IJERST

International Journal of Engineering Research and Science & Technology

www.ijerst.org

ISSN : 2319-5991

Vol. 22 No. 2(1) (2026)

ijerst.editor@gmail.com

editor@ijerst.com

ISSN 2319-5991 www.ijerst.com

Peer Reviewed, Referred & Indexed Journal

Research Paper

Surface Plasmon Resonance in Metal Nanoparticles for Photothermal Applications

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Abstract: The research investigates the mechanics and uses of Surface Plasmon Resonance (SPR) in metallic nanoparticles for photothermal purposes. The objective is to investigate the photothermal conversion process of plasmonic nanomaterials and to assess their applications in the biomedical, energy and environmental sectors. This includes basic principles of SPR, nanoparticle synthesis strategies, characterization, and performance in various applications. This involves a review of theoretical models (Mie theory, Drude model) and comparative studies of chemical and physical synthesis methods and characterization techniques. The results reveal that nanoparticle size, shape, composition and the surrounding dielectric environment play a critical role in SPR and photothermal efficiency. Further, hybrid and core–shell nanostructures improve optical absorption and photothermal efficiency. The findings show that SPR-based photothermal systems are highly efficient for cancer photothermal therapy, solar energy harvesting, pollutant removal and biosensing. But stability, toxicity and scalability are key challenges. In conclusion, the research underscores the need to engineer nanoparticle design and synthesis for high-performance, multifunctional photothermal systems for emerging technologies.

1. Introduction

Nanoplasmonics is a high-level interdisciplinary science, combining the principles of optics, nanotechnology and materials science, to examine the interaction of electromagnetic radiation and free electrons at the nanoscale. In its most basic form, plasmonics deals with the excitation of collective oscillations of conduction electrons, which are called plasmons, in response to light interacting with metallic nanostructures (Sukmanee et al., 2023). In comparison to traditional optics, nanoscale optics allows confinement of light to lengths smaller than the diffraction limit, and offers the ability to manipulate electromagnetic fields with dimensions much smaller than the wavelength of light. This ability enables increased light-matter interactions, which has resulted in important contributions to subwavelength imaging, optical sensing, and nanoscale energy transfer (Ou et al., 2021). Nanoplasmonic systems are highly tuneable to a wide variety of applications due to their unique optical properties that are a result of size, shape, and the local environment. Surface Plasmon Resonance (SPR) is a fundamental concept in plasmonics, whereby conduction electrons in a metal-dielectric interface resonate to the incidence of light. This resonance happens at certain wavelengths, and is very sensitive to alterations in the refractive index of the medium around it. The two main types of SPR are propagating surface plasmons (on thin films) and localized surface plasmon resonance (LSPR) in nanoparticles. The importance of SPR is that it enhances the electromagnetic fields around the metal surface, thereby providing the capacity to detect the molecular interactions with ultrasensitivity. As a result, SPR has become a cornerstone in biosensing, chemical detection, and optical diagnostics (Kesharwani et al., 2023).

The metals nanoparticles are of importance in nanoplasmonics because they have strong plasmonic responses. The most common materials studied among them are gold (Au), silver (Ag), and copper (Cu). Gold nanoparticles are biocompatible, highly stable and can be tuned to have optical properties that make them useful in biomedical applications. Silver nanoparticles have the best plasmonic enhancement and find wide applications in sensing and spectroscopy, but are less chemically stable. Copper nanoparticles are a cheaper alternative and have good plasmonic performance, but are subject to oxidation. The size, shape and dielectric environment of these nanoparticles can be manipulated to provide control over the optical behavior of such nanoparticles, allowing the precise fabrication of plasmonic devices (Huang et al., 2022). Nanoplasmonic materials have become quite popular in photothermal applications because they can effectively convert the absorbed light into heat. Plasmonic nanoparticles have been used in biomedical therapy, especially in cancer treatment, as photothermal therapy (PTT), where local heating destroys malignant cells by selectively heating them. These materials are used in solar energy systems to increase light absorption and efficiency of solar thermal conversion. Also, plasmonic sensing platforms use temperature sensitive optical property variations to sense biological and chemical species. The application of nanoplasmonics to photothermal applications can therefore be considered to hold bright futures in energy, healthcare and environmental monitoring applications (Dement'eva & Kartseva, 2023).

2. Fundamentals of Surface Plasmon Resonance

Surface Plasmon Resonance (SPR) is a collective oscillation of free electrons in metallic structures in the presence of incident electromagnetic radiation. It can be broadly divided into Localized Surface Plasmon Resonance (LSPR) and Propagating Surface Plasmon Resonance (PSPR). LSPR can be found in metallic nanoparticles in which electrons vibrate locally within the particles and cause a high degree of confinement of an electromagnetic field around the particles. It is very sensitive to the particle size and the medium around it and thus can be used in sensing and imaging. Propagating SPR, on the other hand, takes place on long metal dielectric interfaces, like thin films, where surface plasmon waves propagate along the interface. PSPR is popular in optical biosensors because it is sensitive to changes in refractive index (Kesharwani et al., 2023).

