



Eco-Friendly Plasma Jet Synthesis of ZnO Nanoparticles for Sensitive Glucose Biosensing

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Abstract

In this study, zinc oxide nanoparticles were prepared using an environmentally friendly and inexpensive method. Plasma jet technology is economical and clean due to the absence of chemicals involved in the nanoparticle preparation process. Argon gas was used to generate the plasma jet, which reacts with zinc oxide metal in an aqueous medium. Morphological examinations showed that the size of the resulting nanoparticles ranged from 15 to 27 nm, with a hexagonal (wurtzite) structure and a flower-like shape. The resulting particles exhibit high stability, as demonstrated in the zeta potential test. The resulting particles were tested to improve the effectiveness of a biosensor for glucose detection. The sensor showed a significant electrical response after adding glucose to the electrode surface, proving the effectiveness of the resulting materials in biomedical applications.

1. Introduction

Nanotechnology is the science that studies materials and particles with sizes on the nanoscale (10^{-9} m), typically less than 100 nanometres [1-2]. This small size can radically change the chemical and physical properties of these materials [3]. From this perspective, change has taken off as a scientific revolution that has altered the paths of scientific research and encompassed many fields, including industry, agriculture, and medicine [4]. Nanoparticles possess many unique properties and advantages, such as their high reactivity due to their large surface area relative to their size [5-7]. One of the most prominent areas in which nanotechnology has been used is medicine, especially in applications that include drug delivery, the manufacture of biomaterials, and tissue culture [8,9]. Nanomaterials have also become popular in many applications, such as the manufacture of solar cells, batteries, and insulators [10]. These nanomaterials are also used in environmental fields, such as water and air purification, due to their high absorption capacity and ability to catalyze chemical reactions [11]. In the modern

Received: 07/01/2025

Accepted: 24/02/2025

Published: 31/08/2025

Keywords: Plasma jet, ZnO, Glucose Detection, Nanoparticles



era, nanotechnology has become a major and important branch in many industries due to the unique properties of nanomaterials that distinguish them from other particles [12].

One of the most prominent modern technologies used in the production of nanomaterials is non-thermal plasma technology, or "plasma jet" (cold plasma), which is considered economical and environmentally friendly because it does not involve the use of chemicals and produces no waste [13]. Plasma is the fourth state of matter, classified as a partially ionized gas without a high temperature [14]. In the plasma state, electrons have a higher temperature than other particles, such as ions or molecules [115]. Therefore, it is an effective technology in many applications, such as sterilizing surgical instruments and treating wounds [16]. Using this technology to produce nanoparticles allows us to effectively control the shape and size of the produced nanoparticles [17]. This factor is a key factor in preparing pure materials suitable for various applications. Therefore, non-thermal plasma technology has become an effective tool for producing nanoparticles [18].

The present study aimed to prepare zinc oxide nanoparticles using a non-thermal plasma (plasma jetting) method, using argon gas as a non-reactive gas during the plasma formation process. The resulting nanoparticles were characterized using several techniques, such as X-ray diffraction, UV-Vis diffraction, and field-emission scanning electron microscopy. The surface stability and diameter of the nanoparticles were also studied using zeta potential and DLS techniques. In addition to this characterization, the biological activity of these particles was tested in improving the performance of a biosensor for glucose detection.

2. Experimental Method

2.1 Plasma Jet System for Nanoparticle Synthesis and Diagnostics

A cold plasma system was used, consisting of several basic components for plasma generation. These components include an argon gas flow system (1-5 liters per minute), a high-voltage DC power supply (up to 20 kV), several gas deliveries tubes, and a needle representing the plasma ejection nozzle. The cathode electrode was connected to the power supply via an external stainless steel plasma needle, while the other electrode was connected to the reagent used in the experiment. The gas flow rate was fixed at a flow rate of 3 liters per minute, and an S3000-UV-NIR spectrometer was used to collect the spectrum generated during the reaction for analysis and extraction of basic plasma parameters. Figure 1 illustrates the plasma system used.

