SiO_2NC is shown in Figure 3. In the 2θ range of 15° to 30°, a broad diffraction band without any distinct maxima is observed, indicating the amorphous structure of SiO_2. This observation is consistent with the nature of silica synthesized by the Stöber method, which typically remains non-crystalline in the absence of high-temperature treatment [6].

In addition, three sharp diffraction peaks are detected at 2θ values of 38.0°, 44.1°, and 64.2°, corresponding to the (111), (200), and (220) crystal planes, respectively, which are characteristic of the face-centered cubic (fcc) structure with space group $Fm\bar{3}m$ of metallic Ag. This structure is quite agreement with the standard JCPDS card No. 96-901-3047 for pure silver (Ag), confirming that the as-synthesis silver be in the form of crystalline metallic [2,3].

From the XRD pattern and base on the Debye–Scherrer equation:

$$D = \frac{0,9.\lambda}{\beta\cos\theta} \quad (1)$$

where D is the average crystallite size (nm), λ is the wavelength of X-ray (0.15406 nm), θ is Bragg's diffraction (radian), and β is the full-width at half maximum (FWHM) of the diffraction peak (radian). The crystallite size of Ag nanoparticle was calculated to be approximately of 17 nm.

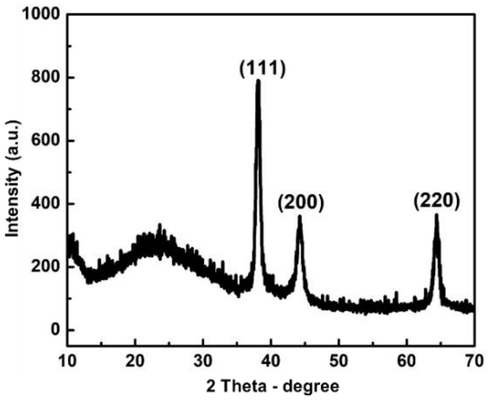

Figure. 3. XRD patterns of Ag/SiO_2 NCs

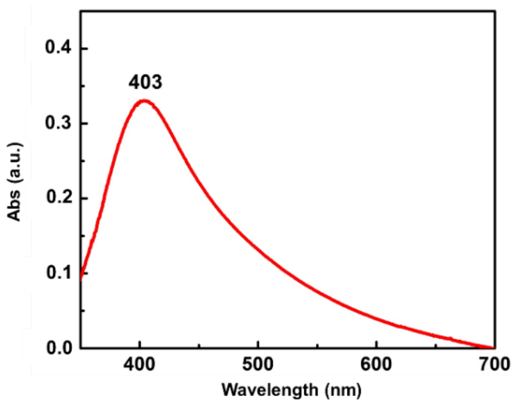

Figure. 4. UV-Vis absorption spectra of Ag/SiO_2 NCs.

Figure 4 shows the UV-Vis absorption spectrum of the Ag/SiO_2 NC, where a broad and symmetric absorption band appears with a maximum at 403 nm, which is quite consistent with the surface plasmon resonance absorption peak of Ag NPs. This effect occurs when the free electrons on the nanoparticle surface oscillate in resonance with the electromagnetic wave of the incident light [12]. The Ag NPs attached to the surface of the SiO_2spheres not only help stabilize and prevent the aggregation of Ag nanoparticles but also enhance the uniformity of the absorption spectrum [2]. The absorption peak at 403 nm indicates that the Ag NPs are of nanoscale size, typically in the range of 10-50 nm, since the surface plasmon resonance of Ag in aqueous solution usually appears in the region of 390-420 nm, with the exact position depending on the particle size, shape, and surrounding environment [3]. In particular, smaller particles shift the SPR peak toward shorter wavelengths, and vice versa. The clearly and symmetric appearance of the peak at 403 nm demonstrates that the Ag NPs have a relatively narrow and uniform size distribution, which is consistent with the SEM and XRD results. In addition, the attachment of Ag on SiO_2NSs enhances the signal in plasmonic sensing applications, with high potential for usage in biosensing, photocatalysis, and residual detections.

