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Laser-Matter Interaction in Liquids: Performance Evaluation and Limitations

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تفاعل الليزر مع المادة في السوائل: تقييم الأداء والقيود

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ABSTRACT

Background

Laser ablation in liquid (LAL) has developed into a multifaceted and effective method for nanoparticle production, material processing, and biomedical applications. This review critically examines the fundamental principles, mechanisms, and operational parameters influencing LAL outcomes. The technique offers several advantages, including the generation of ultrapure nanoparticles, precise control over particle size and composition, and the absence of chemical contaminants. Additionally, LAL enables in situ functionalization, making it highly desirable for advanced material synthesis. However, despite these benefits, the technique presents certain limitations, such as low production yield, high energy consumption, and challenges in achieving uniform particle size distribution. The complexity of the underlying physical and chemical interactions also poses difficulties in process optimization and reproducibility. This review provides a comprehensive discussion of LAL's advantages and disadvantages, highlighting recent advancements and potential strategies for overcoming its limitations. Future research directions are also explored to enhance the efficiency and scalability of LAL for industrial applications.

Keywords: Pulsed laser ablation, Laser matter interaction, Laser induced plasma

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INTRODUCTION

Laser ablation was a process that used high-intensity laser pulses to remove material from a solid substrate. It is widely employed in various fields, including materials science, nanotechnology, medicine, and industry. Nanoparticles exhibit a range of distinctive characteristics absent in bulk materials [1]. A critical factor of nanoparticles is that their characteristics, including electrical, optical, and magnetic properties, are profoundly affected by the size and size distribution of their particles [2]. At ambient temperature, the photoluminescence of silicon nanoparticles manifests in the visible spectrum [3]; the dimensions of nanomaterials are essential for modulating the wavelength of light emission [4]. Titanium particles are highly beneficial for numerous applications, including photovoltaics [5] and optoelectronic devices [6]. The size of the particles and the crystal structure of titanium nanoparticles have a significant impact on the photochemical properties of these particles. The behaviour features of nanoparticles include ferro magnetism There are numerous types of nanoparticles that exhibit these properties. within the nanoscale [7]. Techniques for the creation of nanoparticles were advanced via bottom-up methodologies in the liquid state, such as sol-gel and chemical reduction, as well as vapour phase techniques, including physical and chemical vapour deposition [8-15]. The significant vapour phase steps in synthesizing high-purity nanoparticles using a continuous flow reactor. For both gases and liquids bottom-up methods, solid nanoparticles are generated from the nucleation of supersaturated species. PLA was a method that used the beam of a laser as a source of energy to ablate solid target materials. The fundamental nature of this strategy A focused high-energy laser beam is aimed at a target substance. When target absorption some energy leads to rapid heating, melting, and vaporisation of the material. A plasma plume is produced, suitable for nanoparticle synthesis, thin-film deposition, or surface alteration. A high-energy laser was concentrated on a main location on a solid surface target to swiftly extract light-absorbing material. The term "ablation" denotes the process of extracting atoms from a surface target. This process does not encompass a single photon mechanism that disrupts chemical bonds; instead, it entails multi-photon excitation thermal evaporation [16-25]. The paper overview discusses the processes and mechanisms involved in nanoparticle production using PLA. Following this, laser ablation strategies for synthesizing different kinds of nano particles are discussed. In conclusion, an introduction is made to the laser ablation processes that have been devised for the preparation of nanomaterials [26-30].

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Review work published of Pulse Laser ablation (PLA) in the past

PLA was developed in the 1960s, before the development of the pulsed ruby laser. Multiple additional investigations investigated PLA in vacuum and low-density gases [6, 31-34]. By altering the materials, ambient gases, and laser specifications, many types for thin films can be generated for use in multiple fields such as electrodes and wear-resistant attachments [35]. Metal oxides, semiconductors, and high-temperature superconductors are examples of applicable targets.

In 2011, Ali and Raouf used a pulse laser (Nd: YAG) with a wavelength of (1064) nm , a period of (10) ns , and an energy range of 100-900 mJ in order to generate silver nanoparticles in water that had been distilled and deionised. The resulting silver is spherical in shape and ranges in size from five to fifty nanometers [30, 36-40].

