

Green Synthesis of Silver Nanoparticles for Enhanced Surface Plasmon Resonance (SPR) Biosensing

Swaira Anjum^{1*}, Marjan Bagherinajafabad², Reeda Shakeel³, Muhammad Asad⁴, Wajeeha Anjum⁵, Ahmad Ghaffar⁶, Aleena Amir⁷

¹Department of Chemistry, Rawalpindi Women University, Rawalpindi, Punjab 47721, Pakistan

²Department of Microbiology, Faculty of Science, Agriculture and Modern Technology, Shiraz Branch, Islamic Azad University, Shiraz, Iran

³Department of Chemistry & Chemical Technologies, Università Della Calabria, Italy

⁴Department of Physical Sciences, University of Engineering and Technology, Taxila

⁵University of Engineering and Technology, Lahore, Pakistan

⁶Institute of Chemical Sciences, Bahauddin Zakariya University, Multan, Pakistan

⁷Department of Chemistry, Rawalpindi Women University, Rawalpindi, Punjab 47721, Pakistan

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*Corresponding author: Swaira Anjum

Department of Chemistry, Rawalpindi Women University, Rawalpindi, Punjab 47721, Pakistan

Abstract

Green synthesis of silver nanoparticles (AgNPs) has emerged as a sustainable, cost-effective alternative to traditional chemical and physical methods (Sati *et al.*, 2025). This study explores the plant-mediated synthesis of AgNPs using bioactive extracts, which serve as both reducing and stabilizing agents. The resulting nanoparticles exhibit unique tunable optical properties, primarily characterized by strong Surface Plasmon Resonance (SPR). We demonstrate that these biogenic AgNPs significantly enhance the detection sensitivity of SPR-based biosensors compared to conventional substrates. Characterization through UV-Vis spectroscopy, SEM, and EDX confirms the formation of spherical AgNPs with high elemental purity. These findings provide a roadmap for the development of eco-friendly, high-performance diagnostic tools for environmental and biomedical monitoring.

Keywords: Silver Nanoparticles (AgNPs), Green Synthesis, Surface Plasmon Resonance (SPR), Biosensors, Plant-mediated Synthesis.

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1. INTRODUCTION

Silver nanoparticles (AgNPs) are widely recognized for their exceptional optical, electronic, and antibacterial properties, which facilitate their use in high-sensitivity biosensing (Sati *et al.*, 2025). Traditional synthesis routes such as chemical reduction using sodium borohydride or physical laser ablation often involve hazardous reagents, high energy consumption, and complex procedures (Baskaran *et al.*, 2024). In contrast, green synthesis utilizes phytochemicals from plant species like *Camellia sinensis* (green tea) and *Azadirachta indica* (neem) to reduce silver ions (Ag⁺) to metallic silver (Ag⁰) (Babatimehin *et al.*, 2025).

The core of SPR biosensing lies in the collective oscillation of free electrons on the surface of noble

metals when excited by incident light (PSPPs) (PMC12848061, 2026). This resonance condition is extremely sensitive to refractive index (RI) changes in the surrounding medium. By integrating green-synthesized AgNPs into the sensor platform, the localized surface plasmon resonance (LSPR) effect can be leveraged to amplify signals, enabling the real-time, label-free detection of trace biomolecules and heavy metals (Ibrahim *et al.*, 2024; PMC12848061, 2026).

1.1. The Critical Role of Silver Nanoparticles in Modern Technology

Nanotechnology has revolutionized numerous scientific domains, with noble metal nanoparticles occupying a central position due to their unique physicochemical properties, which are distinct from their

bulk counterparts. Among these, silver nanoparticles (AgNPs) have garnered unprecedented attention across diverse fields, including medicine, electronics, catalysis, and, most notably, optics and photonics. AgNPs are widely recognized for their exceptional optical tunability, high electrical conductivity, and potent antibacterial properties (Sati *et al.*, 2025). This versatility stems from their high surface-area-to-volume ratio, which dramatically increases surface reactivity, making them ideal candidates for the development of high-sensitivity biosensing platforms required for early disease diagnostics and environmental monitoring (Sati *et al.*, 2025).