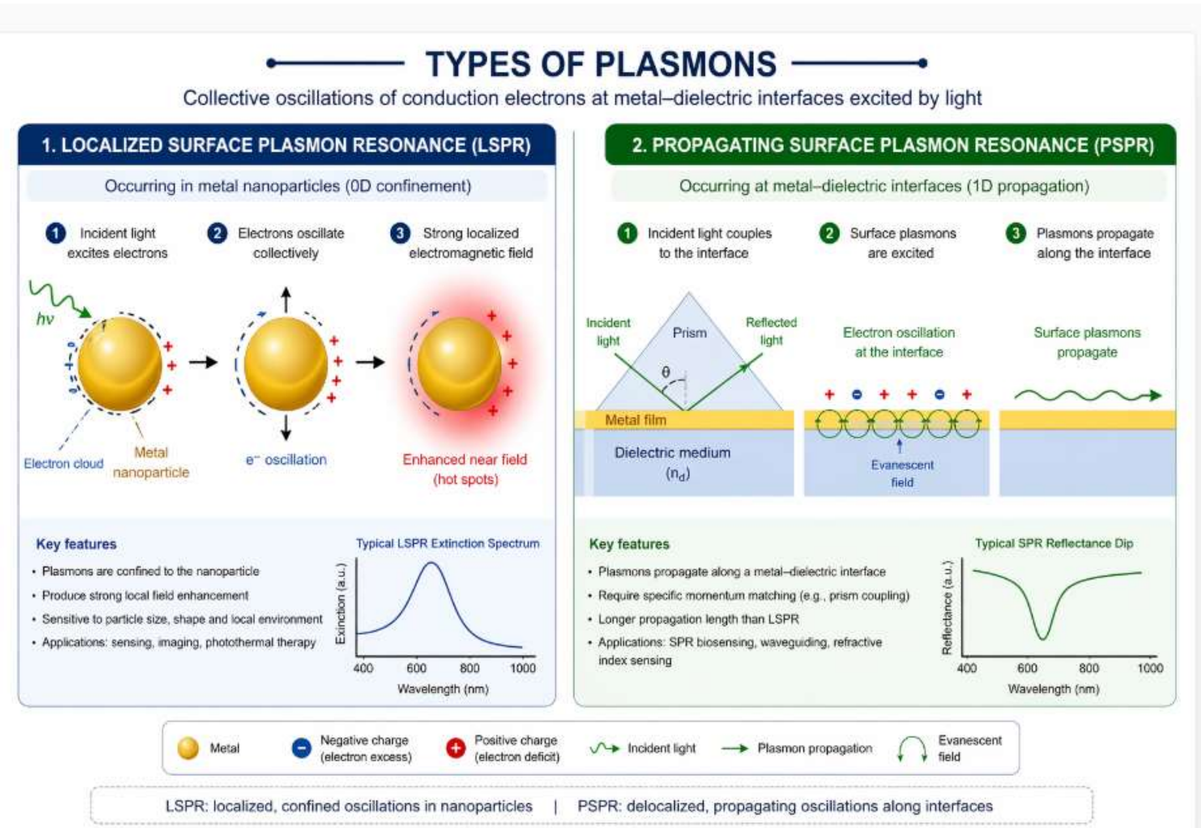

Figure 1. LSPR and PSPR Mechanisms

The fundamental distinction between localized and propagating plasmons is illustrated in Figure 1, where the confinement of electron oscillations in nanoparticles (LSPR) and their propagation along metal–dielectric interfaces (PSPR) are schematically compared to highlight differences in field distribution, resonance behavior, and application domains. Plasmonic interactions produce the characteristic optical properties of metal nanoparticles. These properties are absorption, scattering and extinction. Absorption is the transformation of incident light to other types of energy usually in the form of heat which is pivotal in photothermal applications. Scattering is a light diversion process that improves the image and sensing systems by increasing their visibility. The absorption and scattering are referred to as the extinction, which is the total loss of the incident light. These are highly wavelength-sensitive and can be manipulated by changing the properties of nanoparticles.

There are a number of parameters affecting SPR behavior. Resonance wavelength and intensity depend on size and shape of nanoparticles; e.g. anisotropic shapes like rods or prisms have multiple resonance modes. The composition is also a factor, with various metals having varying electron densities, damping characteristics. Conditions of resonance in the dielectric environment of the nanoparticle are strongly influenced, which forms the foundation of refractive index sensing (Abith & Girisun, 2024). Also, the distance between particles affects plasmon coupling: closely spaced particles may exhibit amplified electromagnetic fields through near-field coupling, called hot spots. The Mie Theory and the Drude Model are examples of theoretical models that support the understanding of SPR. Using Mie Theory, the precision of the analytical solution to light scattering and light absorption in spherical nanoparticles, the optical response of nanoparticles varies with size. The Drude Model is a model of the behavior of free electrons in metals, which relates optical properties with electrical conductivity. The combination of these models lies at the basis of predicting and optimization of plasmonic processes in nanostructures (Tiburski & Langhammer, 2023).