In 2013, Adawiya J. Haider etal. conducted an experiment on TiO2 TiCl4 nanoparticles synthesised as a precursor in a natural setting utilizing a 1:10 solution of ethanol without additions. An analysis of the nanoparticles' structure, morphology, and dimensions was conducted utilizing X-ray diffraction and scanning electron microscopy (SEM). The investigation of optical qualities was carried out with the assistance of a visible ultraviolet spectrophotometer. Based on the findings, it was discovered that the anatase phase was only found in titanium dioxide powder at concentrations of up to 500. It was discovered that the typical size of TiO2 nanoparticles ranged from 3-30 nm.The antibacterial efficacy of TiO2 particles produced at concentrations of 10^-5 and 10^-3 was markedly improved against two bacterial strains, Escherichia coli and Staphylococcus aureus, correspondingly. Titanium dioxide nanoparticles provide superior antibacterial efficacy against Staphylococcus aureus compared to Escherichia coli [41-47]

In 2014, Khashan and coworkers synthesized colloidal titanium dioxide nanoparticles using the laser ablation of titanium metal immersed in anionic water. To investigate the characteristics of nanoparticles floating in liquid, they utilized the transmission electron microscope (TEM), the Fourier transform infrared (FTIR), and the ultraviolet-visible spectrum (UV-Vis). Researchers used Fourier transform infrared (FTIR) analysis to characterise the process of creating titanium oxide particles. The results of transmission electron microscopy (TEM) pictures found granular

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ranges of three to thirty nanometers. Staphylococcus aureus and Escherichia coli were used as test organisms to determine whether or not the nanoparticles possessed antibacterial properties. Inhibition of bacterial growth has been established through the utilisation of nanoparticles of titanium dioxide [48].

In 2015 , Lakshmipathy and Nanda effectively synthesized AgNPS from gallic acid while evaluating the biological potential of these nanoparticles. At a wavelength of 424 nm, the UV-VIS spectra exhibited a little peak with a maximum. The FESEM micrograph displays a limited size variation of silver- nanoparticles, with diameters ranging from 30 nanometers to almost spherical in shape. An IC50 dose of 1 mg/mL was shown to be effective in inhibiting the growth of HEp-2 cells. This inhibition was accompanied by morphological alterations and membrane breakdown. The reason for its toxicity is that it has a strong affinity for intracellular proteins and thiol synthesis, both of which have the potential to be extended for a wide range of biological applications as a universal therapeutic agent. a gentleman [49].

In 2016, Salman *et al*. Synthesized titanium oxide nanoparticles using PLA by injecting high purity titanium (99.9%) into 2 millimeters a laser energy of 500 mJ. The researcher analyzed the properties of nanoparticles using X-ray diffraction (XRD), atomic force microscopy (AFM), and UV/Visible absorption tests, with the mean diameter of the particles varying from 84.78 nm to 95.96 nm at wavelengths of (532 - 1064 nm) [50].

In 2017,by utilizing a PLA technique with a wavelength of 1064 nanometers and a pulse width of 35 nanometers, Caroline and her colleagues were able to manufacture silver nanoparticles. Additionally, they were able to determine the varied consequences that silver target radiation had under various weather circumstances. The researchers made the discovery that the visible UV-visible absorption spectra of the nanoparticles had a peak in the ultraviolet range, which corresponds to the absorption of the surface Plasmon resonance. The dimensions and morphology of the nanoparticles were evaluated using scanning electron microscopic and transmission electron microscopy . results demonstrated that the variability of the laser impact and the liquid media substantially influenced the properties of the AgNPs as well as their rate of generation. Various circumstances have been utilized for produce particles ranging in size from 2 to 80 nm. The investigation yields promising results [51].

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In 2018, Prahlad etal. investigated the augmentation of Plasmon bandwidth in nanoparticles derived from a silver target, signifying a decrease in size of the nanoparticle with increasing laser intensity [35].

In 2019, Billy and his colleagues are conducting research on the production and characterisation of gold nanoparticles (Au NPs) through the use of pulsed laser ablation [52]. In 2020, Chen and colleagues will study both ZnO nanoparticles and colloids. Zinc granules in an aqueous framework will be pulsed laser ablated to produce these particles, and regarding characterization for zirconium oxide nanoparticles, it will show the generation of zinc oxide nanoparticles [31].