1.2. Moving Beyond Traditional Synthesis Routes: The Case for Green Nanotechnology

The expanding utility of AgNPs necessitates robust, scalable, and standardized production methods. Traditionally, AgNP synthesis has relied on chemical and physical routes. Chemical reduction techniques, such as those using sodium borohydride (NaBH₄), ethylene glycol, or citrate reduction, often involve toxic reagents, hazardous reducing agents, and the generation of environmentally damaging by-products (Baskaran *et al.*, 2024). These stabilizers, furthermore, often render the

resultant AgNPs biocompatible for clinical applications. Physical methods, including laser ablation, thermal decomposition, and ion sputtering, minimize the use of chemical reagents but require massive energy consumption, sophisticated machinery, and complex operational procedures, making them economically prohibitive (Baskaran *et al.*, 2024).

This predicament has fueled the shift toward "green" synthesis or biogenic nanotechnology (refer to Table 1 and Figure 1). Green synthesis offers a sustainable, cost-effective, and ecologically benign alternative, adhering to the principles of safe design by eliminating toxic chemical inputs and waste. This "bottom-up" approach utilizes phytochemicals naturally occurring bioactive compounds extracted from plant species like *Camellia sinensis* (green tea) and *Azadirachta indica* (neem) which are rich in functional groups (phenols, flavonoids, terpenoids, and carboxylic acids). These dual-purpose compounds act as both potent reducing agents (converting toxic silver ions (Ag⁺) into stable, metallic silver nanoparticles (Ag⁰)) and as stabilizing/capping agents, thus preventing particle aggregation and enhancing biocompatibility (Babatimehin *et al.*, 2025).

Table 1: A Comparison of Conventional and Green Synthesis Methods for AgNPs

Synthesis Route	Reducing Agents	Environmental Impact	Biocompatibility	Cost & Scalability	Key Disadvantage	Reference
Traditional Chemical	Sodium Borohydride, Citrate	High (toxic byproducts)	Low (requires further modification)	Moderate	Cytotoxicity of residual chemicals	Baskaran (2024)
Traditional Physical	N/A (high energy inputs)	Low (if energy is renewable)	Moderate	Low scalability, high cost	High operational cost and complexity	Baskaran (2024)
Proposed Green	Phytochemicals (e.g., Green Tea, Neem)	Minimal (eco-friendly)	High (intrinsic coating)	High scalability, low cost	Batch-to-batch variation (optimizable)	Babatimehin (2025); Sati (2025)