The most common method of metal nanoparticles production is chemical synthesis because of its simplicity, scalability, and cost-effectiveness. The reduction method is the most widespread in which the chemical reducing agents, e.g., sodium borohydride, citrate, or ascorbic acid, reduce the metal ions (e.g., Ag^+, Au^+). To reduce aggregation and regulate the growth of the particles, stabilizing or capping agents are usually included. Nanoparticles of specific sizes and shapes are realized by modulating parameters like pH, temperature and concentration of reactants (Mal et al., 2024). The use of chemical techniques is especially beneficial in the creation of uniform and monodisperse nanoparticles. Synthesis of metal nanoparticles by chemical methods includes numerous reduction-based methods which vary in terms of reaction mechanisms, reagents, and reaction conditions. These techniques facilitate the accurate regulation of particle size, morphology and the stability of dispersion. Table 1 gives a comparative overview of the most important methods of chemical synthesis, their representative reactions and properties.

Table 1. Chemical Methods for Synthesis of Metal Nanoparticles

Method	**Representative Reaction / Formula**	**Reducing Agent**	**Stabilizing Agent**	**Key Features**	**Advantages**	**Limitations**	**Reference**
Chemical Reduction	$Au^{3+} + 3e^- \rightarrow Au^0$ (e.g., $HAuCl_4 + NaBH_4 \rightarrow Au$ + byproducts)	$NaBH_4$, Citrate	Citrate, PVP, CTAB	Reduction of metal ions in solution	Simple, scalable	Residual chemicals possible	(Szczyglewska et al., 2023; Jamkhande et al., 2019; Marinescu et al., 2020; Zahoor et al., 2021)
Seed-Mediated Growth	Au^0 (seed) + $Au^{3+} + e^- \rightarrow Au$ (growth on seed surface)	Ascorbic acid	CTAB	Controlled nucleation and anisotropic growth	Precise size/shape control	Multi-step synthesis	(He et al., 2023; Capek, 2017; Malassis et al., 2016)
Polyol Method	$M^{n+} + e^- \rightarrow M^0$ (Ethylene	Ethylene glycol	PVP	Solvent acts as	Uniform particles	Requires high	(Fiévet et al., 2018; Reverberi et

	glycol: HO–CH_2–CH_2–OH → oxidized products + e^-)			reducing agent		temperature	al., 2016; Marinescu et al., 2020)
Microemulsion Method	M^{n+} + Reducing agent → M^0 (within micelles acting as nanoreactors)	$NaBH_4$, Hydrazine	Surfactants	Reaction confined in nanoscale droplets	Narrow size distribution	Complex purification	(Marinescu et al., 2020; Zahoor et al., 2021)
Sol–Gel Method	M–OR + H_2O → M–OH → M–O–M (gel network formation)	Alcohol-based reducers	Organic stabilizers	Hydrolysis and condensation reactions	Good compositional control	Time-consuming	(Parashar et al., 2020; Nikam et al., 2018; Alhalili, 2023)

Chemical synthesis methods provide a lot of flexibility in regulating the properties of nanoparticles by means of controlled reaction pathways and stabilizing strategies as seen in Table 1. To reduce functional impurities, the choice of the right reducing and capping agents is also important in order to achieve acceptable functional functionality.

Physical techniques are the top-down production of nanoparticles using bulk materials without any chemical reagents. Laser ablation and thermal evaporation are among the techniques that have been used. In laser ablation, a laser pulse of high energy is focused on a metal target in a liquid or gas medium to produce nanoparticles by vaporizing and condensing the material. Evaporation techniques entail heating the metals in the vacuum until they evaporate and then condense back to nanoscale particles (M. et al., 2025). These methods are very pure and less contaminated but are usually demanding with a complex equipment and increased energy. Unlike chemical techniques, physical techniques use top-down or energy-driven reactions to produce nanoparticles out of bulk materials (Singaravelu et al., 2025). The processes are controlled by several basic physics phenomena and generally yield high-purity nanoparticles, with no chemical impurities. Table 2 lists the key physical synthesis techniques and their equations of state.

Table 2. Physical Methods for Synthesis of Metal Nanoparticles

Method	Governing Formula / Principle	Medium Used	Key Features	Advantages	Limitations	Reference
Laser Ablation	$E = h\nu$ (Photon energy drives ablation); $\Delta T \propto$ Laser fluence	Liquid / Gas	Laser-induced vaporization and condensation	High purity, no chemicals	High cost, low yield	(Jiang et al., 2022; Krishna Podagatlapalli, 2025;
Thermal Evaporation	Rate $\propto \exp(-\Delta H\_vap / RT)$ (Clausius–Clapeyron	Vacuum / Inert gas	Metal vaporization followed by nucleation	High-quality nanoparticles	High energy requirement	(Muthukrishnan et al., 2025; Alhalili, 2023)

	relation)					
Arc Discharge	I^2R heating → T↑ (Joule heating principle)	Inert gas	High-temperature plasma vaporizes metal	Rapid synthesis	Poor size control	(Dhand et al., 2015; Tavakoli et al., 2007)
Ball Milling	$E_k = (1/2)mv^2$ (Mechanical energy induces particle size reduction)	Solid-state	Mechanical fragmentation	Simple and scalable	Broad size distribution	(Rane et al., 2018; Dhand et al., 2015)
Sputtering	$Y \propto (E_i - E_{th})$ (Sputtering yield depends on ion energy)	Vacuum	Plasma ions eject atoms from target	High purity, controlled deposition	Requires vacuum setup	(Muthukrishnan et al., 2025; Nyabadza et al., 2023)

