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Laser-Assisted Antimicrobial Nanotechnology: A Review

1. Introduction

The escalating global challenge of antibiotic resistance poses a significant threat to public health, demanding the urgent exploration and development of innovative antimicrobial strategies. Conventional antibiotics are increasingly losing their effectiveness against emerging drug-resistant bacteria, leading to prolonged illnesses, increased mortality rates, and a substantial burden on healthcare systems. In this context, the synergistic combination of laser technology, antimicrobial agents, and nanotechnology has emerged as a promising avenue to combat microbial infections, including recalcitrant drug-resistant strains and persistent biofilms.¹ This interdisciplinary field harnesses the unique properties of nanomaterials and the precise control offered by laser technology to develop novel approaches for preventing and treating infections. This report aims to provide a detailed overview of the current research landscape in laser-assisted antimicrobial nanotechnology, highlighting key findings, emerging trends, and potential future directions in this rapidly evolving area. The scope of this review encompasses various synthesis methods for antimicrobial nanoparticles using lasers, the diverse mechanisms of action through which these technologies combat microbes, and their wide-ranging applications in medical devices, wound healing, and the fight against antibiotic resistance and biofilms.

The increasing ineffectiveness of traditional antibiotics against a growing number of resistant strains underscores the critical need for alternative antimicrobial approaches.¹ Laser-assisted nanotechnology presents a multifaceted strategy that can potentially overcome the limitations of conventional antibiotics. This approach integrates the targeted action of lasers with the unique physicochemical properties of nanomaterials to disrupt bacterial cells and biofilms through various mechanisms that are less susceptible to traditional resistance mechanisms. Success in this research area could lead to a fundamental change in how infectious diseases are managed, potentially reducing our reliance on conventional antibiotics and mitigating the severe threat of infections that are currently becoming untreatable.

2. Laser Synthesis of Antimicrobial Nanoparticles

Lasers play a crucial role in the synthesis of nanoparticles that exhibit inherent antimicrobial properties. Among the various techniques available, laser ablation in liquids (LASL) stands out as a prominent method for producing pure and surfactant-free nanoparticles, which is particularly advantageous for biomedical applications.³ LASL involves the ablation of a solid target material immersed in a liquid medium using pulsed laser irradiation. This process generates a plasma plume, which then condenses to form nanoparticles in the liquid. A key advantage of LASL is that it does not require chemical precursors or involve chemical reactions, thus eliminating the risk of harmful byproducts that can be detrimental, especially when the nanoparticles are intended for biomedical use.³ Furthermore, the LASL technique offers the ability to control both the size and shape of the synthesized nanoparticles by carefully adjusting the laser processing parameters such as wavelength, pulse duration, and laser fluence.³

For instance, palladium nanoparticles (Pd-NPs) have been successfully synthesized using pulsed lasers with wavelengths of 532 nm and 1064 nm via LASL for subsequent antimicrobial studies.³ In one study, a palladium plate was ablated in water or methanol using these two laser sources to obtain pure Pd-NPs with a crystalline microstructure and rounded shape.³ The researchers observed that the nanoparticle size was more homogeneous when a laser wavelength of 532 nm was used, and the size further decreased to less than 6 nm when methanol was employed as the solvent.³ Nd:YAG lasers, operating at a fundamental wavelength of 1064 nm or its harmonics, are also commonly used for synthesizing various nanoparticles with antimicrobial potential. For example, nickel oxide (NiO) nanoparticles with different particle sizes have been synthesized using a nanosecond infrared Nd:YAG laser by varying the laser fluence per pulse to enhance their antibacterial activity against several pathogens.⁴ Similarly, gold nanoparticles (AuNPs) have been prepared using an Nd-YAG laser with specific parameters, including a wavelength of 1064 nm, constant ablation energy, and varying numbers of pulses.⁴ The ability to precisely control nanoparticle characteristics through laser synthesis is a significant advantage, allowing researchers to tailor their antimicrobial efficacy and biocompatibility for specific applications. This "green" approach to nanoparticle synthesis, as laser ablation is often referred to, minimizes environmental impact compared to traditional chemical methods because it avoids the use of toxic chemical precursors and byproducts.³ The specific parameters of the laser used, such as wavelength, pulse duration, and fluence, directly influence the size, shape, and ultimately the antimicrobial properties of the synthesized nanoparticles.³

3. Mechanisms of Laser-Enhanced Antimicrobial Action of Nanomaterials

Lasers and nanoparticles can work synergistically to combat microbes through several primary mechanisms, offering a multifaceted approach to antimicrobial therapy.