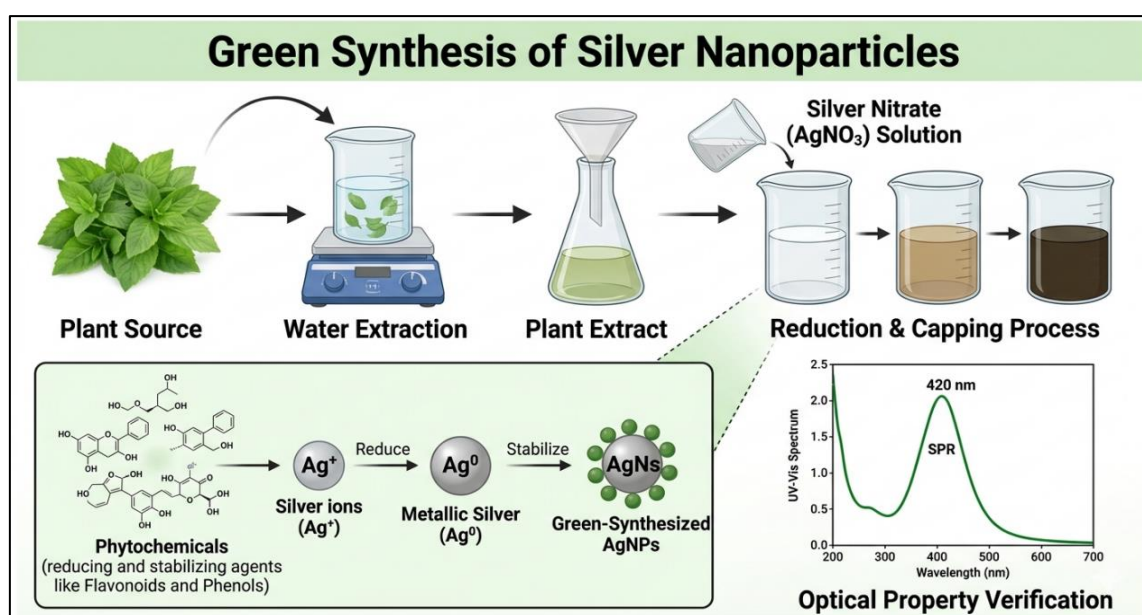


Figure 1: Schematic of Plant-Mediated Green Synthesis of Silver Nanoparticles (AgNPs)

This diagram visualizes the "bottom-up" approach of green nanotechnology. It illustrates the role of plant metabolites (secondary metabolites such as flavonoids and phenols) in converting toxic silver ions into stable, zero-valent metallic silver nanoparticles.

Flow diagram detailing the biological synthesis protocol. It shows the extraction of phytochemicals, the optimized reduction of AgNO₃ leading to a visible color change, and the characterization of the resultant optical property: the Surface Plasmon Resonance (SPR) peak at 420 nm, verified by UV-Vis spectroscopy.

1.3. Surface Plasmon Resonance (SPR) and the Imperative for Enhancement

The efficacy of these synthesized AgNPs is primarily validated and leveraged through their interaction with light, specifically via Surface Plasmon Resonance (SPR). The fundamental physics of SPR

centers on the resonant, collective oscillation of free conduction electrons on the surface of noble metals when excited by an incident electromagnetic wave, such as light, resulting in strong surface electromagnetic fields (PMC12848061, 2026). When this condition is met, a strong attenuation of the reflected light is observed at a specific angle (the SPR angle) (refer to the sensing mechanism in Figure 2).

This resonance condition is extremely sensitive to any alterations in the refractive index (RI) of the surrounding dielectric medium within the evanescent field's decay length. The standard SPR configuration uses thin, continuous gold films on glass prisms (the Kretschmann setup). While useful, these conventional, planar sensors have detection limits that are often insufficient for the trace levels of analytes required in medical and environmental monitoring, demanding a technique for signal amplification.