Table 2 indicates that physical methods of synthesis are beneficial in the manufacture of clean nanoparticles that have controlled composition. They are, however, frequently restricted in their practical use by excessive power requirements, equipment complexity, and difficulties in obtaining uniform size distribution. Green synthesis is an alternative to the conventional method that is environmentally friendly by using biological agents like plant extracts, bacteria, fungi, or algae as reducing and stabilizing agents. These environmentally-friendly methods do not require the use of toxic chemicals or severe conditions, so they could be applied in the biomedical and environmental contexts. Phytochemicals that are found in plant extract, flavonoids and phenolics are important in reducing metal ions and stabilizing nanoparticles. Green synthesis is environmentally friendly, economical and complies with the tenets of green chemistry. The optical and plasmonic properties of nanoparticles can only be tuned by controlling their size and morphology (Hamida et al., 2025). Depending on a careful adjustment of reaction conditions, surfactants, and templates, it is possible to produce different nanostructures, including nanorods, nanoshells, and nanostars. An example is nanorods, which possess anisotropic properties with multiple plasmon resonance modes, and nanoshells with tunable optical response depending on core and shell size. Nanostars have sharp ends that form high localized electromagnetic fields. Accurate manipulation of these structures allows optimization to be used in sensing, imaging and photothermal therapy. The photothermal effect in plasmonic nanomaterials starts with the interaction of light with metallic nanoparticles. Incident photons of certain energies generate collective oscillations of conduction electrons, called plasmons, on the surface of the nanoparticle. This happens when the photon frequency is equal to the natural frequency of the electron oscillations, leading to effective absorption of electromagnetic waves (Arellano-Galindo et al., 2022).

The strength of this process is governed by the size, shape and material of the nanoparticles, which affects the resonance wavelength. Localized Surface Plasmon Resonance (LSPR) results in a high increase of the electromagnetic field on the surface of the nanoparticle, enhancing light absorption and allowing for effective energy transfer on the nanoscale. Once a plasmon is excited, the energy from incident light is quickly transferred to heat energy via relaxation processes. The most common pathway is non-radiative decay of the excited plasmon. This process creates "hot" electrons, and these electrons then scatter with each other, transferring energy between electrons within femtoseconds (Jiao et al., 2024). These "hot" electrons then dissipate energy to the lattice via electron-phonon interactions, causing lattice vibrations and thermal energy. Heat then dissipates to the medium through phonon–phonon interactions. This complex process underpins efficient conversion of optical energy to heat, enabling photothermal applications like cancer treatment and solar thermal energy collection. Photothermal conversion efficiency depends on a number of factors. The choice of material is important because metals such as gold and silver have high plasmonic absorption due to their free electron concentrations. The size and shape of nanoparticles influence the relative contributions of absorption and scattering; smaller particles promote absorption, leading to increased heat production (Yoo et al., 2022). Dielectric medium affects the resonance conditions, affecting energy absorption efficiency. Moreover, spectral matching between the incident light and plasmon resonance peak is crucial for energy conversion efficiency. Surface coatings, aggregation and inter-particle interactions can also increase or decrease efficiency through modulation of electromagnetic fields. In summary, fine-tuning these factors is crucial for developing efficient photothermal systems for biomedical, environmental and energy technologies (Campu et al., 2024).

3. Characterization Techniques

The structural characterization is necessary in order to interpret the morphology, size, crystallinity, and surface characteristics of metal nanoparticles. Transmission Electron Microscopy (TEM) is a high-resolution imaging technique that can be used to determine the size, shape, and internal structure of particles at the nanoscale. It is especially applicable in the determination of morphology like nanorods, nanostars, and core shells. SEM is a technique that is used to complement TEM and provide a detailed surface topology and distribution of particles, particularly of aggregated or bulk samples. X-ray Diffraction (XRD) is used to identify the crystalline structure and phase composition of nanoparticles. It also allows the determination of crystallite size by the Debye-Scherrer equation, which proves the presence of metallic phases and detects any impurities or oxides.The optical properties of plasmonic nanoparticles are commonly studied with the help of UV Vis Spectroscopy (UV Vis) that is essential in the investigation of Surface Plasmon Resonance (SPR). The magnitude, shape, and size of the particles can be learned using the SPR peak position, intensity, and width. An example of this is that a red shift of the SPR peak is commonly a signal of increased particle size or aggregation whereas a blue shift indicates smaller dimensions of the particles (Li et al., 2021). The broadening of the peaks can be an indication of polydispersity or surface interactions. The popularity of UV Vis analysis is based on its simplicity, quickness of measurement and its capability to track the production of nanoparticles in real time. Thermal Characterization involves assessing the photothermal activity of nanoparticles. Photothermal efficiency measurements Photothermal efficiency measurements are performed by illuminating suspensions of nanoparticles with a light source (usually a laser) and recording the temperature change with time. The efficiency is calculated by comparing the rates of heat generation and dissipation typically through energy balance equations. Performance is determined by parameters like maximum temperature increase, heating rate, and cooling profile. This discussion is essential to applications such as photothermal therapy and solar energy conversion, which demand the efficient conversion of light to heat. These characterization methods together help to gain a complete picture of the properties of the nanoparticles and their functional performance (Pini et al., 2022).