3.1 Photothermal Therapy (PTT)

Photothermal therapy involves the use of certain types of nanoparticles that can efficiently convert absorbed laser light into heat.² When these nanoparticles, such as gold nanorods or silver nanoparticles, are exposed to laser irradiation at a specific wavelength that matches their plasmon resonance, they generate localized heat. This increase in temperature in the immediate vicinity of the nanoparticles can lead to the destruction of bacterial cells by causing damage to their cell membranes and denaturing essential proteins.⁹ For instance, researchers have demonstrated the use of sugar-coated gold nanoparticles and laser light to rapidly destroy bacterial accumulations known as biofilms, which are often difficult to treat with conventional antibiotics.¹¹ In this study, the gold nanoparticles, encased in larger gold cages and coated with dextran, were able to convert laser light into heat, effectively killing 100 percent of the plaque on infected rat teeth.¹¹ Another application of PTT involves the evaluation of gold nanorods attached to implant surfaces for their potential as antibacterial agents to sterilize medical implants.¹⁰ Near-infrared (NIR) lasers are often preferred for PTT applications because light in the NIR range can penetrate deeper into tissues compared to visible light, allowing for the treatment of infections that are not on the surface.²

3.2 Photodynamic Therapy (PDT)

Photodynamic therapy is another mechanism that utilizes laser light and nanoparticles to combat microbes. PDT involves a photosensitizer (PS), a molecule that, upon activation by laser light of a specific wavelength, generates reactive oxygen species (ROS).¹³ These ROS, such as singlet oxygen, are highly toxic to cells and can lead to the rapid killing of bacteria. Nanoparticles can play a crucial role in PDT by acting as carriers to deliver photosensitizers to the site of infection or by enhancing the activity of the photosensitizers themselves.¹⁷ For example, blue laser-activated silver nanoparticles synthesized from grape seed extract have shown effectiveness in photodynamic antimicrobial therapy (aPDT) against both *Escherichia coli* and *Staphylococcus aureus*.¹⁴ In this case, the silver nanoparticles likely act as both a source of antimicrobial action and potentially as an enhancer of ROS generation upon blue laser irradiation. Methylene blue, a well-known photosensitizer, is often activated by diode lasers in aPDT to combat a wide range of endodontic infectious diseases.¹⁹ The combination of PDT with nanomaterials can lead to a synergistic effect, resulting in enhanced antimicrobial efficacy compared to using either PDT or nanoparticles alone.⁸

3.3 Generation of Reactive Oxygen Species (ROS) by Nanoparticles

Beyond their role in PTT and PDT, some nanoparticles, such as silver nanoparticles (AgNPs) and zinc oxide nanoparticles (ZnO NPs), possess inherent antimicrobial properties that are closely associated with their ability to generate reactive oxygen species (ROS).⁸ This ROS generation can damage various cellular components of bacteria, including membranes, proteins, and DNA, leading to cell death. Laser

irradiation can further enhance the generation of ROS by these nanoparticles, boosting their antimicrobial activity. Additionally, laser irradiation can stimulate the release of ions from certain nanoparticles, which also contribute to their antimicrobial effects. For instance, studies have shown that laser irradiation of silver nanoparticles can enhance the release of silver ions (Ag^+), which are known to have strong antibacterial properties.²³

3.4 Physical Disruption of Bacterial Membranes

Some nanomaterials, particularly those with unique structural features like sharp edges, can exert their antimicrobial action by physically disrupting bacterial cell membranes.²⁷ Graphene and its derivatives, such as graphene oxide, are examples of such nanomaterials. The sharp edges of graphene-based materials can pierce or damage the bacterial cell membrane, leading to leakage of intracellular contents and ultimately cell death.