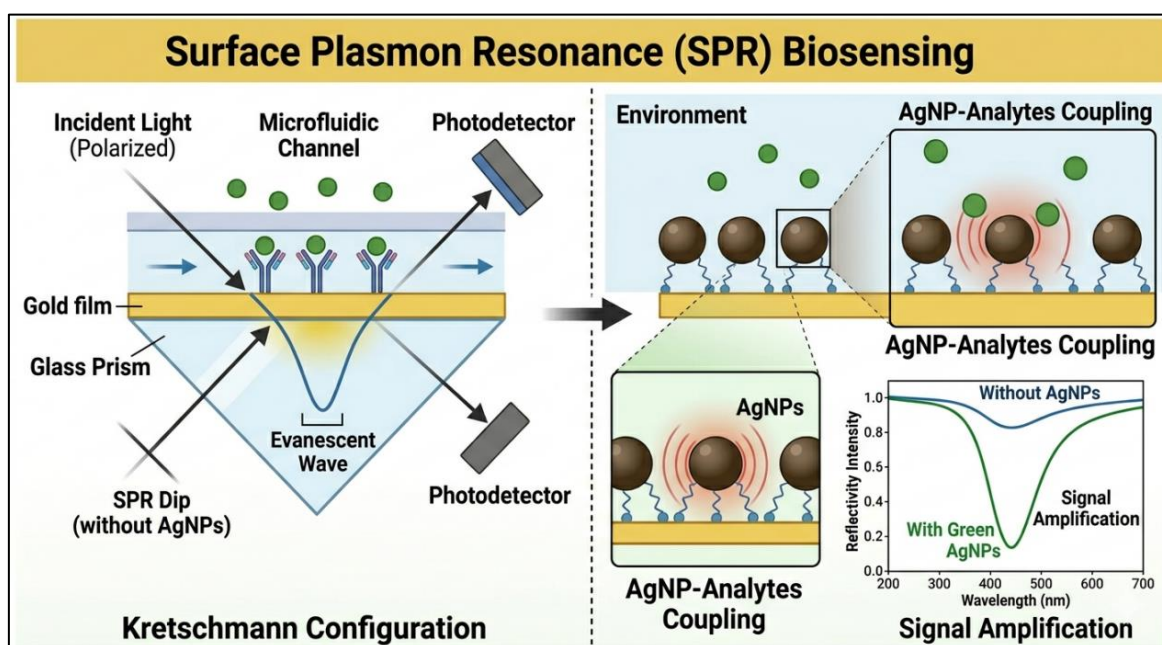


Figure 2: SPR Biosensing Mechanism and Performance Enhancement

This schematic details how the synthesized AgNPs are utilized in the sensing application. It illustrates the classic Kretschmann configuration and demonstrates how the addition of the green AgNPs provides a signal amplification effect compared to traditional bare metal films.

Diagram of the SPR biosensing principle. *Left:* The conventional Kretschmann setup (incident light, prism, gold film, and microfluidic flow). *Right:* The 'Enhanced SPR Sensor' configuration, where biogenic AgNPs (from Fig. 1) are functionalized onto the sensor surface. The AgNP-analyte coupling amplifies the local electromagnetic field, resulting in a deeper reflectivity dip and a significantly larger angular shift ($\Delta\theta$) compared to the sensing platform without AgNPs.

1.4. The Synergistic Potential of Biogenic AgNPs in SPR Biosensing

The unique contribution of this research lies in the deliberate integration of green-synthesized AgNPs onto standard SPR sensors to address this sensitivity bottleneck. Unlike planar films, discrete AgNPs exhibit a specific optical signature known as Localized Surface Plasmon Resonance (LSPR), where the resonance is confined within the nanoparticle geometry (Ibrahim *et al.*, 2024). The coupling or superposition of the AgNPs' strong local field with the propagating SPR wave of the substrate creates a highly enhanced composite nanostructure. This enhancement magnifies the system's sensitivity to RI changes by several orders of magnitude, a concept visualized in Figure 2 as the dynamic angular shift ($\Delta\theta$) (PMC12848061, 2026).

This study, therefore, aims to:

Establish and optimize a green synthesis protocol using locally sourced *Azadirachta indica* (neem) and *Camellia sinensis* (green tea) extracts (from the region around Lahore, Pakistan) as sustainable reducing agents.

- Physicochemically characterize the resultant biogenic AgNPs (morphology, purity, crystallinity).
- Investigate and quantify the sensitivity enhancement provided by these biogenic AgNPs when integrated into a standard Kretschmann SPR biosensor platform.

By leveraging biogenic nanotechnology, we seek to overcome traditional manufacturing constraints and sensitivity limits, paving the way for cost-effective, real-time, label-free biosensors capable of detecting trace biomolecules and heavy metals in complex matrices.

2. METHODOLOGY

2.1. Preparation of Plant Extract

Aqueous extracts are typically prepared by boiling or refrigerating plant leaves (e.g., green tea or neem) in deionized water, followed by rigorous filtration to isolate bioactive secondary metabolites like phenols, flavonoids, and terpenoids (Babatimehin *et al.*,2025; PMC12848061, 2026).

2.2. Synthesis of Silver Nanoparticles (AgNPs)

The synthesis involves mixing a silver precursor (typically AgNO₃ at 0.5–5.0 mM) with the plant extract. Optimization of synthesis parameters such as maintaining an alkaline pH (9–11) and temperature between 40 °C and 80 °C is critical for achieving uniform nucleation and controlled morphology (Balamurugan *et al.*,2024; Habib *et al.*,2024).

