Pulsed Lazer Ablation Method of Nanoparticle Synthesis: A Review

[1,2]Isyaka, M. S., [4]Odih, C., [5]Bakare, D. M., [5]Giza, A.M., [6]Ferdinand, C. and *[3]Abdullahi, M.A.

[1]Department of Chemical Science, North-Eastern University Gombe State, Nigeria.
[2]Centre for African Medicinal Plant Research (CAMPRE), North-Eastern University, Gombe State, Nigeria.
[3]Department of Chemistry, Directorate of Science, Remedial and General Studies, Federal University of Health Sciences, Azare, Bauchi State, Nigeria.
[4]Department of Chemistry, Michael Okpara University of Agriculture, Umudike, Umuahia, Abia State, Nigeria.
[5]National Biotechnology Research Development Agency, Abuja.
[6]Department of Chemistry, University of Abuja, Abuja, Nigeria.
*Corresponding Author: abdullahi.muhammadjika@fuhsa.edu.ng

Accepted: October 29, 2024. Published Online: November 6, 2024

ABSTRACT

For a number of uses, including in energy harvesting, catalysis, medical detection and treatment, nanoparticles have grown in significance and popularity. To maximize the performance of nanoparticles for specific applications, a range of compositions, sizes, and surface characteristics must be produced. A green chemistry technique, called pulsed laser ablation in liquid, makes it possible to extract ligand-free nanoparticles in a variety of phases and forms. Pulsed laser-assisted nanotechnology offers several advantages for synthesizing nanomaterials. It allows for the production of nanoparticles with high purity and controlled sizes, without the need for surfactants. It allows for precise control over the synthesis process, including parameters such as laser power, wavelength, reaction time, and solvent, resulting in high purity nanomaterials with no byproducts. Laser technology also enables the rapid and contactless manufacturing of complex nanostructures with innovative surface functions. Laser-assisted synthesis provides reliability and reproducibility in the joining process. Additionally, lasers have played a significant role in the synthesis and processing of various nanomaterials, including carbon-based nanomaterials, enabling their dynamic development. Moreover, it allowed the production of ultrapure, less toxic nanoparticles. However, there are also limitations to laser-assisted nanotechnology. The absence of external order in laser-induced structures can be a challenge in controlling the growth of nanostructures. The method is also not suitable for using organic solvents as medium and also volume cost optimization issues exist. Furthermore, there may be challenges in implementing laser-induced nano-joining, and further research is needed to address these challenges.

Key words: Pulsed lazer ablation, nanoparticles, synthesis, lens, applications, wavelength

INTRODUCTION

The Greek word "nano," which means "dwarf" or "very small," is used to represent one thousand millionth of a meter (10^{-9} m) [1]. Norio Taniguchi (1912–1999), a Japanese professor from Tokyo University of Science, is credited with coining the term "nanotechnology" in 1974 [1]. He was the first to define it as "the processing of separation, consolidation, and deformation of materials by one atom or one molecule." The definition was later changed to "the understanding and control of matter at the nanoscale, at dimensions between approximately 1 and 100 nanometers, where unique phenomena enable novel applications" by the National Nanotechnology Initiative [1]. Metal nanoparticles, such as those of silver, zinc, or copper, are emerging as a new class of antimicrobials for use in biomedical applications due to advances in nanotechnology [2]. Humans have been using nanoparticles for millennia; the earliest known applications of these materials date back to the Roman Empire. Gold nanoparticles in the Lycurgus cup, a piece of 4th-century A.D Roman glassware, produce an eye-catching optical dichroism effect [3]. The interaction of light with the gold nanoparticles causes the cup to appear red when illuminated from the back and green when lit from the front [3]. This historic relic offers an astounding proof of the special qualities and possible uses of nanoparticles. The field of nanotechnology has grown enormously since then [3]. According to Aliya et al, [4], research on the synthesis, stabilization, and usage of transition metal nanoparticles which are widely employed in chemical, physical, engineering, and biological processes is one of the key areas where modern chemistry is currently developing.