In 2020, N. A. Inogamov, et al studied that laser. Laser ablation, which refers to the process of removing target material by the use of irradiation, is now being considered; many technologies make extensive use of this technique. Since the first lasers were invented, the physical models that are necessary for gaining a knowledge of ablation have been continuously developed. There are a number of occurrences that have been thoroughly explored; nevertheless, there are still a great deal of issues that need to be investigated further. These phenomena, which have received little research, include surface structure. There is still a lack of thorough comprehension regarding the issues that arise with laser forging and peening, as well as ablation in liquid [53].

In 2021, Rashad Hamed Ahmed examined the impacts of laser on aluminum nanoparticles (Al NPs), which were synthesized via the Nd:YAG laser ablation technique utilizing a pump wavelength of 1064 nm. UV spectroscopy was utilized to examine the optical characteristics, encompassing absorbance and transmission spectra, in conjunction with alterations in the power of the laser and wavelengths.

In 2022, Tahseen H. Mubarak et al. investigated multiple physical characteristics of aluminum nanoparticles employing the PLA in liquid technique [35]. In 2023, Alireza Ghasempour et al. emphasize the investigation of cadmium sulphide features pertinent to biomedical applications, including bio-imaging, antibacterial agents, and biosensors [34, 51, 52].

In 2024, Esmaeil Ghadiri Zahrani et al. asserted that lasers have become a feasible and efficient alternative to conventional mechanical methods in numerous precise material removal operations. Nonetheless, laser ablation of materials constitutes a sophisticated, multi-parameter procedure that requires multiple repetitions of scanning pathways. This repetition causes

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changes in absorbency and distribution of temperatures throughout the scanning path, hence affecting the accuracy of the ablation. Therefore, it's essential to thoroughly analyze these occurrences. This work examines the laser ablation of bronze (DIN: 1705) through a multi-track ablation process, providing both experimental and numerical analyses. Specifically, six consecutive passes were conducted using a nanosecond laser operating at three different energy densities. Following each pass, measurements of the ablation depth and pile-up height were recorded at three distinct locations along the track (the start, the midpoint, and the endpoint) to assess the efficacy and quality of the technique [39].

In 2025, Andreozzi et al. found that laser ablation is a non-invasive treatment regimen that is currently being developed for this condition. It offers the option of preserving the prostate's ability to function normally. However, because there are not enough in-vivo tests, not only for ethical but also for practical reasons, it is difficult to design the treatment in an acceptable manner. This can result in incomplete elimination of the tumor and the formation of metastasis, which can be attributed to an inadequate exposure period or concentration of the laser [40].Numerous case studies on nanoparticle formation using laser ablation have been documented; however, a comprehensive assessment of the conditions influencing nanoparticle creation is lacking. The factors influencing the creation of nanoparticles by the laser method are summarized in Figure 1.