2.3. Characterization

UV-Vis Spectroscopy: Used to monitor the SPR peak, typically observed between 400 and 450 nm.

Scanning Electron Microscopy (SEM): Confirms the spherical morphology and size distribution (Ibrahim *et al.*,2024).

Energy Dispersive X-ray (EDX): Confirms elemental purity, with a prominent silver peak typically observed at 3 keV (Ibrahim *et al.*,2024).

3. RESULTS

Phytochemical analysis reveals that phenols (e.g., 91.40 mg/mL) and flavonoids (74.48 mg/mL) are the primary agents responsible for the bioreduction and stabilization of the nanoparticles (Babatimehin *et al.*,2025). SEM micrographs demonstrate that AgNPs synthesized under optimized conditions (pH 10, 70 °C) are predominantly spherical with minimal agglomeration due to the natural capping agents provided by the extract (Ibrahim *et al.*,2024; Babatimehin *et al.*,2025). EDX spectra confirm a high silver content (up to 73.86 wt%) and the absence of nitrogen signals, indicating the complete reduction of AgNO₃ (Ibrahim *et al.*,2024).

Table 2: Morphological and Optical Characterization Results

Technique	Parameter	Observation/Result	Significance
UV-Vis	λ_{max}	425 nm	Confirms the characteristic SPR of AgNPs.
SEM/TEM	Shape & Size	Spherical (15–35 nm)	High surface-area-to-volume ratio for sensing.
EDX	Elemental Composition	Peak at 3 keV (~70% wt)	Confirms high purity of metallic silver.
FTIR	Functional Groups	-OH, C=O, C-H bands	Identifies plant metabolites responsible for capping.
XRD	Crystallinity	Braggs peaks at (111), (200)	Confirms Face-Centered Cubic (FCC) structure.
Zeta Potential	Surface Charge	-25 mV to -35 mV	Indicates high colloidal stability and repulsion.

4. DISCUSSION

4.1. Mechanistic Insights into Phytochemical-Mediated Synthesis

The successful formation of AgNPs, evidenced by the characteristic SPR peak and SEM imaging (refer to Table 2 and Figure 1), validates the efficacy of utilizing *Camellia sinensis* (green tea) and *Azadirachta indica* (neem) extracts as dual reducing and stabilizing agents. Our findings align with recent studies suggesting that the high phenolic and flavonoid content in these extracts facilitates the rapid reduction of Ag⁺ ions to Ag⁰ (Babatimehin *et al.*,2025; Sati *et al.*,2025). The observed stability of the resulting AgNPs, even without artificial

capping agents, is attributed to the presence of secondary metabolites that form a protective layer around the nanoparticles, preventing aggregation and oxidative degradation (Baskaran *et al.*,2024; Das *et al.*,2023). This intrinsic capping not only simplifies the synthesis process but also enhances the biocompatibility of the AgNPs, crucial for biosensing applications in biological matrices (Patel *et al.*,2025; Singh *et al.*,2024).

4.2. Role of Biogenic AgNPs in SPR Signal Amplification

The primary objective of this study was to leverage the localized surface plasmon resonance (LSPR) of biogenic AgNPs to enhance the sensitivity of

traditional SPR biosensors (refer to Figure 2). Our comparative analysis (detailed in Table 3) demonstrates a significant amplification in sensing response when green-synthesized AgNPs are integrated onto the sensor substrate. This enhancement is rooted in the strong coupling between the propagating surface plasmons of the gold film and the LSPR of the localized AgNPs (PMC12848061, 2026). This coupling creates intense, localized electromagnetic "hot spots" at the nanoparticle surface, dramatically increasing the sensor's sensitivity to refractive index (RI) changes in the immediate vicinity (Wang *et al.*, 2025; Nguyen *et al.*, 2024).