Cobalt nanoparticles hold a unique position among known transition metal nanoparticles since they are utilized for extremely significant purposes including the development of novel catalysts, magnetic devices, or drug delivery vehicles [5]. Nanotechnology studies structural behavior at the molecular and submolecular level as well as electrical, optical, and magnetic activity. Nanoparticles find application in many industrial production domains, including biological labeling, electronics, sensors, pharmaceuticals, cosmetics, apparel, optics, photocatalysis, sterilization, and solar and oxide fuel cells for energy storage [6]. Nanotechnology is significant for a number of uses. Due to the various synthetic modes or mechanisms of bimetallic nanoparticles, including chemical, physical, and biosynthetic approaches, the majority of researchers have concentrated their research on these materials [7]. Because of their high catalytic activity and vast application potential, these nanoparticles are quite interesting [7]. Nanotechnology has the power to completely transform a wide range of biotechnology and medical instruments and processes, making them more affordable, portable, secure, and user-friendly [5]. The synthesis of nanoparticles (NPs) using the laser ablation method is the subject of numerous investigations, although the factors impacting NP synthesis have not been well reviewed.

This work is a critical analysis of the variables and characteristics discussed in the literature about the application of the pulsed laser ablation (PLA) technique.

[

Lazer Ablation Method

Alcohol is used to wash pure 99.95% silver plates in order to get rid of bacteria and other impurities. Next, 20 milliliters of colloid distilled water were added to the petri dish holding the 99.95% pure silver plate [8]. To create colloids of silver nanoparticles, Neodymium Yttrium Aluminum Garnet, or Nd: YAG 1064 nm laser was directed towards the sample's surface and blasted for 13 hours. To achieve uniformly distributed nanoparticle colloids, the petri dish containing the silver samples is moved gently and constantly during the shooting process. The illustration below displays a photo of 20 ppm silver nanoparticles at a concentration of 33 ppm along with an experimental setup for Nd:YAG 1064 nm laser ablation [8].

To create and distribute different nanoparticles in different media, a variety of techniques were employed, such as solution phase, photochemical, sonochemical, electrochemical synthesis, photolytic reduction, radiolytic reduction, solvent extraction reduction, microemulsion technique, polyol method, and microwave irradiation. These techniques rely on a material's interaction with an external field or a chemical reaction [9]. In a nutshell, the photochemical approach uses light absorption to carry out the chemical reaction. The foundation of the sonochemical and microwave approaches is the use of ultrasound and microwaves, respectively, to start chemical reactions in liquids [9]. Other techniques based on chemical reactions in liquids and reduction of another type of salty metals include microemulsion technology, solvent extraction reduction, photolytic reduction, radiolytic reduction, electrochemical synthesis, and polyol approaches. However, the laser ablation process works by interacting a laser with a metal plate, and the resulting nanoparticles are distributed throughout the liquid [9]. Figure 1 is the arrangement for the experiment..