3.2. Raman Spectral Analysis of Glucose

D-glucose powder, also known as dextrose, is a refined form of glucose derived from natural sources such as corn starch. It is used as an alternative carbon source, particularly in intensive shrimp farming. D-glucose can be readily metabolized, and it also increases blood glucose levels while providing calories. The Raman spectrum of commercial D-glucose powder ($C_6H_{12}O_6$, 99.6%) shows characteristic peaks in the region of 800-1500 cm^{-1} (Figure 5a). The strong intensities at the characteristic Raman shifts reflect the chemical structure of the glucose molecule. Specifically, the peaks at 857 cm^{-1} and 915 cm^{-1} are assigned to C-O-C and C-C vibrations within the sugar ring. The peak at 1023 cm^{-1} arises from the stretching vibrations of C-O-C/C-C bonds, whereas the peaks at 1073 cm^{-1} and 1120 cm^{-1} correspond to the stretching of C-C and C-O bonds; notably, the band at 1120 cm^{-1} is often used as a marker for quantitative glucose analysis in biomedical studies. In addition, the peak at 1331 cm^{-1} is attributed to the bending vibration of the $-CH_2$ group. These values are consistent with the Raman spectra reported for crystalline D-glucose [13, 14]. While the Raman signals of Ag/SiO_2 substrate are recorded too weak, peaks are not shown obviously (Figure 5b). It is affirmed that characteristic peaks at SERS do not belong to the Ag/SiO_2. Without Ag/SiO_2 substrate, the Raman signal of glucose can only be observed at a concentration of 10^4 ppm on the Si substrate (Figure 5c).

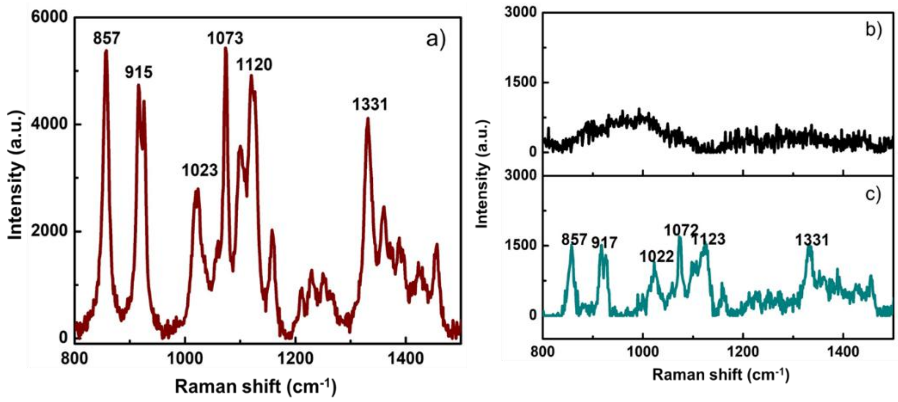

Figure 5. a) Raman spectrum of commercial glucose powder; b) Raman spectrum of Ag/SiO_2 on silic substrate; c) Raman spectrum of 10^4 ppm glucose on silic substrate.

Figure 6a presents the results using Ag/SiO_2 NC as the substrate for detecting glucose at low concentrations, clearly evidenced by the two characteristic peaks at 999 cm^{-1}, corresponding to symmetric stretching vibrations of C-C and C-O, and 1334 cm^{-1}, corresponding to CH_2 bending vibrations, demonstrating the sensing capability of this material. Characteristic peaks at 999 cm^{-1} and 1334 cm^{-1} of glucose solutions from 1 to 20 ppm were successfully detected. Intensity of peak at 999 cm^{-1} is almost unchanged, while the signal intensity of 1334 cm^{-1} peak is sensitive to the molecule's concentration. Therefore, a linear correlation between glucose concentration and SERS intensity at 1334 cm^{-1} peak were plotted (Figure 6b). Therefore, the 1334 cm^{-1} band is an important characteristic peak for identifying glucose concentration. Meanwhile, the glucose concentration in human blood normally ranges from 70-110 mg/dL (equivalent to 700-1100 ppm), while in diabetic patients it usually exceeds 126 mg/dL (~1260 ppm) in the fasting state and may rise above 200 mg/dL (~ 2000 ppm) after meals [15]. Thus, the detection limit achieved in this study (1 ppm) is several hundred times lower than the actual blood glucose concentration. This comparison indicates that the Ag/SiO_2 substrate exhibits high sensitivity and holds strong potential for detecting glucose at extremely low concentrations, thereby opening up prospects for non-invasive diabetes diagnostic techniques [14]. In the as-synthesis nanocomposite material, Ag and glucose are well dispersed on the surface of SiO_2 spheres. As a result, the enhanced electromagnetic field generated at the metal-dielectric interface is effectively transferred to the glucose molecules. Therefore, glucose can be detected at concentrations as low as 1 ppm.