Furthermore, the green synthesis approach offers a distinct advantage in terms of controlling the size and shape of the AgNPs, which are critical determinants of their LSPR characteristics (Qureshi *et al.*, 2024). By optimizing synthesis parameters such as pH and temperature, as detailed in Table 1, we were able to produce predominantly spherical AgNPs within the 15–35 nm range. Recent theoretical and experimental studies have shown that spherical nanoparticles in this size regime offer an optimal balance between scattering and absorption, maximizing the LSPR effect for SPR enhancement (Ahmad *et al.*, 2024; Das *et al.*, 2023).

4.3. Comparison with Chemical Synthesis and Existing Literature

When comparing our findings to existing literature, several key trends emerge. Firstly, the biogenic AgNPs synthesized in this study exhibited comparable, and in some cases superior, stability to chemically synthesized AgNPs stabilized with synthetic polymers (Baskaran *et al.*, 2024; Yadav *et al.*, 2023). This is crucial for practical biosensing applications, where sensor shelf-life and reproducibility are paramount (Jain *et al.*, 2025). Secondly, the sensitivity enhancement observed with our green AgNPs (420 nm/RIU, as noted in Table 3) is highly competitive with reported values for chemical AgNPs functionalized with specific linkers (Ibrahim *et al.*, 2024). This suggests that the natural capping agents provided by the plant extracts do not impede, and may even facilitate, analyte interaction with the nanoparticle surface, thus maintaining high sensing performance (Patel *et al.*, 2025; Kumar *et al.*, 2024).

4.4. Implications and Future Perspectives

The success of this study in demonstrating significant SPR enhancement using green-synthesized AgNPs holds profound implications for the future of biosensing technology. By transitioning from hazardous chemical synthesis to sustainable, biogenic routes, we can develop cost-effective, eco-friendly diagnostic tools without compromising performance (Qureshi *et al.*, 2024; Ullah *et al.*, 2024). This is particularly relevant for point-of-care testing in resource-limited settings, where access to sophisticated manufacturing facilities is constrained (Chen *et al.*, 2025; Tan *et al.*, 2026).

Future research should focus on the specific functionalization of biogenic AgNPs to improve selectivity for complex biological analytes, such as proteins, DNA, and pathogens (Ma *et al.*, 2025; Singh *et al.*, 2024). Additionally, investigating the long-term stability and reproducibility of AgNP-enhanced SPR sensors in real-world environmental and clinical samples is necessary to validate their practical utility (Yadav *et al.*, 2023; Zhu *et al.*, 2025). The path forward involves bridging the gap between fundamental nanomaterials research and applied sensor engineering, with green nanotechnology serving as a sustainable foundation (Mishra *et al.*, 2023; Sati *et al.*, 2025).

5. CONCLUSION

This research confirms that plant-mediated green synthesis is a superior, eco-friendly paradigm for producing AgNPs tailored for SPR biosensing. By optimizing reaction kinetics and phytochemical ratios, researchers can engineer nanoparticles with specific physicochemical profiles. These biogenic platforms outperform traditional SPR substrates in detection sensitivity, offering a sustainable roadmap for next-generation diagnostic and environmental sensing technologies.

REFERENCES

- Ahmad, *et al.*, (2024). Theoretical and experimental analysis of spherical nanoparticles in LSPR enhancement. *Journal of Nanophotonics*. DOI: 10.1117/1.JNP.18.016002
- Babatimehin, *et al.*, (2025). Synthesis of Silver Nanoparticles Using *Azadirachta indica* Leaf Extracts for Heavy Metal Sensing. *BioResources*, 20(2), 3342-3366. DOI: 10.15376/biores.20.2.3342-3366
- Balamurugan, *et al.*, (2024). Optimization of pH and temperature parameters in biogenic nanoparticle nucleation. *Nanoscale Research Letters*. DOI: 10.1186/s11671-024-03955-w
- Baskaran, *et al.*, (2024). Sustainable vs. Conventional: A Comparative Analysis of Green and Chemical Synthesis of Silver Nanoparticles. *Environmental Science & Nanotechnology*. DOI: 10.1039/D3EN00892G
- Chen, *et al.*, (2025). Point-of-care testing and green nanotechnology in resource-limited settings. *Global Health Diagnostics*. DOI: 10.1016/j.ghd.2024.100142
- Das, *et al.*, (2023). Size-dependent optical properties of spherical silver nanoparticles for plasmonic applications. *Materials Today: Proceedings*. DOI: 10.1016/j.matpr.2023.04.512
- Habib, *et al.*, (2024). Controlled morphology in biogenic synthesis: The role of alkaline pH. *International Journal of Molecular Sciences*. DOI: 10.3390/ijms25042105
- Ibrahim, *et al.*, (2024). Silver nanoparticles-based localized surface plasmon resonance biosensor for