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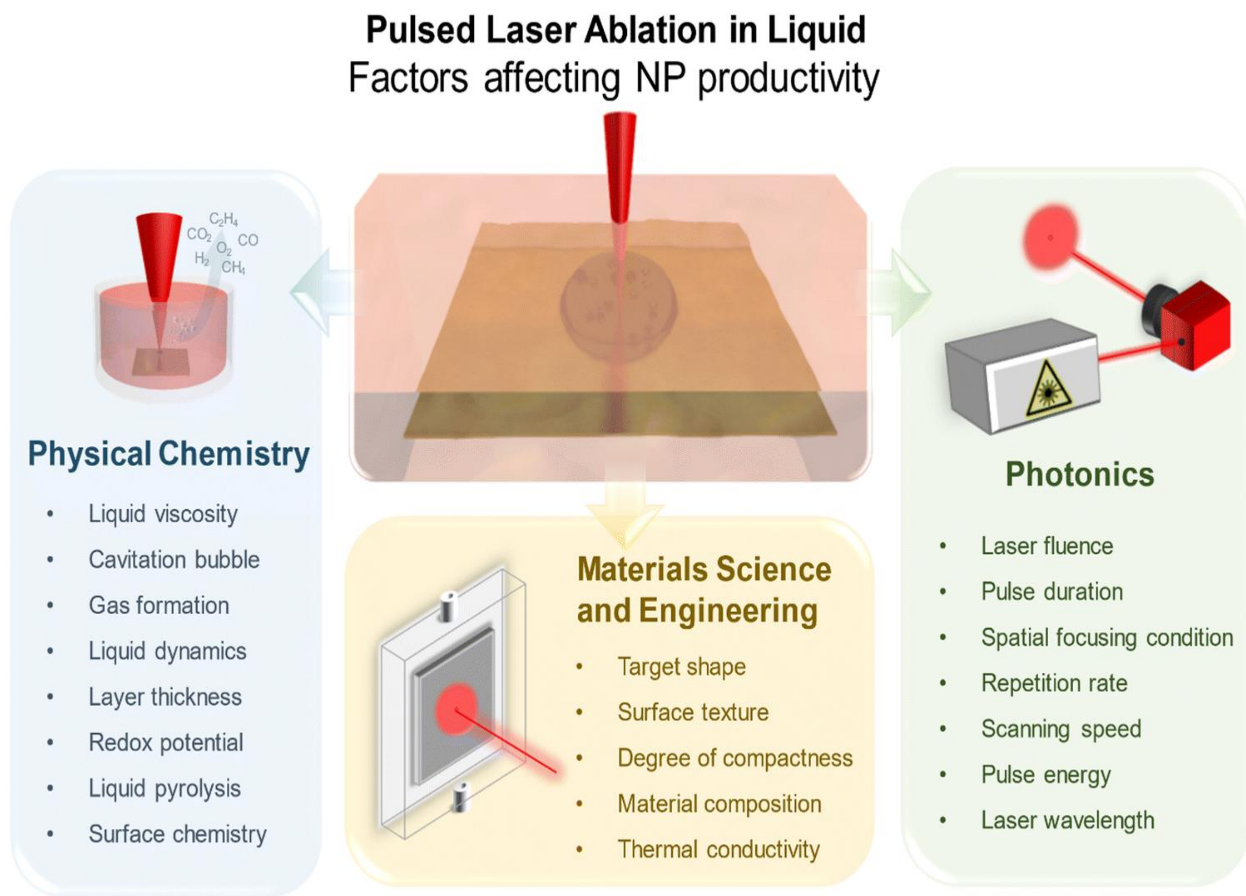

Figure 1. The parameters influencing particle generation through a laser system[43].

Process for the synthesis of laser ablation

Laser ablation is an effective physical technique employed for nanoparticle synthesis, providing **chemical-free and high-purity nanoparticle creation. The procedure entails directing a** high-energy laser pulse onto a target material immersed in a liquid media, resulting in the expulsion of nanoparticles. This method is extensively employed for its capacity to generate stable, regulated, and contamination-free nanoparticles. The synthesis procedure can produce Numerous varieties of nanoparticles are depicted in Figure 2 [31].

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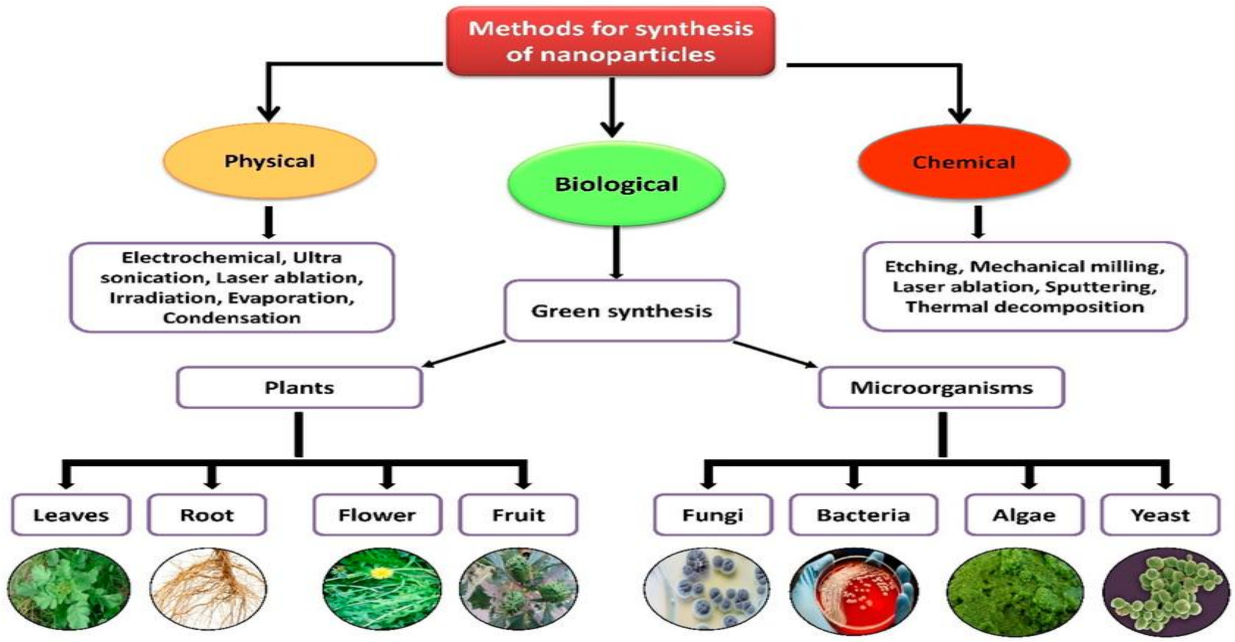