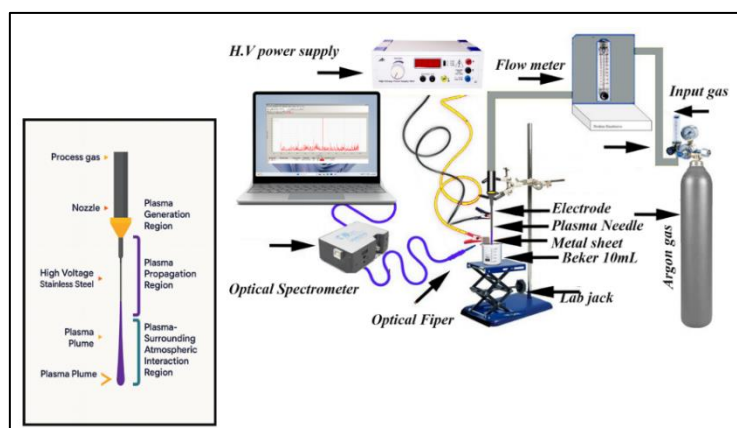


Fig 1: Sectional Schematic design of the experimental setup of atmospheric plasma jet to synthesize the nanoparticles.

2.2 Synthesis of zinc oxide nanoparticles (ZnO NPs)

Zinc oxide nanoparticles were prepared using a plasma jetting technique in sequential steps. First, pure zinc metal (99% purity, from Sigma-Aldrich) with dimensions of 1 cm × 6 cm was prepared and exposed to direct plasma jetting in an aqueous medium, resulting in the production of a nanosolution containing zinc oxide particles. The plasma generated by the needle nozzle reacted with the aqueous medium and zinc metal, generating reactive chemical species such as oxygen and hydroxyl radicals, resulting in the production of a zinc oxide nanosolution, as evidenced by the color change of the suspension to a milky white. A heat-resistant container and a suitable reaction medium were used to ensure process stability during plasma exposure. The nanoparticle preparation time was 10 minutes.

2.3 Electrochemical cell preparation

The Vertex-One device manufactured by Ivium Technologies was used, which consists of a three-electrode system (a working carbon electrode, a reference electrode made of silver/silver chloride, and a third carbon electrode serving as an auxiliary electrode). A 1 M glucose solution was prepared, and the sample was deposited onto the electrode surface by cleaning the electrode surface with distilled water, alcohol, and ultrasonic waves to ensure the removal of all impurities and suspended particles. The nanomaterial was placed on the surface of a 50 μL working carbon electrode and evenly distributed over the electrode surface. A cyclic voltammetry scan was performed by scanning a range from -0.2 to 0.6 V at a frequency of 100 mV/s. Figure 2 illustrates the three-electrode system and the electrochemical cell.



Fig 2: Steps of setting up and connecting electrochemical cell

3. Results and Discussion

3.1 Plasma diagnosis

Figure 3 shows the spectral characterization of the argon-emitting plasma produced at a constant flow rate of 5 liters per minute and a constant voltage of 13 kV. Several argon emission peaks were recorded, starting at 696.02 nm and ending at 965.77 nm. The highest wavelength, 811.21 nm, was also used to calculate the Stark exposure, with the aim of calculating the electron density [19], which was $4.6632 \times 10^{17} \text{ (cm}^3\text{)}$. In addition, five spectral lines were used to calculate the electron temperature using the Boltzmann plot method [20], where the electron temperature was 0.632 eV.