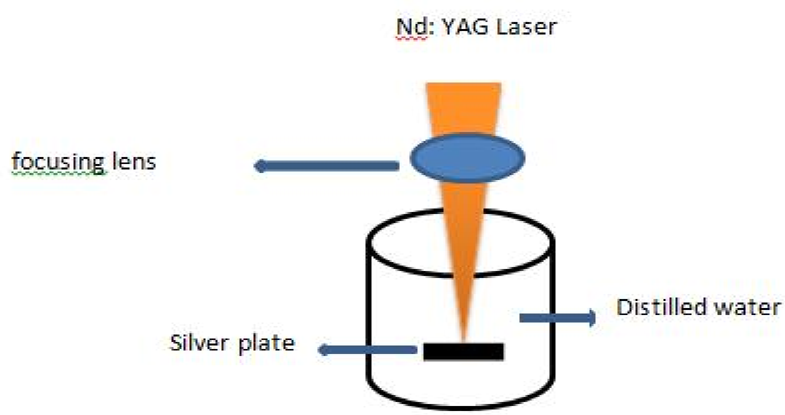

Figure 1. Arrangement of Nd: YAG 1064 nm laser ablation experiment

Literature Review of Work Published on PLA

In the 1960s, a device known as PLA was developed before the pulsed ruby laser. Following that, a lot of studies have looked into laser ablation in diluted or vacuum gases. By adjusting the target materials, background gases, and laser parameters, a variety of thin films can be produced for use in a range of applications, such as semiconductor devices, wear-resistant coatings, and electrodes [10]. This work includes information on laser pulse parameters, laser fluency, laser focusing parameters, and the ambient medium of ablation for the optimal synthesis of nanoparticles as documented in the literature [11]. For the purpose of synthesizing NPs, the laser ablation approach is an excellent technique with few adverse consequences. This process can be used to create a wide variety of NPs [11]. The liquid medium at room temperature determines the composition of the NPs and has an impact on their size, shape, and dispersion in colloidal/solutions for various targets. Vacuum chambers with solid target gas media inside are thought to offer a flexible deposition technique for growing thin films from nearly any type of solid target material [11]. PLA approach has a number of benefits over other methods, whether it is in liquid or solid phase. Comparing the liquid phase technique to its solid version, the experimental cost is much lower. The targets needed for the synthesis are less costly than the other chemicals and metal salts needed for the chemical pathways. The method is renowned for being extremely repeatable and for being a green way [10]. The most significant benefit is that as-fabricated NPs are naturally surfactant-free, making functionalization easy if needed [10].

The PLA method can be used to create semiconducting, magnetic, and organic NPs in a variety of forms and sizes in addition to producing metal NPs [10]. To fully assess the productivity of pulsed lazer ablation in liquid (PLAL), a number of factors, including wavelength, target characteristics, and effect of light absorption, effect of pressure, variation of laser time duration, variation of laser pulse width, effect of liquid environment should be considered in each experiment [3]. Despite the apparent substantial correlation between productivity and the material and architecture of the ablation system, the PLAL approach still has a great deal of potential for widespread industrial adoption [3]. Furthermore, layers can absorb Nd or CO_2, YAG pulsed lasers can be used for surface priming, coating removal, and surface cleaning without damaging the underlying surface, especially on metal [10]. A strong laser pulse might potentially clear a large amount of debris. Low-power lasers scan a surface with a large number of short pulses. In certain domains, laser ablation and cleaning may be combined. One benefit is the lack of solvents, which ensures that users won't come into contact with chemicals and makes it safe for the environment (if nothing hazardous is vaporized) [10]. Operating costs are lower than with dry media or dry-ice blasting, but capital investment costs are significantly higher. The approach is more gentle than abrasive methods. For example, carbon fibers in composite materials are not damaged [11]. The target warms up very little. Forming the removed material into new structures that are either impossible or prohibitive to generate using current procedures is another class of uses for laser ablation. Carbon nanotube production is one such example from recent times [11].

Some conventional methods used to synthesize silver material into silver nanoparticles (AgNP) are cryochemical synthesis [12], electrochemical reduction [13], chemical reduction [14], co-precipitation method [15], bio-mechanochemical [16]. Conventional physical and chemical synthesis methods are generally costly and can have adverse effects on the environment [17]. Because of the agents utilized in the experiment, high purity silver nanoparticles (AgNPs) cannot be produced from silver material synthesized using the above-mentioned approach. On the other hand, a straightforward and inexpensive synthesis procedure called laser ablation can create high purity nanoparticles without the need for a combination of hazardous ingredients [8]. Nanoparticles can be created using the Laser Ablation technique with or without the use of a stabilizer. Neodymium Yttrium Aluminum Garnet, or Nd: YAG 1064 nm, laser was utilized in this investigation, with a low energy of 30 mJ. By adjusting the wavelength, spot size, pulse duration, repetition rate, and fluid medium, one may ascertain how nanoparticles form [8]. The most preferred method for producing nanoparticles is laser ablation, which has few drawbacks. This method can be applied to produce a large range of nanoparticles [18].

Without the need for a chemical surfactant or other additive, laser ablation provides an environmentally friendly and straightforward technique for creating metal nanoparticles with special qualities [9]. Recent years have seen a significant amount of research on laser ablation in liquids because of the many potential applications for laser material microprocessing, including the synthesis of nanomaterials and nanostructures [19]. Pulsed laser ablation in liquid is a straightforward and environmentally friendly technical technique that works in water or other organic liquids under ambient circumstances, in contrast to other chemical approaches [19]. When compared to current techniques, the approach provided can accurately provide an alternative adaptability that is controllable, predictable, repeatable, sensitive, exact, and simple [19].