The combination of photothermal and photodynamic therapies with nanomaterials often results in a synergistic antimicrobial effect, enhancing bacterial killing compared to individual treatments.² This suggests that simultaneously targeting multiple cellular components or pathways can be a more effective strategy against microbes, especially those that have developed resistance to traditional antibiotics. The wavelength of the laser used is critical in these processes, as it must be carefully selected to match the absorption spectrum of the nanoparticles or photosensitizer to efficiently generate heat or activate ROS.¹⁰ This highlights the need for precise control over laser parameters depending on the specific nanomaterial and the intended application. Overall, laser-enhanced antimicrobial action of nanomaterials offers diverse

mechanisms of bacterial inactivation, providing multiple avenues to target and eliminate microbes and potentially reducing the likelihood of resistance development.¹

4. Applications in Medical Devices and Coatings

The use of laser-activated or laser-synthesized antimicrobial nanoparticles in coatings for medical devices holds significant promise for preventing device-associated infections. Biofilm formation on medical implants and catheters is a major concern as it can lead to serious and often difficult-to-treat infections.³⁷

One innovative approach involves the laser treatment of metal surfaces to create nanoscale patterns that can intrinsically kill bacteria on orthopedic implants.³⁴ Researchers at Purdue University developed a one-step laser-texturing technique that enhances the bacteria-killing properties of copper surfaces, enabling them to immediately kill superbugs like MRSA.³⁷ This method creates a rugged texture with increased surface area, allowing for more direct contact with bacteria and causing their membranes to rupture.³⁷ This approach is advantageous as it modifies the surface of the metal itself, eliminating the need for coatings that could potentially leach off or be toxic.³⁷

Palladium nanoparticles (Pd-NPs) synthesized by laser ablation in liquids have also shown potential for preventing bacterial adhesion.³ A study reported that Pd-NPs immobilized on the surface of titanium discs significantly prevented the adhesion of *Staphylococcus aureus* bacteria.³ The release of palladium ions from the nanoparticles was found to play a crucial role in their bactericidal activity, and importantly, these nanoparticles also demonstrated good cytocompatibility, suggesting their potential for use in biomedical applications.³

Furthermore, light-activated antimicrobial nanoparticle-polymer composites are being explored for coating various biomedical devices.³⁴ These composites often incorporate photothermal agents (PTAs) or photodynamic agents (PDAs) that generate heat or reactive oxygen species, respectively, upon exposure to light, effectively killing bacteria and fungi.³⁴ Such coatings have the potential to provide enhanced bacterial control for a range of medical devices, including implants, catheters, meshes, and wound dressings.³⁴ Silver nanoparticles (AgNPs) are also widely investigated for their use in antimicrobial coatings for medical devices due to their broad-spectrum antimicrobial properties.²⁹

The ability of laser texturing to intrinsically enhance the antimicrobial properties of surfaces without relying on coatings that might degrade or leach off represents a significant advancement.³⁷ The development of antimicrobial coatings for medical devices using laser-based nanotechnology holds the potential to substantially reduce the incidence of hospital-acquired infections and lead to improved patient outcomes. Laser-assisted nanotechnology offers promising and durable solutions for creating effective antimicrobial surfaces on medical devices, addressing a critical need in healthcare.

5. Laser and Nanoparticles for Wound Healing and Disinfection

Lasers and nanoparticles are finding increasing applications in promoting wound healing and disinfecting infected wounds. Laser-activated nanoparticles can be employed for wound disinfection by leveraging their photothermal or photodynamic effects to kill bacteria present in the wound.¹¹

For example, researchers have developed a novel therapy using sugar-coated gold nanoparticles and laser light to rapidly disinfect infected

wounds in mice.¹¹ The gold nanoparticles, designed to target biofilms within the wounds, convert the laser light into heat, effectively killing the bacteria without the need for antibiotics.¹¹ This targeted approach minimizes potential damage to the surrounding healthy tissue.

Blue laser-activated silver nanoparticles from grape seed extract have also demonstrated efficacy in promoting wound healing in mice infected with *Staphylococcus aureus*.¹⁴ A study showed that the combination of these nanoparticles with blue laser therapy significantly improved wound healing outcomes, leading to a substantial reduction in wound size and bacterial load.⁴¹ The combined therapy also enhanced the immune response and accelerated tissue regeneration, highlighting the synergistic benefits of using nanoparticles and laser activation for wound care.⁴¹

Nanoparticle-assisted laser therapies are also being explored for treating recalcitrant infections associated with chronic, nonhealing wounds.⁴⁰ These therapies often involve using pulsed laser energy to disperse the biofilm matrix, thereby removing the barrier to antibiotic penetration and enhancing the effectiveness of antimicrobial treatments.⁴⁰ Gold nanoparticles coated with antibacterial antibodies can be used to target the infection site, and laser irradiation then causes rapid heating and mechanical damage to the biofilm and bacteria.⁴⁰

In a different approach, lasers are being used in conjunction with nanoparticle-based bonding agents for soldering wounds.⁴³ This technique involves a bonding agent containing metallic and ceramic nanoparticles that convert laser light into heat, allowing for fast, stable, and biocompatible bonding of wounds on organs and tissues.⁴³

The combination of nanoparticles and laser therapy offers a localized

and targeted approach to wound disinfection, which can potentially minimize damage to surrounding healthy tissue.¹¹ Furthermore, laser activation of nanoparticles can enhance the immune response and accelerate tissue regeneration in the wound healing process.⁴¹ Laser-assisted nanotechnology shows significant promise for revolutionizing wound care by providing effective disinfection and promoting faster healing.