Figure 2. Various methods for nanoparticle production [40].

The laser ablation process, employing a top-down methodology, is a more renowned method for mineral creation. [31]. The ablation process eliminates material from the surface due to the interaction of a beam of laser with the solid material. It originates from the Latin term "ablation," signifying eradication [39, 53].

The pulse-laser ablation technique used to create the nanoparticles can result in the production of an equilibrium plasma plume that may attain to 1000c^0. A portion of the energy emitted via the pulse of a laser was reflected from the surface of the sample. It is essential to keep in mind that the reflectivity of a material is influenced not only by the laser wavelength but also by the material itself. When the target absorb heat is converted level of energy, and then the lattice is responsible for distributing the electrons scattered throughout the material [37]. The production of (photochemical reactions) that remove atoms and molecules from the surface can be accomplished through the use of pulses of high energy bursts. The vaporisation process quickens as the temperature of the heated surface gets closer and closer to the critical temperature. The process of vaporisation results. In the production of plasma, this consists of ionized particles and electrons that have been vaporised. A minor fraction of the incident energy from lasers was absorbed via the plasma cloud, which means that only a little portion of

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the laser energy is able to pass through. Due to the fact that the relationship between the laser and the material shifts slightly throughout the course of different time intervals [40].

Figure 3 illustrates the production of nanoparticles using laser ablation. When laser radiation was focused on the surface of a substance in gas or liquid media, the temperatures for the irradiated region swiftly increased, leading to the vaporization of the targeted material. The collisions among evaporating atoms. The excitation of electrons state, followed by the emission of light and the creation of electrons and ions, thus generating a laser-induced plasma plume (Fig. 3). The targeting materials, surrounding medium (liquid or gas), ambient pressure, and laser parameters have an effect on structures of plasma , including plume dimensions and spectrum of emission[38].