4. Applications of SPR-Based Photothermal Systems

Photothermal systems based on SPR have found great relevance in biomedical applications, especially in cancer photothermal therapy (PTT). This method involves the delivery of plasmonic nanoparticles, namely gold nanorods or nanoshells, into the tumor tissues and excitation by near-infrared (NIR) light. These nanoparticles have high SPR absorption, thus efficiently converting light into heat, and thereby triggering localized temperature increases targeting the destruction of cancer cells with limited activity on healthy tissues. Moreover, SPR-active nanoparticles find extensive applications in drug delivery systems, serving as vectors of therapeutic agents. Controlled drug release that is induced by the heat created in the process of photothermal effects can be used to increase treatment efficiency and minimize side effects in the system. Photothermal materials based on SPR are very important in solar thermal conversion in the energy sector. Plasmonic nanoparticles are able to increase light absorption in a wide spectral range, which enhances solar collector efficiency and photothermal devices. These systems are able to change solar radiation into heat that can be used as electricity or stored as thermal power (Tiburski & Langhammer, 2023). In addition to that, the implementation of SPR-based systems can be utilized in the water purification area, where localized heating provided by plasmonic materials can be used to achieve efficient solar-driven desalination and evaporation. The method is sustainable and energy efficient as it can be used in generating pure water especially in areas where resources are scarce. Photothermal systems based on SPR can also be used in the degradation of pollutants. Localized heating of plasmonic nanoparticles speeds up chemical reactions and increased catalytic efficiency, which makes it possible to treat organic pollutants, including dyes, pharmaceuticals, and industrial pollutants. Photothermal effects are synergistic with photocatalysis in certain systems, leading to enhanced reaction kinetics and efficiency of degradation. This renders SPR-based materials very promising in wastewater treatment and environmental clean-up (Zhang et al., 2021). The optical and thermal peculiarities of SPR-active nanoparticles render it suitable to be used in biosensing and imaging. The detection of biomolecules, pathogens or chemical analytes in biosensors can be detected with high sensitivity by changes in SPR signals caused by molecular interactions. Also in biomedical imaging, plasmonic nanoparticles have been used as contrast agents, as they have good light absorption and scattering capabilities. A combination with photothermal effects allows the use of advanced imaging modalities and real-time tracking of biological processes using these nanoparticles. Altogether, SPR-based photothermal systems are versatile and high-performance in healthcare, energy, environmental, and sensing fields (Yoo et al., 2022).

5. Recent Advances and Research Trends

The advancement in SPR-based photothermal systems has revolved around enhancing the performance through material innovation. Bimetallic nanostructures, such as metal-semiconductor and metal-polymer hybrids, have shown improved absorption and stability through hybridisation. Core-shell structures like Au@SiO_2 and Au@Ag nanoparticles allow greater control over optical properties and plasmon resonance, resulting in enhanced photothermal efficiency (Chavda et al., 2023). Furthermore, AI-driven nanoparticle design, employing machine learning to predict the best sizes, shapes, and compositions for specific applications, allows for accelerated and cost-effective experimentation. Finally, there is a focus on improving photothermal performance by designing anisotropic nanoparticles and controlling inter-particle interactions. These innovations are helping with energy conversion efficiency, stability and versatility, enhancing the use of plasmonic systems for biomedical, environmental and energy applications (Smolková et al., 2023; Yoo et al., 2022).

6. Challenges and Limitations

While considerable advances have been made, various factors limit the use of SPR-based photothermal systems. A key challenge is stability and aggregation, where nanoparticles aggregate over time, affecting their optical properties and consistency. Toxicity, especially of silver (Ag) and copper (Cu) nanoparticles, restricts their biomedical applications because of the potential for harmful biological consequences. The expenses associated with using noble metals like gold limit their widespread use. Additionally, large-scale production for industrial applications is a crucial consideration, as it is challenging to retain consistent particle size, shape and performance. Optical and thermal properties may vary due to changes in synthesis parameters. To overcome these challenges, stable, biocompatible and low-cost nanoparticles together with scalable synthesis methods are needed (George et al., 2022; Zamora-Perez et al., 2021).

7. Future Perspectives

The next frontier of SPR-based photothermal research will involve green nanomaterials, such as environmentally-friendly and cost-effective substitutes for precious metals. Multifunctional nanoparticles that can sense, image and treat will also enhance utility. Coupling with intelligent systems, including AI-based platforms and smart materials, will allow for real-time monitoring and optimization of photothermal applications. Furthermore, the focus on clinical translation and commercialization will prioritise safety, scalability and regulatory considerations. These innovations will help translate research from the lab bench to practical applications in health care, energy, and environmental applications.