6. Combating Antibiotic Resistance and Biofilms

Research projects in laser-assisted antimicrobial nanotechnology are increasingly focusing on addressing the critical challenge of antibiotic-resistant bacteria and the persistent problem of biofilm infections. Laser-activated nanoparticles offer a promising strategy to overcome antibiotic resistance mechanisms due to their multiple modes of action.¹

Near-infrared (NIR) laser-excited silver triangular nanoparticles (Tri-Ag) have been shown to efficiently kill both Gram-negative *Escherichia coli* and Gram-positive *Staphylococcus aureus*, including multidrug-resistant clinical isolates like MRSA.⁸ The combined treatment of Tri-Ag with NIR laser irradiation exhibited a synergistic antibacterial ability, demonstrating the potential of this approach to strengthen the antimicrobial arsenal against bacterial infections.⁸ The photothermal effect achieved by these nanoparticles upon laser irradiation also contributed to their synergistic antibacterial action.⁸

Gold nanoparticle-targeted laser therapy has shown promising results in enhancing the efficacy of antibiotics against MRSA biofilms.⁴⁰ A study reported that the combination of GNP-targeted pulsed laser therapy followed by gentamycin treatment led to a significant 4-log reduction in viable bacteria within the biofilms.⁴⁰ The laser therapy effectively

dispersed the biofilm, allowing the antibiotic to penetrate and act against the bacteria, suggesting a synergistic enhancement of the treatment.⁴⁰

Laser-induced graphene (LIG) has also emerged as a material with inherent antibacterial properties against various bacteria, including drug-resistant strains.³² LIG papers with tunable microstructures have demonstrated high reduction rates for both *E. coli* and *Staphylococcus aureus*.³² The antibacterial mechanism of LIG is attributed to a combination of membrane stress and reactive oxygen species-independent oxidative stress.³²

The combination of photothermal therapy (PTT) and photodynamic therapy (PDT) using multifunctional nanomaterials is another trend in combating antibiotic resistance and biofilms.² This synergistic approach leverages the advantages of both heat-induced bacterial killing and ROS generation to effectively eradicate even the most resistant microbes and disrupt the protective biofilm matrix.¹³

Furthermore, near-infrared (NIR) laser irradiation has been shown to enhance the antimicrobial photodynamic inactivation of biofilms.²⁰ Pretreating biofilms with NIR laser irradiation after exposure to a photosensitizer increased the accumulation of the photosensitizer within the bacteria and led to a significant synergistic reduction in bacterial viability upon subsequent visible light irradiation.²⁰ The NIR irradiation also helped in dispersing the biofilms and inducing clefts in the biofilm matrix, further enhancing the effectiveness of the photodynamic therapy.²⁰

Nanoparticles have the ability to enhance the efficacy of traditional antibiotics against resistant bacteria through various mechanisms,

including improving drug delivery, disrupting the biofilm structure that protects bacteria, and inhibiting the resistance mechanisms employed by the bacteria themselves.² Laser-assisted antimicrobial nanotechnology offers promising and innovative strategies to combat the growing threat of antibiotic resistance and the persistent challenge posed by biofilm infections.

7. Laser-Induced Graphene (LIG) for Antimicrobial Applications

Laser-induced graphene (LIG) is an emerging material with significant potential for creating antimicrobial surfaces and has garnered increasing attention for its diverse applications. LIG is typically generated by directly irradiating carbon-based materials, such as polyimide films, with a laser, which converts the surface into a porous, electrically conductive graphene structure.³²

Research has demonstrated that LIG exhibits inherent antibacterial and anti-fouling properties.³² For instance, studies have shown that LIG papers with tunable microstructures can achieve high reduction rates against both Gram-positive and Gram-negative bacteria.³² The interconnected open-cell network of LIG provides numerous bacteria trapping sites, contributing to its effectiveness.³² Furthermore, LIG has shown corrosion resistance, suggesting its potential for use in environmental protection applications where antimicrobial properties are needed.³²