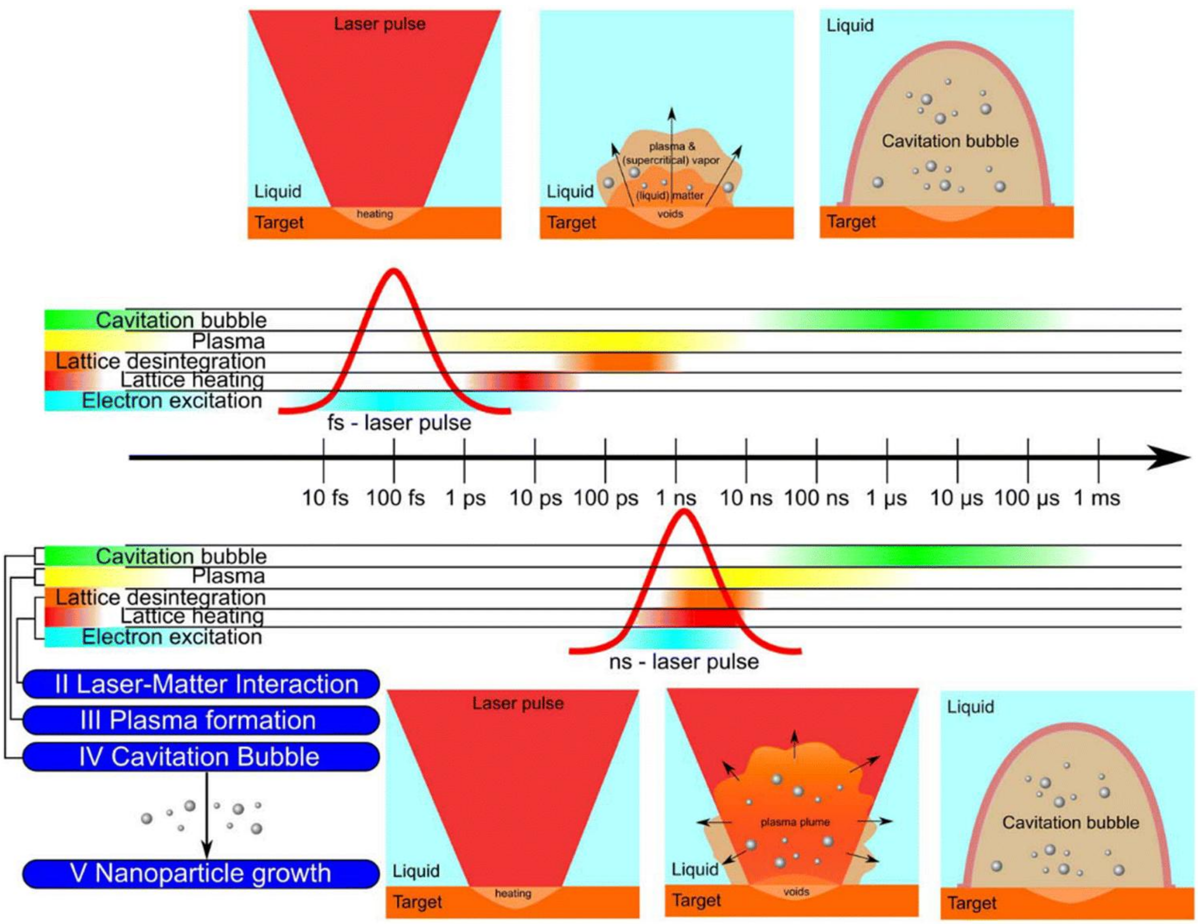

Figure 3: Schematic representation of the particle formation process in the laser ablation procedure[43].

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The mechanism for laser ablation:

The steps of the laser-induced plume formation in nanomaterials involve several complex processes, typically studied in the context of laser ablation or laser-induced breakdown spectroscopy (LIBS) in fig.4:

1-Laser Pulse Interaction: When a high-energy laser pulse strikes the surface of a material, it rapidly heats the material. This leads to a rapid increase in temperature, causing the surface to melt, vaporize, or undergo ablation. For nanomaterials, the energy input can also cause the materials to undergo non-thermal processes due to their small size and high surface area [42].

2-Plume Formation: The intense heat from the laser induces rapid vaporization and ionization of the material, resulting in the creation of a plume composed of vapour, plasma, and particles. The plume consists of ionized atoms, molecules, and clusters that are expelled from the material's surface. In the case of nanomaterials, these plumes can contain a high concentration of nanoparticles [43].

3-Plume Expansion: The laser-induced plume typically expands outward from the surface. In the initial moments after the laser impact, the plume may exhibit a high degree of turbulence. As the material cools and the plasma recombines, smaller nanoparticles can form within the plume. The temperature and pressure gradients within the plume are crucial in determining the dynamics of nanoparticle formation [46].

4-Nanoparticle Formation: In the case of nanomaterials, the plume may lead to the formation of nanoclusters or nanoparticles. The rapid cooling of the vaporized material within the plume promotes condensation, leading to the nucleation and growth of nanoparticles. This process is influenced by factors such as the pulse duration, laser intensity, and material properties [47].

5-Deposition and Nanostructuring: The expelled particles from the plume can deposit on surrounding surfaces, potentially forming thin films, coatings, or other nanostructures. The deposition process can be influenced by the velocity and kinetic energy of the particles as well as the distance from the laser focus [45].