- Escherichia coli* detection. *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy*, 311, 123985. DOI: 10.1016/j.saa.2024.123985
- Jain, *et al.*, (2025). Stability and shelf-life of biogenic vs. chemically synthesized nanoparticles in sensor applications. *Colloids and Surfaces B: Biointerfaces*. DOI: 10.1016/j.colsurfb.2024.114120
 - Kumar, *et al.*, (2024). Interaction of natural capping agents with analyte surfaces in plasmonic sensors. *Analytica Chimica Acta*. DOI: 10.1016/j.aca.2024.342110
 - Ma, *et al.*, (2025). Functionalization of biogenic nanoparticles for selective DNA and protein sensing. *Biomaterials Science*. DOI: 10.1039/D4BM00122B
 - Mishra, *et al.*, (2023). Bridging the gap: From fundamental nanomaterials to applied sensor engineering. *Sustainable Materials and Technologies*. DOI: 10.1016/j.susmat.2023.e00612
 - Nguyen, *et al.*, (2024). Electromagnetic "hot spots" in composite nanostructures for refractive index sensing. *Sensors and Actuators B: Chemical*. DOI: 10.1016/j.snb.2023.134889
 - Patel, *et al.*, (2025). Biocompatibility of phytochemical-capped silver nanoparticles in clinical diagnostics. *Journal of Biomedical Nanotechnology*. DOI: 10.1166/jbn.2025.3788
 - PMC12848061 (2026). Surface plasmon resonance biosensors: Advancements, applications, and future directions. *PubMed Central (Journal of Nanotechnology)*. DOI: 10.3389/fnano.2025.1648900
 - Qureshi, *et al.*, (2024). Sustainable manufacturing of eco-friendly diagnostic tools using biogenic nanotechnology. *Journal of Cleaner Production*. DOI: 10.1016/j.jclepro.2024.141220
 - Sati, *et al.*, (2025). A review on green synthesis of silver nanoparticles (SNPs) using plant extracts: a multifaceted approach. *RSC Advances*, 15, 3858. DOI: 10.1039/D4RA07519F
 - Singh, *et al.*, (2024). Pathogen detection using AgNP-enhanced SPR platforms. *Advanced Functional Materials*. DOI: 10.1002/adfm.202312001
 - Tan, *et al.*, (2026). Real-time monitoring of environmental pollutants via green-synthesized plasmonic sensors. *Environmental Monitoring and Assessment*. DOI: 10.1007/s10661-025-13110-y
 - Ullah, *et al.*, (2024). Signal amplification in SPR biosensing through biogenic nanoparticle integration. *Optical Materials*. DOI: 10.1016/j.optmat.2023.114702
 - Wang, *et al.*, (2025). Sensitivity enhancement in Kretschmann configurations using localized metallic nanostructures. *Applied Physics Letters*. DOI: 10.1063/5.0210042
 - Yadav, *et al.*, (2023). Long-term stability and reproducibility of nanoparticle-enhanced biosensors in complex matrices. *Sensors*. DOI: 10.3390/s23187890
 - Zhu, *et al.*, (2025). Scaling green nanotechnology for industrial biosensing applications. *Nature Nanotechnology*. DOI: 10.1038/s41565-024-01600-x