Short Comings of the PLA Technique

Nevertheless, if the procedure is carried out in an organic solvent medium, the solvents will pyrolyze the organic molecules, resulting in contamination on the surface of the NPs, according to the PLA's liquid phase report [11]. The relatively basic experimental setup makes controlling the size and dispersion of the NPs as-fabricated easy, although it is still constrained. The yield is repeatable, as was previously mentioned, but volume and cost optimization are still issues [13]. Inadequate optimization frequently leads to flaws in the ensuing structures and film development. Micro and nanoparticles from the target may be incorporated by high-intensity laser sources, lowering the quality of the films that are later deposited [11]. The high input energy and limited laser irradiating region for target material evaporation are disadvantages of laser ablation [20].

Laser Ablation Applications

The most common application of laser ablation is accurate material removal from solid surfaces. One example is laser drilling, which creates incredibly small, deep holes in hard materials using pulsed lasers [21]. Therefore, laser drilling is appropriate since it removes material quickly and produces less heat absorption in the surrounding material [22]. Several researchers have produced metal, metal oxide, and metal carbide nanoparticles using gas condensation and laser ablation [22].

Laser Ablation-Generated Silver Nanoparticles

According to Ahmad et al [21], by making changes, original method's productivity or the nanoparticles size was boosted. The effectiveness of liquid laser-produced silver nanoparticles as bactericides against a variety of bacteria, including gram-positive and gram-negative bacteria like *Escherichia coli and Pseudomonas aeruginosa* and *Staphylococcus aureus* and *Bacillus subtilis*, has already been shown in numerous studies [21].

Laser Ablation Generated Graphene Oxide Nanoparticles

It was possible to successfully produce graphene oxide (GO) nanoparticles by employing pure graphite as a laser target in a laser ablation system. Several techniques were used to characterize the produced GO nanoparticles [23]. The results of the GO absorption spectra showed that when the laser energy was increased from 500 to 600 mJ, the absorption peaks were displaced toward lower wavelengths, but when the laser energy was increased to 700 mJ, the absorption peaks did not shift [24]. Additionally, increasing the laser energy from 500 to 600 mJ boosted the peak intensity. However, when the laser energy was increased to 700mJ, the peak's intensity drastically diminished [23].

Laser Ablation Setups

A lens, a liquid container, a stirrer, a linear positioner, and a high intensity pulsed laser make up the laser ablation system . The metal targets, which consisted of 99.99% copper, silver, and gold, were immersed in liquid. The metal plate was ablated using a 532 nm or 1064 nm pulsed Nd:YAG laser beam [9]. A Q-switched Nd:YAG laser, a travel linear stage, a metal plate, a solution container, a lens (f = 30 cm), and a stirrer are all included. Both the pulse duration and the laser ablation time are adjustable, ranging from 10 to 60 Hz and 5 to 60 minutes, respectively

[9]. The laser beam's path through the liquid must be set to the smallest length in order to prevent energy absorption by the liquid solution [10]. In order to get the optimal laser beam energy on the target's surface, the distance between the target and the entrance windows is therefore an important consideration. The solution is stirred during the ablation of the metal plate to ensure that the metal nanoparticles dispersed uniformly in the liquid solution, and the solution container moves horizontally using a travel linear stage to provide a fresh region to ablate the target [9].

The Effect of Thermal Properties in Laser Ablation of Metal Plates

Diffusion length can be used to greatly simplify this problem. The heat diffusion length is, in fact, shorter than the laser spot size [9]. As a result, it is possible to regulate the temperature while the metal plate is being laser-ablated. For instance, in certain standard experiments, the spot size exceeds the diffusion length and is around 10 µm [11]. Additionally, the laser beam has a flat top profile, and the target layer's temperature rises as a result of the laser beam's absorbed energy. The area of the layer that the laser beam covers is equal to the laser's spot size, and it is surrounded by a liquid that absorbs heat and lowers the layer's temperature [10]. The average temperature rises when a liquid is present [10].