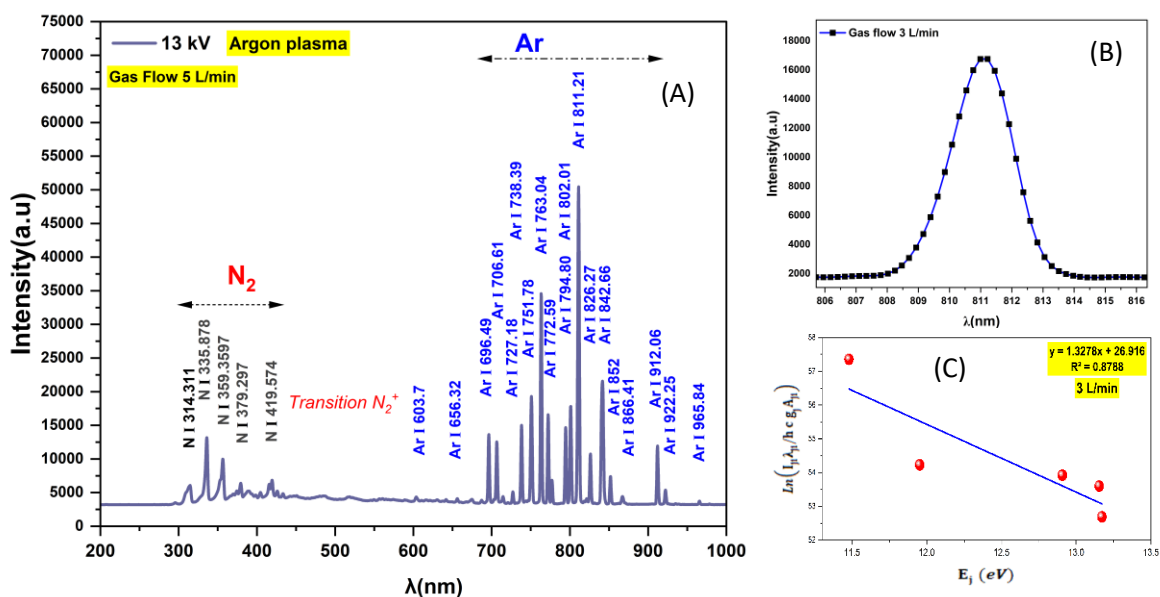


Fig 3: (A) Optical emission spectrum of the plasma generated from Argon gas. (B) Lorentzian structure of the emission line used to analyze the Stark broadening. (C) Boltzmann diagram to estimate the electron temperature in the plasma.

3.2 Characterization of the Synthesized Nanoparticles

Figure 4 shows the X-ray diffraction (XRD) analysis of the nanoparticles produced by plasma jetting technique at a preparation time of 10 min. The results show the formation of a regular crystalline structure of hexagonal wurtzite zinc oxide. The peaks appeared at 2 theta angles as follows: 31.7, 47.5, 56.6, 62.8, and 67.9, corresponding to the (100), (002), (101), (102), and (110) planes. The Scherrer equation was used to calculate the average crystal size and found it to be 14.69 nm, which is consistent with previous studies [21].

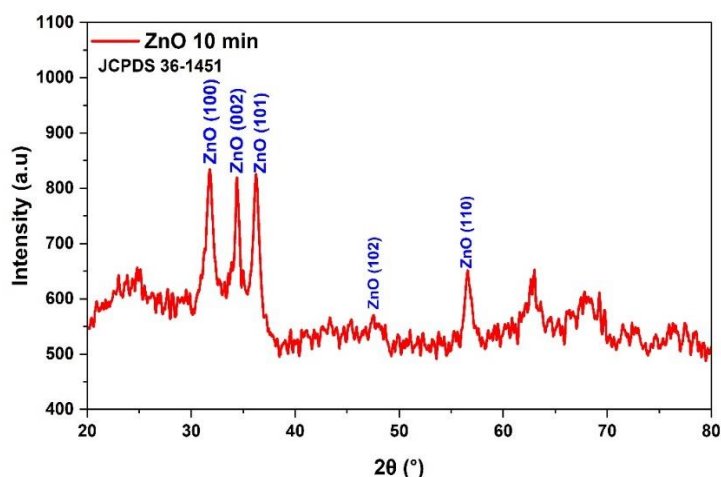


Fig 4: XRD pattern for ZnO at 10 min

Figure 5 shows the UV-vis absorption curves of the prepared zinc oxide nanoparticles after a 10-minute preparation time. The results show a bandwidth in the UV-vis region, indicating high absorbance at visible wavelengths. This is because the smaller the nanoparticle size, the greater

the absorption due to the increased surface-to-volume ratio, which increases the efficiency of interaction with light. On the other hand, the band gap energy gradually decreases due to the quantum confinement effect. Small nanoparticles bring the energy levels somewhat closer together, making them capable of absorbing low-energy photons. Therefore, the absorption extends to longer, positive wavelength ranges.