Conclusion

This study offers a detailed review of Surface Plasmon Resonance (SPR) in metal nanoparticles for photothermal applications. The research shows that SPR is a valuable mechanism for efficient photothermal conversion through plasmon excitation and non-radiative relaxation. The study confirms that factors like size, shape, composition and surrounding dielectric medium significantly influence optical and thermal characteristics. Different synthesis techniques, such as chemical, physical, and green synthesis, allow flexibility in nanoparticle design, while state-of-the-art characterization techniques enable accurate measurement of structural, optical and thermal properties. Biomedical therapy (cancer photothermal treatment), solar energy conversion, water purification and environmental purification are some of the applications of SPR-based systems. Despite such developments, challenges include nanoparticle stability, toxicity, cost of material, and scalability. Sustainable materials, multifunctional nanostructures and smart system integration are likely to overcome these challenges in future. In conclusion, SPR-based photothermal systems have great potential for practical use, as long as research continues to address the challenges of translating nanotechnology innovations from the lab bench to commercial production.

References

1. Abith, M., & Girisun, T. C. S. (2024). Localized surface plasmon resonance induced nonlinear absorption and optical limiting activity of gold decorated graphene/MoS2 hybrid. *Carbon Trends*, *17*(100417), 100417. https://doi.org/10.1016/j.cartre.2024.100417
2. Arellano-Galindo, L., Villar-Alvarez, E., Varela, A., Figueroa, V., Fernandez-Vega, J., Cambón, A., Prieto, G., Barbosa, S., & Taboada, P. (2022). Hybrid gold nanorod-based nanoplatform with chemo and photothermal activities for bimodal cancer therapy. *International Journal of Molecular Sciences*, *23*(21), 13109. https://doi.org/10.3390/ijms232113109
3. Campu, A., Muresan, I., Potara, M., Lazar, D. R., Lazar, F.-L., Cainap, S., Olinic, D. M., Maniu, D., Astilean, S., & Focsan, M. (2024). Portable microfluidic plasmonic chip for fast real-time cardiac troponin I biomarker thermoplasmonic detection. *Journal of Materials Chemistry. B, Materials for Biology and Medicine*, *12*(4), 962–972. https://doi.org/10.1039/d3tb02190d
4. Chavda, V. P., Balar, P. C., & Patel, S. B. (2023). Nanotheranostics-based management of Head and neck cancer. *Nanotheranostics*, *7*(2), 202–209. https://doi.org/10.7150/ntno.81724
5. Dement'eva, O. V., & Kartseva, M. E. (2023). Noble metal nanoparticles in biomedical thermoplasmonics. *Colloid Journal*, *85*(4), 500–519. https://doi.org/10.1134/s1061933x23700187
6. George, B. P., Chota, A., Sarbadhikary, P., & Abrahamse, H. (2022). Fundamentals and applications of metal nanoparticle- enhanced singlet oxygen generation for improved cancer photodynamic therapy. *Frontiers in Chemistry*, *10*, 964674. https://doi.org/10.3389/fchem.2022.964674
7. Hamida, R. S., Sotoma, S., Kah, J. C. Y., Harada, Y., & Suzuki, M. (2025). Microalgae-mediated synthesis of functionalized gold nanoparticles with high photothermal stability. *ACS Sustainable Chemistry & Engineering*, *13*(45), 19599–19612. https://doi.org/10.1021/acssuschemeng.5c07786
8. Huang, X., Mahmudul, H. M., Li, Z., Deng, X., Su, X., Xiao, Z., Zhao, L., Liu, T., & Li, H. (2022). Noble metal nanomaterials for the diagnosis and treatment of hematological malignancies. *Frontiers in Bioscience (Landmark Edition)*, *27*(2), 40. https://doi.org/10.31083/j.fbl2702040
9. Jiao, S., Dai, K., Besteiro, L. V., Gao, H., Chen, X., Wang, W., Zhang, Y., Liu, C., Pérez-Juste, I., Pérez-Juste, J., Pastoriza-Santos, I., & Zheng, G. (2024). Differentiating plasmon-enhanced chemical reactions on AgPd hollow nanoplates through surface-enhanced Raman spectroscopy. *ACS Catalysis*, *14*(9), 6799–6806. https://doi.org/10.1021/acscatal.3c06253
10. Kesharwani, P., Ma, R., Sang, L., Fatima, M., Sheikh, A., Abourehab, M. A. S., Gupta, N., Chen, Z.-S., & Zhou, Y. (2023). Gold nanoparticles and gold nanorods in the landscape of cancer therapy. *Molecular Cancer*, *22*(1), 98. https://doi.org/10.1186/s12943-023-01798-8
11. Li, Y., Song, W., Hu, Y., Xia, Y., Li, Z., Lu, Y., & Shen, Y. (2021). "Petal-like" size-tunable gold wrapped immunoliposome to enhance tumor deep penetration for multimodal guided two-step strategy. *Journal of Nanobiotechnology*, *19*(1), 293. https://doi.org/10.1186/s12951-021-01004-1
12. M., S., Shetty, S. J., Bhat, S. S., Gummagol, N. B., Surabhi, S., Jeong, J.-R., & S., G. (2025). Nonlinear optical and power limiting characteristics of noble metal decorated reduced graphene oxide and Ti3C2 MXene. *Carbon*, *235*(120025), 120025. https://doi.org/10.1016/j.carbon.2025.120025
13. Mal, S., Chakraborty, S., Mahapatra, M., Pakeeraiah, K., Das, S., Paidesetty, S. K., & Roy, P. (2024). Tackling breast cancer with gold nanoparticles: twinning synthesis and particle engineering with efficacy. *Nanoscale Advances*, *6*(11), 2766–2812. https://doi.org/10.1039/d3na00988b
14. Ou, X., Liu, Y., Zhang, M., Hua, L., & Zhan, S. (2021). Plasmonic gold nanostructures for biosensing and bioimaging. *Mikrochimica Acta*, *188*(9), 304. https://doi.org/10.1007/s00604-021-04964-1
15. Pini, F., Pilot, R., Ischia, G., Agnoli, S., & Amendola, V. (2022). Au-Ag alloy nanocorals with optimal broadband absorption for sunlight-driven thermoplasmonic applications. *ACS Applied Materials & Interfaces*, *14*(25), 28924–28935. https://doi.org/10.1021/acsami.2c05983
16. Singaravelu, S., Motsoene, F., Abrahamse, H., & Dhilip Kumar, S. S. (2025). Green-synthesized metal nanoparticles: a promising approach for accelerated wound healing. *Frontiers in Bioengineering and Biotechnology*, *13*, 1637589. https://doi.org/10.3389/fbioe.2025.1637589
17. Smolková, R., Mariychuk, R., Iľkovič, S., Grishchenko, L. M., & Lisnyak, V. V. (2023). Green synthesis of gold nanoparticles using peppermint extract for potential plasmonic photothermal therapy. *NANOCON Conference Proeedings*.
18. Sukmanee, T., Szuster, M., Gorski, A., Hołdyński, M., & Gawinkowski, S. (2023). Tunable-wavelength nanosecond laser tailoring of plasmon resonance spectra of gold nanoparticle colloids. *Nanoscale Advances*, *5*(14), 3697–3704. https://doi.org/10.1039/d3na00225j
19. Tiburski, C., & Langhammer, C. (2023). Engineering optical absorption in late transition-metal nanoparticles by alloying. *ACS Photonics*, *10*(1), 253–264. https://doi.org/10.1021/acsphotonics.2c01597