Effect of Wavelength in Laser Ablation of Metal Plate

Metal targets and nanoparticles can absorb laser beam energy at a specific wavelength because the optical constants of the materials are wavelength dependent [9]. Metal clusters break free from the metal plate at the nano scale and can create the ideal environment for laser energy to be absorbed with each pulse, allowing the metal target to melt and accelerates the production of nanoparticles. As a result, a higher rate of laser pulse repetition can result in a faster rate of nanoparticle production [9]. The target material absorbs light differently at different wavelengths, resulting in different concentrations that affect the sizes of the particles. It should be noted, nevertheless, that this has no effect on the final materials' morphology [24, 25].. Nowadays, there is a growing interest in NPs because small electronics are becoming more and more common and demand improved material properties. Size control is therefore essential because the physico-chemical properties of the material depend on its size [11]. Metal colloids are an essential type of nanomaterial because of their superior optical characteristics and catalytic activity [11]. One practical method for creating metal colloids is laser ablation in a solution. With this technique, pure colloids can be created without the need for chemical reagents [11]. The efficiency of the nanoparticles produced and the metal target's absorption energy are both enhanced by the short laser wavelength. But because of its open absorption effect, which boosts ablation efficiency particularly in noble metal materials like silver, gold, and platinum, this effect is negligible [26].

Effect of Variation of Laser Time Duration

The laser ablation time (LAT) and laser fluence (LF) have a substantial correlation with the UV–visible absorption characteristics of the synthesized NP's sizes. A number of studies were used to clarify how the parameters affected the size of the NPs. Both an increase in NP density and a decrease in liquid molecules were caused by longer ablation times [11, 26].

Effect of Variation of Laser Pulse Width on Nanoparticle Size

Additionally, it has been noted that when ultra-short laser pulses are used, the energy received by the target stays relatively low. Thus, it is beneficial to use ultra-short laser pulse lengths of ps/fs since it can be utilized to boost laser ablation process efficiency [26, 27].

Effect of Liquid Environment on Nano Particle's Size

A higher liquid temperature causes the nanomaterial's shape to change from spherical to elongate [26]. The observed morphological alteration can be explained by the fact that the increased kinetic energy leads to a higher rate of collision between the big NPs that are created during the condensation process and the NPs that are in the laser beam's path [26]. The size of the NPs may theoretically be further reduced by the fragmentation resulting from these impacts. To reduce the size of the NPs, additional laser pulses can be irradiated onto colloidal solution using liquid-phase laser ablation [11]. Following laser excitation, the NPs experience photo-fragmentation, which produces smaller NP fragments [11].

Effect of Pressure

Kulinich, et al [28], investigated the influence of pressure on medium in PLA on NPs synthesis in order to investigate the effects of variations in medium pressure on Zn laser ablation and ZnO NP production, they employed varying pressures. ZnO nano-crystals were produced via PLA of Zn at different pressures (0.1 to 31 MPa) in distilled water [27]. The findings demonstrate that smaller, uniformly sized nanoparticles with higher green fluorescence were created at elevated medium pressures [28].

The Effect of Light Absorption With Nanoparticles in Laser Ablation Method

The effective factor of the laser ablation procedure at high laser fluence to manufacture the nanoparticles in an aqueous solution is the absorption of laser beam with nanoparticles [8]. The produced nanoparticles combine close to the target when their mobility in a liquid is low [8]. They can therefore absorb laser beam energy [8]. Because more nanoparticles are created when the laser fluence is increased, this impact gets stronger. As a result, the laser beam's ability to penetrate the metal target is reduced in intensity [9]. Furthermore, due to laser-induced fragmentation, the size of the nanoparticles that absorb the incident laser beam diminishes [9].

Laser Ablation Synthesis of Nickel Nanoparticles

By dispersing the microsized Ni powder in the liquid phase of acetone, the PLA approach was utilized to synthesize stabilized and purified nickel NPs into a narrow size distribution and nano-spherical shape [26].