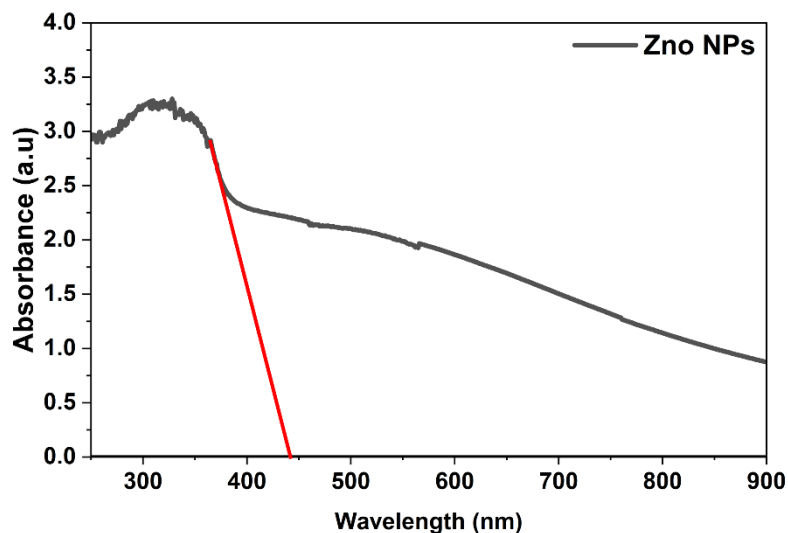


Fig 5: The absorbance spectrum ZnO NPs

Figure 6 shows field emission scanning electron microscope (FESEM) images of plasma-jet-prepared nanoparticles at a preparation time of 10 min. The results showed that the resulting nanoparticles had a flower-like, hierarchical arrangement consisting of dense arrays of nanorods. The average particle size was 26.5 nm. EDS analysis of the nanoparticles also revealed the ratios of zinc and oxygen. The ratios shown in the analysis indicate that the chemical composition is approximately constant.

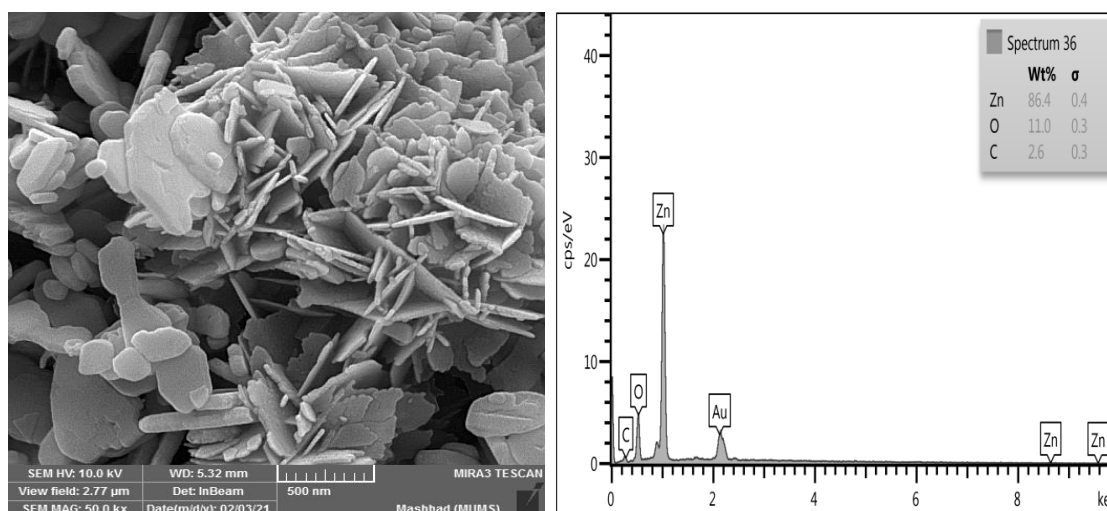


Fig 6: FE-SEM images and an energy-dispersive X-ray analysis for ZnO NPs

Figure 7a shows the zeta potential of zinc oxide nanoparticles prepared at a preparation time of 10 min. This approach is important for studying the stability of nanomaterials in liquid, as its high negative or positive value indicates the surface charge of these particles, which prevents

or hinders them from reassociating or agglomerating through interparticle repulsive forces [22]. The results showed that the zeta potential value reached -37.7 . This high zeta potential value indicates that the produced samples have high stability, making them a suitable choice for biological applications.