Although the signal intensity is still low, these results show that Ag/SiO_2 NC is a promising material for glucose detection, particularly in very low-concentration environments. To improve performance, background signals should be minimized through surface functionalization to increase selectivity, and the nanostructure optimized, such as Ag particle size or the Ag:SiO_2 ratio. With these enhancements, AgSiO_2 NC is expected to serve as an efficient SERS sensor, offering significant prospects for bioanalytical and chemical applications.

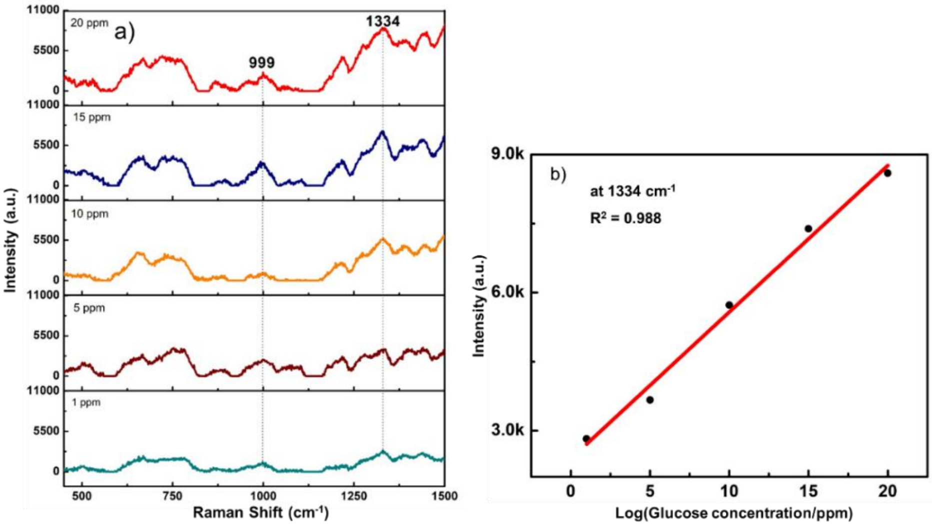

Figure 6. (a) SERS spectra of Glucose with concentrations ranging from 1 to 20 ppm, measured on the Ag/SiO_2/Si SERS substrate and (b) Linear correlation between Glucose concentration and SERS intensity at 1334 cm^{-1} peak.

To quantitatively evaluate the signal enhancement capability, the enhancement factor (EF) is used as an index reflecting the amplification efficiency of the SERS substrate compared to conventional Raman. The EF is calculated using the formula:

$$EF = \frac{I_{SERS}/N_{Surf}}{I_{RS}/N_{vol}} \quad (2)$$

where: Nvol = C_{RS}·V is the average number of molecules in the probed volume V at the Raman - measured concentration C_{RS} (without SERS), and N_{Surf} is the average number of molecules adsorbed within scattering volume for SERS experiments. Using equation (3) for 1334 cm^{-1} peak, the EF were calculated to be approximately 10^4.

4. Conclusion

Ag/SiO_2 NC have shown strong potential for application as a SERS substrate for glucose detection, with characteristic peaks clearly appearing at 999 cm^{-1} and 1334 cm^{-1}, even at a low concentration of 1 ppm. This result not only confirms the signal enhancement efficiency of Ag/SiO_2 NC but also opens up the possibility of applications in other complex environments. Although there are still limitations regarding sensitivity and background noise, these factors can be completely improved through optimization of the nanostructure and surface functionalization to increase selectivity. With outstanding potential for improvement and broad applicability in fields such as biomedicine, food safety, and environmental monitoring, Ag/SiO_2 NC promises to be a breakthrough solution in the development of efficient and reliable SERS sensors.

References

[1] D V Viazmitinov, L B Matyushkin, A I Maximov, (2014). "Synthesis of core-shell Ag/SiO_2 nanoparticles for SPASER structures", Journal of Physics, Conference Series, 541(1), 012015. http://doi:10.1088/1742-6596/541/1/012015.