CONCLUSION

Due to a greater need for more effective ways to synthesize nanomaterials as the world population and demands continue to rise. In this context, pulsed lazer ablation has come to light as a viable strategy with a wide range of applications, backed by a sizable research community dedicated to the advancement of environmentally friendly and efficient technologies. More research is needed on pulsed lazer ablation method of nanoparticle synthesis, and its merit/demerit.

REFERENCES

[1] Atikur, R. & Grégory, G. (2024). Synthesis of Nickel-Based Nanoparticles by Pulsed Laser Ablation in Liquids: Correlations between Laser Beam Power, Size Distribution and Cavitation Bubble Lifetime. *Metals*, *14(2)*, 224**;** https://doi.org/10.3390/met14020224

[2] Nabila, D. R., Rebriarina, H., Tyas, P. & Ali, K. (2023). Synthesis, characterization, and antimicrobial properties of copper oxide nanoparticles produced by pulse laser ablation method in chitosan solution. *Journal of Applied Research and Technology.* 21 (2), 196-204.

[3] Inna, Y. K., Gladys, M., Bilal, G., Carlos, D. & Bilal, G. (2023). Green nanoparticle synthesis at scale: a perspective on overcoming the limits of pulsed laser ablation in liquids for high-throughput production. *Phys. Chem. Chem. Phys.,* 25, 19380. DOI: 10.1039/d3cp01214j

[4] Aliya, F. K., Maria, C., Evamarie, H. H., Oleg, G. S. & Dmitry, G. Y. (2021). Preparation of Cobalt Nanoparticles. *European Journal of Inorganic Chemistry*. 2021(30), 3023-3047.

[5] Jhilirani, M., Banashree, D., and Soumen, D., (2020): Magnetic cobalt oxide nanoparticles: sucrose-assisted self-sustained combustion synthesis, characterization, and efficient removal of malachite green from water. *Journal of Chemical and Engineering Data.* 65(5), 2819-2829.

[6] Saba, H. (2015). A Review on Nanoparticles Their Synthesis and Type. *Research Journal for Recent Science.* 4(3), 1-3.

[7] Danbature, W. L., Isyaka, M. S., Abdullahi, M. A., Gambo, A. A. & Abdulmalik, S. S. (2023). UV-VIS, FTIR and XRD characterization of synthesized magnetic cobalt (co3o4) nanoparticle used in catalytic decomposition of hydrogen peroxide. *FUDMA Journal of Sciences.* 7(6), 222 -227

[8] Mohammad, Z. A., Beny, S. H. & Ali, K., (2019). Synthesis of silver nanoparticles using laser ablation Method utilizing Nd:YAG Laser. AIP Conf. Proc. 2202, 020013. https://doi.org/10.1063/1.5141626.

[9] Amir, R. S., Mohd, A. M., Farideh, A. & Suraya, A., (2018). Laser Ablation Technique for Synthesis of Metal Nanoparticle in Liquid. Chapter four. Intech Open publishers. DOI: 10.5772/intechopen.80374.

[10] Zhang, D., Wada, H., (2021). Laser Ablation in Liquids for Nanomaterial Synthesis and Applications. In: Sugioka, K. (eds) Handbook of Laser Micro- and Nano-Engineering. Springer, Cham. https://doi.org/10.1007/978-3-030-63647-0_30

[11] Hameed, N., Alghoul, M. A., Mohammad, K. H., Nilofar, A., Abdullah, M. F., Mohammed, S. A., Feras, G. A. & Amin, N., (2019). The role of laser ablation technique parameters in synthesis of nanoparticles from different target types. *J Nano part Res* 21:249 https://doi.org/10.1007/s11051-019-4690-3

[12] Sergeev, B. M., Kasaikin, V. A., Litmanovich, E. A., Sergeev, G. B. & Prusov, A. N., (1999). Cryochemical Synthesis And Properties Of Silver Nanoparticle Dispersions Stabilised By Poly(2-Dimethylaminoethyl Methacrylate), Mendeleev *Commun*, 4 : 130–132.

[13] Zhu, J. J., Liao, X. H., Zhao, X. N. & Chen, H. Y., (2001). Preparation of Silver Nanorods by Electrochemical Methods, *Mater. Lett.,* 49 : 91–95.