Figure 7b shows the hydrodynamic diameter of zinc oxide, where the degree of variation in molecular mass or particle size was studied according to the polydispersity index. The sample showed a distribution spanning 600 to 1100 nm, indicating a homogeneous distribution and consistent with field emission scanning electron microscopy (FESEM) examinations.

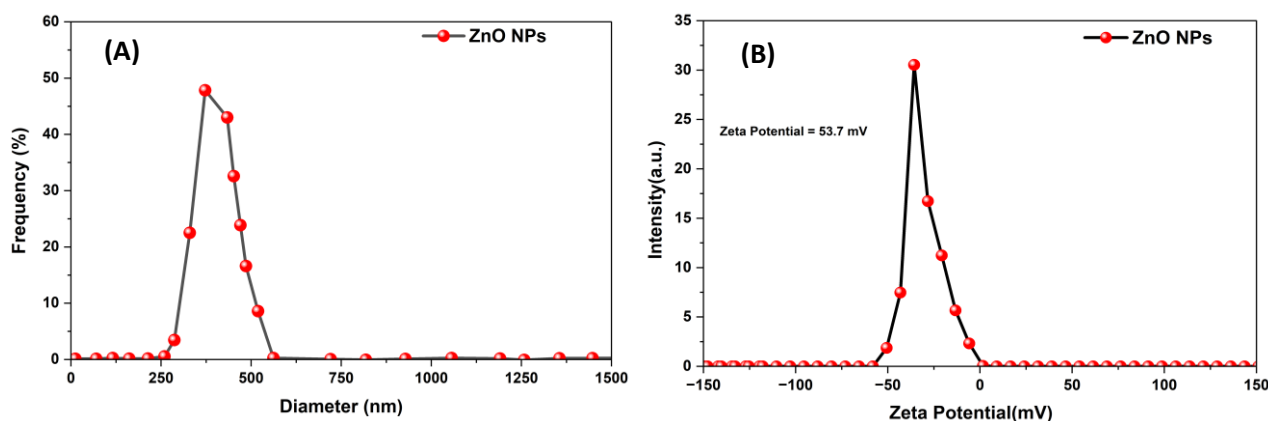


Fig 7: Zeta potential and DLS of ZnO NPs

Figure 8 shows the cyclic voltammetry of the zinc oxide sample prepared by plasma jet at a 10-min preparation time before and after adding glucose. The results show that the maximum current before adding glucose reached $+0.12 \times 10^{-1}$ mA during oxidation and -0.12×10^{-1} mA during reduction. The maximum current after adding glucose was $+0.14 \times 10^{-1}$ mA during oxidation and -0.18×10^{-1} mA during reduction. These increases and decreases in the current resulting from the cyclic voltammetry indicate that active reactions occurred on the electrode surface upon glucose addition, indicating a clear response from the nanoparticle-coated electrode, indicating good electrochemical activity. Overall, these results indicate that zinc oxide nanoparticles produced by plasma jet are a viable option for the manufacture of biosensors, particularly for glucose sensing.