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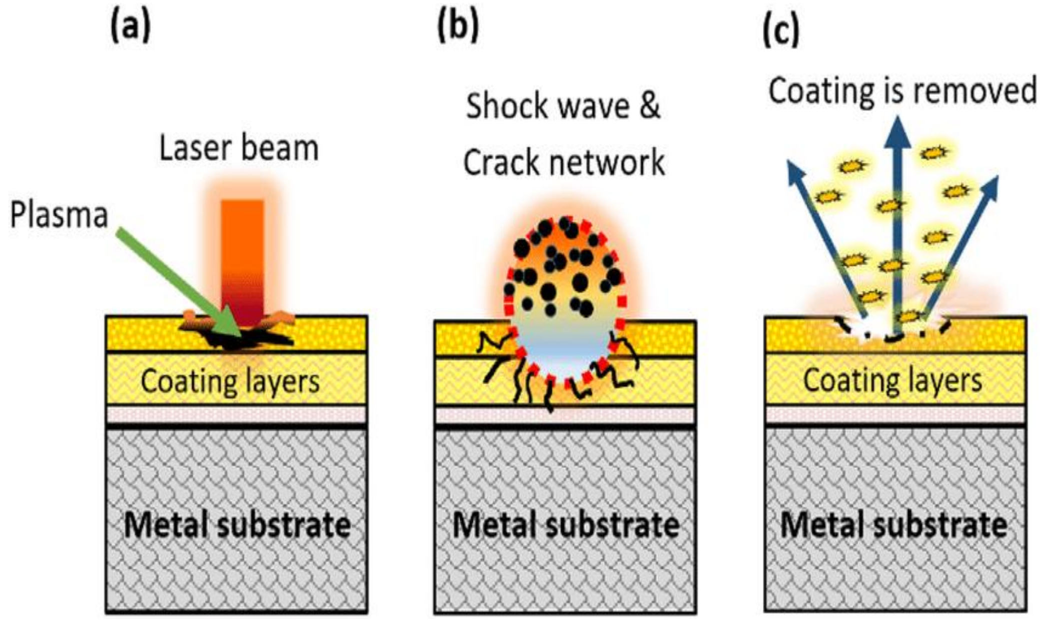

Figure 4: The Process of Laser-Induced Nanomaterial Plume[50].

Laser pulse's impact on nanoparticle formation

1. The effect of laser irradiation on number pulse wavelength:

Variable concentrations of the target material, which in turn determine its particle size, are caused by its variable absorption at different wavelengths. Yet the end materials retain their original shape [44]. The instability and thermal fluctuations caused by small particles [48].

2. The impact of varying laser the pulse widths on nanoparticles:

The main factor to obtain particles in scale nanometers is the duration of the pulse. Phase explosion replaces melting and heat evaporation as the ablation mechanism as the time scale changes from nanoseconds - picoseconds to femtoseconds. Process by laser ablation is improved when rang of pulse is very low, leading to rapid vaporization with a small heat-affected zone. The metal's lower threshold allowed for faster ablation in picoseconds rather than nanoseconds. That is according to [48]. Researchers have found that when using extremely short bursts of laser light, the amount of energy that reaches the target is quite low. Consequently, employing ultra-short laser pulse durations in the picosecond/femtosecond range is beneficial, as it may be

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Vol. 33 ; No. 3 | 2025

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utilised in various applications, including biomedical, environmental, and sensor technologies, among others [49, 50, 54].

The effect of the Laser system

Nd-YAG laser system: Nd:YAG stands for Neodymium-doped Yttrium Aluminum Garnet. It is a solid-state laser, meaning it uses a solid material (in this case, a crystal) as the gain medium to generate laser light. Nd:YAG lasers are widely used in various scientific, industrial, medical, and military applications due to their efficiency, versatility, and reliability. Gain Medium (Nd:YAG Crystal): The core of the laser is a crystal of yttrium aluminum garnet (YAG) doped with neodymium ions (Nd^{3+}). The neodymium ions are responsible for the laser action, as they can absorb energy from a pump source and then re-emit it as coherent light. Pumping Source: The Nd:YAG crystal needs external energy to excite the neodymium ions. This energy typically comes from a flashlamp (a type of electric light) or a diode laser. The pump energy excites the neodymium ions to a higher energy state. Laser Cavity: The laser cavity consists of mirrors that are positioned at both ends of the Nd:YAG crystal. One of the mirrors is partially transparent (the output coupler), allowing a portion of the light to exit as the laser beam. The other mirror is fully reflective, directing the light back through the crystal to amplify the light through multiple passes [28, 55-57].