[14] Zhang, Q., Li, N., Goebl, J., Lu, Z. D. & Yin, Y. D., (2011). A Systematic study of the synthesis of silver nanoplates: Is citrate a "Magic" Reagent, *J. Am. Chem. Soc*., 133 : 18931–18939.

[15] Danbature W. L., Isyaka, M. S., Abdullahi. M. A., and Abdulmalik S. S., (2023). Chemical Synthesis and Characterization of Magnetic Iron (Fe3O4) Nanoparticles Used in Catalytic Decomposition of Hydrogen Peroxide. *Bima Journal of Science and Technology.* 7 (4), 200-208.

[16] Matej, B., Nina, D., Ludmila, B., Erika, D., Ludmila, T., Jaroslav, B., Maria, V., Miriama, B., Anna, Z. & Peter, B. (2017). Biomechanochemical synthesis of silver nanoparticles with antibacterial activity, *Advanced Powder Technology.*28(12), 3307-3312.

[17] Gurunathan, S., Kalishwaralal, K., Vaidyanathan, R., Venkataraman, D., Pandian, S. R., Muniyandi, J., Hariharan, N. & Eom, S. H. (2009). Biosynthesis, purification and characterization of silver nanoparticles using Escherichia coli. *Colloids, Surf. B Biointerfaces.,* 74, 328–335.

[18] Nadia, M. J., Alyaa, H. A. & Nada, I. I. (2023). A Review of Laser Ablation- Synthesis of Nanoparticles: Concepts and the Principles. *Journal of Natural Sciences Research.* 14(13), 26-32.

[19] Ganjali, M., Ganjali, M., Vahdatkhah, P. S. & Marashi, M. B. (2015). Synthesis of Ni Nanoparticles by Pulsed Laser Ablation Method in Liquid Phase. *Procedia Materials Science* 11, 359 – 363

[20] Myungjoon, K., Saho, O., Taesung, K., Hindenori, H. & Takafumi, S., (2016). Synthesis of Nanoparticles by Laser Ablation: A Review. *KONA powder and Particle Journal.* 201. 009.

[21] Ahmad, K. Y., Andi, H. Z. & Suryani, D. A., (2024). Review of Silver Nanoparticle Synthesis Using Laser Ablation; Its Characterization, Antioxidant And Antibacterial For Skin Wounds. *Jurnal Teknologi (Sciences & Engineering)* 86(5), 121-135

[22] Astuti, S. D., Widya, I. W., Arifianto, D. & Apsari, R. (2019). Effectiveness Photodynamic Inactivation with Wide Spectrum Range of Diode Laser to Staphylococcus aureus Bacteria with Endogenous Photosensitizer: An in vitro Study. *Journal of International Dental and Medical Research*. 12(2): 481-486.

[23] Atiaf, K. J. & Qusay, A. A. (2020). Synthesis of Graphene Oxide Nanoparticles by Laser Ablation System. *Iraqi Journal of Science*, 61(9):2241-2250 DOI: 10.24996/ijs.2020.61.9.11.

[24] Chewchinda, P., Tsuge, T., Funakubo, H., Odawara, O. & Wada, H., (2013). Laser wavelength effect on size and morphology of silicon nanoparticles prepared by laser ablation in liquid *Japanese. J Appl Phys* 52:025001

[25] Swarnkar, R., Singh, S. & Gopal, R., (2011). Effect of aging on copper nanoparticles synthesized by pulsed laser ablation in water: structural and optical characterizations. *Bull Mater Sci* 34, 1363–1369.

[26] Hamed, N. S. & Reza, S. R. (2024). Synthesis of Nanoparticles Using Pulsed Laser. Intech Open. doi: 10.5772/intechopen.1004415.

[27] Schwenke, A., Wagener, P., Nolte, S. & Barcikowski, S. (2011). Influence of processing time on nanoparticle generation during picosecond-pulsed fundamental and second harmonic laser ablation of metals in tetrahydrofuran. *Appl Phys A* 104:77 82

[28] Kulinich, S., Kondo, T., Shimizu, Y. & Ito, T. (2013). Pressure effect on ZnO nanoparticles prepared via laser ablation in water. *J Appl Phys* 113:033509