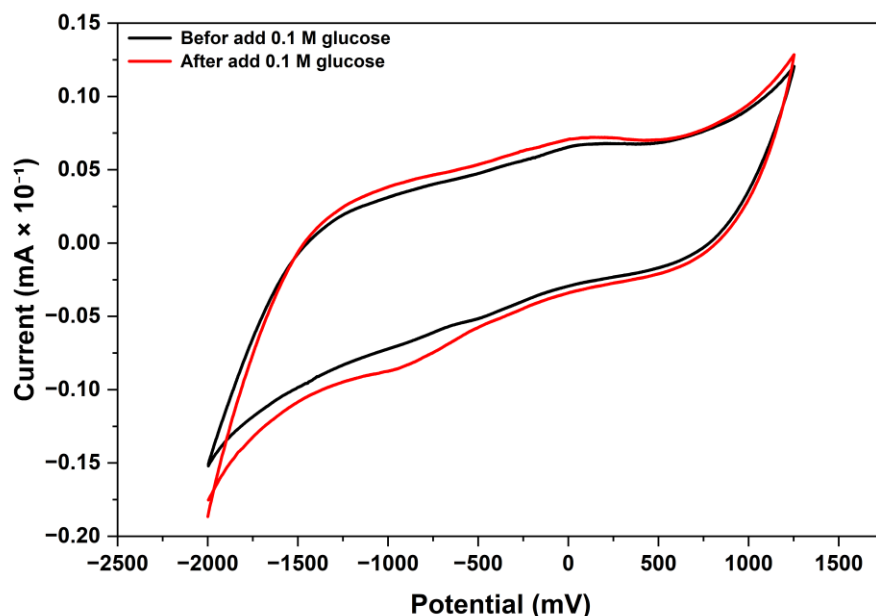


Fig 8: CV before and after adding glucose

4. Conclusions:

The present work demonstrated the success of cold plasma technology in producing zinc oxide nanoparticles with promising properties in biomedical applications, particularly in improving the sensitivity of biosensors for detecting various substances such as glucose, urea, and others. XRD, UV-Vis, FE-SEM, and Zeta spectroscopy measurements showed that the resulting particles were of good nanoscale size, had a flower-like shape, and were highly stable in liquid media. Electrochemical experiments, on the other hand, showed that these particles responded clearly to the addition of glucose, indicating that they have a high sensing efficiency. Overall, the results and the method used are promising for producing environmentally friendly and inexpensive nanoparticles that can be used as a basis for developing effective biosensors, opening the way for promising biomedical applications.

Conflict of Interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

Funding

This research received no external funding.

References

- [1] Ahmed, R.T., Ahmed, A.F., Aadim, K.A., Influence of laser energy on structural and morphological properties of CdO and CdO:Sn production by laser-induced plasma. *J. Opt.* 53, 1564–1573 (2024).<https://doi.org/10.1007/s12596-023-01291-x>
- [2] Khan, Y., et al.: Classification, synthetic, and characterization approaches to nanoparticles, and their applications in various fields of nanotechnology: A review. *Catalysts* 12, 1386 (2022).<https://doi.org/10.3390/catal12111386>
- [3] Pourrahimi, A.M., Olsson, R.T., Hedenqvist, M.S., The role of interfaces in polyethylene/metal-oxide nanocomposites for ultrahigh-voltage insulating materials. *Adv. Mater.* 30, 1703624 (2018).<https://doi.org/10.1002/adma.201870025>
- [4] Grinenko, A.V., Chumaevskii, A.V., Cheremnov, A.M. et al. Structure and properties of pure copper surface layers after reverse-polarity plasma cutting. *Russ Phys J* 67, 2011–2017 (2024). <https://doi.org/10.1007/s11182-024-03339-2>
- [5] Jamal, R.K., Ali, F.H., Hameed, M.M., Aadim, K.A., Designing A zener diode using $Ag_2O_{(1-x)}ZnO_{(x)}$ /Psi structures deposited by laser induced plasma technique, *Iraqi Journal of Science*, 61(5), 1032–1039(2020) <https://doi.org/10.24996/ij.s.2020.61.5.12>
- [6] Wan, J., Wang, G., Ren, H., Huang, J., Joo, S.W.: Synthesis of porous flower-like Sn/CdSnO₃ microstructures with excellent sensing performances for volatile organic compounds. *Front. Mater. Sci.* 18, 240677 (2024).<https://doi.org/10.1007/s11706-024-0677-9>
- [7] Saadi, B., Rahmane, S., Temam, E.G.: Structural, optical and electrical properties of spray deposited indium-doped Cr₂O₃ thin films. *J. Opt.* 53, 582–589 (2024).<https://doi.org/10.1007/s12596-023-01252-4>
- [8] Charrada, G., Ajili, M., Jebbari, N., Kamoun, N.T.: Investigation on physical properties of CuO and Sn:F mixed oxide sprayed thin films for photocatalytic application: Coupling effect between oxides. *J. Mater. Sci. Mater. Electron.* 35, 685 (2024).<https://doi.org/10.1007/s10854-024-12453-3>
- [9] Shbeeb, R.T., Mutlak, F.A.-H.: Silicon photodetectors enhanced by metal oxide semiconductor (MOS) and developed using PLD technique. *J. Opt.* (2025), 1–15.<https://doi.org/10.1007/s12596-025-02494-0>
- [10] Mariappan, R., Ponnuswamy, V., Suresh, P., Suresh, R., Ragavendar, M., Sankar, C.: Deposition and characterization of pure and Cd doped Sn thin films by the nebulizer spray pyrolysis (NSP) technique. *Mater. Sci. Semicond. Process.* 16, 825–832 (2013).
- [11] Gnanam, S., Rajendran, V., Preparation of Cd-doped SnO₂ nanoparticles by sol–gel route and their optical properties. *J. Sol-Gel Sci. Technol.* 56, 128–133 (2010).<https://doi.org/10.1007/s10971-010-2285-7>
- [12] Popov, S.A., Dubrovskaya, E.L., Batrakov, A.V.: Experimental study of space charge structure and expansion dynamics of laser ablation plasma. *Russ. Phys. J.* 63, 508–515 (2020).<https://doi.org/10.1007/s11182-020-02063-x>