20. Wei, Q., He, J., Wang, S., Hua, S., Qi, Y., Li, F., Ling, D., & Zhou, M. (2021). Low-dose X-ray enhanced tumor accumulation of theranostic nanoparticles for high-performance bimodal imaging-guided photothermal therapy. *Journal of Nanobiotechnology*, *19*(1), 155. https://doi.org/10.1186/s12951-021-00875-8
21. Yoo, S., Yoon, S.-W., Jung, W.-N., Chung, M. H., Kim, H., Jeong, H., & Yoo, K.-H. (2022). Photothermal inactivation of universal viral particles by localized surface plasmon resonance mediated heating filter membrane. *Scientific Reports*, *12*(1), 1724. https://doi.org/10.1038/s41598-022-05738-2
22. Zamora-Perez, P., Pelaz, B., Tsoutsi, D., Soliman, M. G., Parak, W. J., & Rivera-Gil, P. (2021). Hyperspectral-enhanced dark field analysis of individual and collective photo-responsive gold-copper sulfide nanoparticles. *Nanoscale*, *13*(31), 13256–13272. https://doi.org/10.1039/d0nr08256b
23. Zhang, L., Jiang, C., Li, B., Liu, Z., Gu, B., He, S., Li, P., Sun, Y., & Song, S. (2021). A core-shell Au@Cu2-xSe heterogeneous metal nanocomposite for photoacoustic and computed tomography dual-imaging-guided photothermal boosted chemodynamic therapy. *Journal of Nanobiotechnology*, *19*(1), 410. https://doi.org/10.1186/s12951-021-01159-x
24. Alhalili, Z. (2023). Metal oxides nanoparticles: General structural description, chemical, physical, and biological synthesis methods, role in pesticides and heavy metal removal through wastewater treatment. *Molecules (Basel, Switzerland)*, *28*(7), 3086. https://doi.org/10.3390/molecules28073086
25. Capek, I. (2017). Noble Metal Nanoparticles. In *Noble Metal Nanoparticles* (pp. 125–210). Springer Japan.
26. Dhand, C., Dwivedi, N., Loh, X. J., Jie Ying, A. N., Verma, N. K., Beuerman, R. W., Lakshminarayanan, R., & Ramakrishna, S. (2015). Methods and strategies for the synthesis of diverse nanoparticles and their applications: a comprehensive overview. *RSC Advances*, *5*(127), 105003–105037. https://doi.org/10.1039/c5ra19388e
27. Fiévet, F., Université Paris Diderot, Sorbonne Paris Cité, ITODYS, CNRS UMR 7086, 15 rue J. A. de Baïf, 75205 Paris Cedex 13, France. fievet@univ-paris-diderot. fr jean-yves. piquemal@univ-paris-diderot. fr, Ammar-Merah, S., Brayner, R., Chau, F., Giraud, M., Mammeri, F., Peron, J., Piquemal, J.-Y., Sicard, L., & Viau, G. (2018). The polyol process: a unique method for easy access to metal nanoparticles with tailored sizes, shapes and compositions. *Chemical Society Reviews*, *47*(14), 5187–5233. https://doi.org/10.1039/c7cs00777a
28. He, M.-Q., Ai, Y., Hu, W., Guan, L., Ding, M., & Liang, Q. (2023). Recent advances of seed-mediated growth of metal nanoparticles: From growth to applications. *Advanced Materials (Deerfield Beach, Fla.)*, *35*(46), e2211915. https://doi.org/10.1002/adma.202211915
29. Jamkhande, P. G., Ghule, N. W., Bamer, A. H., & Kalaskar, M. G. (2019). Metal nanoparticles synthesis: An overview on methods of preparation, advantages and disadvantages, and applications. *Journal of Drug Delivery Science and Technology*, *53*(101174), 101174. https://doi.org/10.1016/j.jddst.2019.101174
30. Jiang, Z., Li, L., Huang, H., He, W., & Ming, W. (2022). Progress in laser ablation and biological synthesis processes: "top-down" and "bottom-up" approaches for the Green synthesis of Au/Ag nanoparticles. *International Journal of Molecular Sciences*, *23*(23), 14658. https://doi.org/10.3390/ijms232314658