[2] Stefan Alexander Maier, (2007), "Plasmonics: Fundamentals and Applications", Springer, ISBN: 978-0-387-37825-7. https://doi.org/10.1007/0-387-37825-1.

[3] Yang, Lin, Ren, Xinyue, & Tang, Fangqiong (2008), "Preparation and characterization of monodisperse silver nanoparticles embedded into silica spheres", Journal of Colloid and Interface Science, 322(2), 435-441. https://doi.org/10.1016/j.jcis.2008.03.031.

[4] Zhang, Xi-Feng, Liu, Zhi-Guo, Shen, Wei, & Gurunathan, Sangiliyandi (2016), "Silver nanoparticles: synthesis, characterization, properties, applications, and therapeutic approaches", International Journal of Molecular Sciences, 17(9), 1534. https://doi.org/10.3390/ijms17091534.

[5] Xiangcheng Sun, Stephen Peter Stagon, Hanchen Huang, Jun Chen and Yu Lei, (2014), "Functionalized aligned silver nanorod arrays for glucose sensing through surface enhanced Raman scattering", RSC Advances, 4, 23382-23388. https://doi.org/10.1039/C4RA02423K.

[6] Leonardo Pérez-Mayén, Jorge Oliva, Patricia Salas, and Elder De la Rosa-Cruz, (2016), "Nanomolar detection of glucose using SERS substrates fabricated with albumin-coated gold nanoparticles", Nanoscale. https://doi.org/10.1039/C6NR00163G.

[7] Nguyen Thi Hue, Tien Dai Nguyen, Hong Van Bui, Thi Bich Vu, Dang Van Thai, Thuy Phuong Nhat Tran, Duc Tran Trong, Huong Giang Nguyen Thi, Quoc Tran Ha, & Nguyen Manh Hung (2025), "Fabrication of Ag/SiO_2 nanocomposite via the Stöber and chemical reduction approach for detecting sub ppm tetracycline concentration", Materials Chemistry and Physics, 341, 130885. https://doi.org/10.1016/j.matchemphys.2025.130885.

[8] Stöber, Werner, Fink, Arthur, & Bohn, Ernst (1968), "Controlled growth of monodisperse silica spheres in the micron size range", Journal of Colloid and Interface Science, 26(1), 62-69. https://doi.org/10.1016/0021-9797(68)90272-5.

[9] Rahman, Irfan A., & Padavettan, Varathan (2012), "Synthesis of silica nanoparticles by sol-gel: size-dependent properties, surface modification, and applications in silica-polymer nanocomposites", Journal of Nanomaterials, 2012, Article ID 132424. https://doi.org/10.1155/2012/132424.

[10] Li, Zhiqiang, Barnes, Jason C., Bosoy, Alexander, Stoddart, J. Fraser, & Zink, Jeffrey I (2012), "Mesoporous silica nanoparticles in biomedical applications", Chemical Society Reviews, 41(7), 2590-2605. https://doi.org/10.1039/C1CS15246G.

[11] Stöber, Werner, Fink, Arthur, & Bohn, Ernst (1968), "Controlled growth of monodisperse silica spheres in the micron size range", Journal of Colloid and Interface Science, 26(1), 62-69. https://doi.org/10.1016/0021-9797(68)90272-5.

[12] Jha, Ashish Kumar, Prasad, Kamal, Kulkarni, Anushree Ramesh, & Prasad, Kiran (2009), "Synthesis of silver nanoparticles by endosymbiont Pseudomonas fluorescens CA 417 and their bactericidal activity", Letters in Applied Microbiology, 48(3), 280-286.

[13] John J. Cael, Jack L. Koenig, and John Blackwell (1974), "Infrared and Raman spectroscopy of carbohydrates. Part IV. Identification of configuration- and conformation-sensitive modes for D-glucose by normal coordinate analysis," Carbohydrate Research, vol. 32, pp. 79-91. http://doi.org/10.1016/S0008-6215(00)82465-9.

[14] Xiangcheng Sun (2022), "Glucose detection through surface-enhanced Raman spectroscopy: A review," Analytica Chimica Acta, Art. ID 339226, vol. 1206, http://doi.org/10.1016/j.aca.2021.339226.

[15] American Diabetes Association, (2010). "Diagnosis and Classification of Diabetes Mellitus", Diabetes Care, 33(Suppl. 1), S62-S69. https://doi.org/10.2337/dc10-S062