- [13] Mohammed, R.S., Aadim, K.A., Ahmed, K.A., Estimation of plasma parameters in a DC atmospheric pressure Argon plasma jet, AIP Conference Proceedings, 2386, 080050(2022) <https://doi.org/10.1063/5.0066788>
- [14] Fu, L.J., et al.: Surface modifications of electrode materials for lithium ion batteries. *Solid State Sci.* 8, 113–128 (2006). <https://doi.org/10.1016/j.solidstatesciences.2005.10.019>
- [15] Kopytov, G.F., Malyshko, V.V., Goryachko, A.I. et al. Estimation of the Sorption Activity of Silver Nanoparticles on Biodegradable Fibers of Natural and Artificial Origin. *Russ Phys J* 64, 255–260 (2021). <https://doi.org/10.1007/s11182-021-02323-4>
- [16] Rashid, T.M., Rahmah, M.I., Mahmood, W.K. et al. Eco-friendly Laser Ablation for Synthesis of CNF@Au Nanoparticles: Insights into Enhancing NO₂ Gas Detection and Antibacterial Activity. *Plasmonics* (2025). <https://doi.org/10.1007/s11468-025-02874-z>
- [17] Mohammed, F.A., Ajaj, K. & Al-Jubbori, M.A. UVC Irradiation Effect on Gold Nanoparticles Prepared by Pulsed Laser Ablation and their Biological Activity. *Russ Phys J* 67, 1015–1032 (2024). <https://doi.org/10.1007/s11182-024-03211-3>.
- [18] Pozdnyakov, G.A., Gareev, T.I. Condensation in an expanding high-enthalpy plasma jet producing nanoparticles and their deposition on a surface. *Thermophys. Aeromech.* 31, 1081–1088 (2024). <https://doi.org/10.1134/S0869864324050160>
- [19] Hayif, N.D., Hadi, H.A. & Hashim, I.H. Enhancement of Performance Au/PSi/n-Si/Ag Heterojunction Photodetector by Non-thermal Plasma Jet: Design and Impact of Plasma Voltage. *Silicon* 17, 531–554 (2025). <https://doi.org/10.1007/s12633-024-03208-0>
- [20] Subrahmanyam, A. (2024). Cold Plasma-Assisted Nano-Matter Synthesis: Basic Principles and Techniques. In: *Cold Plasma in Nano-Matter Synthesis*. Springer, Cham. https://doi.org/10.1007/978-3-031-64041-4_5
- [21] Kopytov, G.F., Malyshko, V.V., Goryachko, A.I. et al. Estimation of the Sorption Activity of Silver Nanoparticles on Biodegradable Fibers of Natural and Artificial Origin. *Russ Phys J* 64, 255–260 (2021). <https://doi.org/10.1007/s11182-021-02323-4>