31. Krishna Podagatlapalli, G. (2025). The fundamentals of synthesis of the nanomaterials, properties, and emphasis on laser ablation in liquids: a brief review. *Discover Nano*, *20*(1), 98. https://doi.org/10.1186/s11671-025-04235-5
32. Malassis, L., Dreyfus, R., Murphy, R. J., Hough, L. A., Donnio, B., & Murray, C. B. (2016). One-step green synthesis of gold and silver nanoparticles with ascorbic acid and their versatile surface post-functionalization. *RSC Advances*, *6*(39), 33092–33100. https://doi.org/10.1039/c6ra00194g
33. Marinescu, L., Ficai, D., Oprea, O., Marin, A., Ficai, A., Andronescu, E., & Holban, A.-M. (2020). Optimized synthesis approaches of metal nanoparticles with antimicrobial applications. *Journal of Nanomaterials*, *2020*, 1–14. https://doi.org/10.1155/2020/6651207
34. Muthukrishnan, S., Bhakya, S., & Ramalingam, V. (2025). Metal nanoparticles synthesis: an overview of different synthesis methods, mode of action and their biomedical application. *Discover Applied Sciences*, *7*(10). https://doi.org/10.1007/s42452-025-07210-y
35. Nikam, A., Bhagavatula, P., & Kulkarni, A. (2018). Wet chemical synthesis of metal oxide nanoparticles: A review. *CrystEngComm*. https://doi.org/10.1039/c8ce00487k
36. Nyabadza, A., McCarthy, É., Makhesana, M., Heidarinassab, S., Plouze, A., Vazquez, M., & Brabazon, D. (2023). A review of physical, chemical and biological synthesis methods of bimetallic nanoparticles and applications in sensing, water treatment, biomedicine, catalysis and hydrogen storage. *Advances in Colloid and Interface Science*, *321*(103010), 103010. https://doi.org/10.1016/j.cis.2023.103010
37. Parashar, M., Shukla, V. K., & Singh, R. (2020). Metal oxides nanoparticles via sol–gel method: a review on synthesis, characterization and applications. *Journal of Materials Science: Materials in Electronics*, *31*(5), 3729–3749. https://doi.org/10.1007/s10854-020-02994-8
38. Rane, A. V., Kanny, K., Abitha, V. K., & Thomas, S. (2018). Methods for synthesis of nanoparticles and fabrication of nanocomposites. In *Synthesis of Inorganic Nanomaterials* (pp. 121–139). Elsevier.
39. Reverberi, A. P., Salerno, M., Lauciello, S., & Fabiano, B. (2016). Synthesis of copper nanoparticles in ethylene glycol by chemical reduction with vanadium (+2) salts. *Materials*, *9*(10), E809. https://doi.org/10.3390/ma9100809
40. Szczyglewska, P., Feliczak-Guzik, A., & Nowak, I. (2023). Nanotechnology-general aspects: A chemical reduction approach to the synthesis of nanoparticles. *Molecules (Basel, Switzerland)*, *28*(13), 4932. https://doi.org/10.3390/molecules28134932
41. Tavakoli, A., Sohrabi, M., & Kargari, A. (2007). A review of methods for synthesis of nanostructured metals with emphasis on iron compounds. *Chemical Papers*, *61*(3). https://doi.org/10.2478/s11696-007-0014-7
42. Zahoor, M., Nazir, N., Iftikhar, M., Naz, S., Zekker, I., Burlakovs, J., Uddin, F., Kamran, A. W., Kallistova, A., Pimenov, N., & Ali Khan, F. (2021). A review on silver nanoparticles: Classification, various methods of synthesis, and their potential roles in biomedical applications and water treatment. *Water*, *13*(16), 2216. https://doi.org/10.3390/w13162216