Laser excimer ablation

An excimer laser is a form of ultraviolet (UV) laser that produces light via an excimer, a molecule composed of a noble gas (such as argon, krypton, or xenon) and a halogen (such as chlorine or fluorine). Excimer lasers are recognised for their capacity to generate high-energy, short-wavelength ultraviolet light, typically ranging from 193 nm to 351 nm. These lasers can concentrate UV light onto a small region with great precision. Gaseous substances serve as the excimer laser's active medium. From 193 to 351 nanometers is the range of the emitted beam's wavelength. Reportedly, the excimer laser has been around since the late 1970s. Gas lifetimes and electrical control systems for computers have come a long way since then [50, 54].

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CONCLUSION

Laser ablation in liquid represents a powerful tool with wide-ranging applications due to its precision, minimal thermal damage, and versatility. However, its complexity, high cost, and challenges related to scalability and medium selection pose significant hurdles. Ongoing advancements in laser technology and process optimization may mitigate some of these limitations, enhancing its practicality in industrial and research settings. Precision and control of laser ablation allow for precise material removal, offering high spatial resolution and minimal collateral damage, which is essential in applications such as microfabrication, nanotechnology, and material science. Minimal thermal damage by compared to other techniques, laser ablation in liquid typically generates less heat, reducing the potential for heat harm to adjacent materials or the intended substrate. Adaptability in This approach can be utilised on various materials, such as metals, polymers, and biomaterials, and is frequently employed in areas like nanoparticle production. surface modification, and bioengineering. Environmentally friendly laser when carried out in liquid, the process can help to reduce harmful emissions, making it more environmentally friendly compared to traditional laser ablation in air. But the limitations of laser ablation Complexity and cost the equipment for laser ablation in liquid is expensive, and the setup requires careful optimization to ensure efficient processing, making it less accessible for some applications. Dependence on liquid medium the choice of liquid medium plays a critical role in the success of the process, as it affects the laser interaction and energy transfer. In some cases, this can limit the types of materials or processes that can be effectively carried out. Scalability issues while laser ablation in liquid works well for small-scale or precision applications, scaling the process for larger volumes or industrial production can be challenging, requiring further technological advancements.

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Conflict of interest.

There are non-conflicts of interest.

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الخلاصة

المقدمة

تطورت تقنية الاستئصال بالليزر في السوائل (LAL) لتصبح طريقةً متعددة الجوانب وفعالة لإنتاج الجسيمات النانوية، ومعالجة المواد، والتطبيقات الطبية الحيوية. تتناول هذه المراجعة بشكل نقدي المبادئ الأساسية والآليات والمعايير التشغيلية المؤثرة على نتائج هذه التقنية. تقدم هذه التقنية العديد من المزايا، بما في ذلك إنتاج جسيمات نانوية فائقة النقاء، والتحكم الدقيق في حجم الجسيمات وتركيبها، وغياب الملوثات الكيميائية. كما تتيح تقنية الاستئصال بالليزر في السوائل (LAL) إمكانية التشغيل في الموقع، مما يجعلها مرغوبة للغاية في عمليات تخليق المواد المتقدمة. ومع ذلك، ورغم هذه المزايا، تواجه هذه التقنية بعض القيود، مثل انخفاض إنتاجيتها، وارتفاع استهلاكها للطاقة، وصعوبات في تحقيق توزيع موحد لحجم الجسيمات. كما أن تعقيد التفاعلات الفيزيائية والكيميائية الأساسية يُشكل صعوبات في تحسين العملية وإمكانية تكرار النتائج. تقدم هذه المراجعة مناقشة شاملة لمزايا وعيوب تقنية الاستئصال بالليزر في السوائل، مع تسليط الضوء على التطورات الحديثة والاستراتيجيات المحتملة للتغلب على قيودها. كما تستكشف هذه المراجعة اتجاهات بحثية مستقبلية لتعزيز كفاءة تقنية الاستئصال بالليزر في السوائل وقابليتها للتوسع في التطبيقات الصناعية.

الكلمات المفتاحية:.الاستئصال بالليزر النبضي ,تفاعل الليزر مع المادة ,البلازما المحتثة بالليزر