The anti-fouling characteristics of LIG make it a promising candidate for applications in water treatment, oil drilling operations, hospitals, and various underwater applications where preventing biofilm formation is crucial.³² Notably, the antibacterial traits of LIG can be significantly enhanced by applying a low voltage current, effectively turning the

graphene into a "bug zapper" for bacteria.³³ Experiments have shown that applying a low voltage (e.g., 1.5 V) to LIG electrodes in a solution containing *Pseudomonas aeruginosa* bacteria can lead to the complete disappearance of the bacteria within 30 seconds.⁴⁵ At a higher voltage (e.g., 2.5 V), surface bacteria almost completely disappeared within just one second.⁴⁵

The method of producing LIG by laser irradiation is scalable and allows for the creation of graphene patterns on various surfaces, offering versatility in designing antimicrobial materials for different applications.³² The ability to tune the microstructure and properties of LIG by adjusting laser parameters further enhances its potential for tailored antimicrobial applications. Laser-induced graphene represents a novel class of antimicrobial materials with unique properties and a wide range of potential uses, from medical devices to environmental protection.

8. Challenges and Future Perspectives

While laser-assisted antimicrobial nanotechnology holds tremendous promise, several challenges need to be addressed to facilitate its widespread clinical translation. One significant concern is the potential for cytotoxicity associated with some nanoparticles.¹ Studies have shown that certain nanoparticles, particularly silver nanoparticles, can exhibit toxicity to human cells depending on factors such as size, concentration, and exposure time.⁴² Therefore, the development of more biocompatible and targeted nanomaterials is crucial for ensuring the safety of these therapies.²

Another challenge lies in achieving precise and efficient delivery of nanoparticles to deep tissues and infection sites within the body.⁴⁰

Current limitations in nanoparticle delivery, particularly to sites without sufficient vasculature, may restrict the applicability of certain laser-nanoparticle therapies to surface infections or localized abscesses.⁴⁰ Advancements in targeted drug delivery systems using functionalized nanoparticles that can specifically bind to bacteria or infected tissues are needed to overcome this limitation.²

The standardization of treatment protocols for laser-assisted antimicrobial therapies is also essential for their successful clinical implementation.¹⁶ Variations in laser parameters, nanoparticle concentrations, and treatment durations across different studies highlight the need for establishing optimized and reproducible protocols to ensure consistent efficacy and safety.¹⁶

Understanding the long-term effects of nanoparticle exposure and the potential for bacteria to develop resistance to the mechanisms of action of nanoparticles are also important considerations.¹ While nanoparticles often exhibit multiple modes of action that make it difficult for bacteria to develop resistance, further research is needed to fully assess this aspect and to develop strategies to mitigate any potential for resistance emergence.¹

Looking towards the future, several trends and potential advancements in the field of laser-assisted antimicrobial nanotechnology can be anticipated. The development of more biocompatible and targeted nanomaterials with enhanced antimicrobial efficacy and reduced toxicity will be a key focus.² Combination therapies that synergistically integrate photothermal, photodynamic, and other antimicrobial mechanisms using multifunctional nanomaterials are expected to gain further traction.² The exploration of new nanomaterials beyond noble

metals, such as metallic compounds, carbon-based materials, and organic photothermal polymers, as well as the optimization of various laser sources and their parameters, will continue to drive innovation in this field.² Advanced microscopy and imaging techniques will play an increasingly important role in understanding the interactions between nanomaterials, lasers, and bacteria at the nanoscale, facilitating the design of more effective therapies.⁵⁰ The development of intelligent and responsive nanosystems that can sense the local environment of infection and deliver therapy on-demand with high precision represents another exciting future direction.² Furthermore, there is a growing interest in utilizing natural compounds in the synthesis of nanoparticles to reduce manufacturing costs, minimize environmental impact, and potentially enhance biocompatibility.⁴¹ Ultimately, continued rigorous in vitro and in vivo studies, followed by well-designed clinical trials, will be crucial for translating the promising findings from the laboratory into effective and safe clinical applications of laser-assisted antimicrobial nanotechnology.

While laser-assisted antimicrobial nanotechnology shows great promise, its successful transition to widespread clinical use necessitates careful consideration of the biocompatibility and potential toxicity of nanomaterials, as well as the development of standardized and effective methods for delivering these therapies to the site of infection.¹ Future research efforts should prioritize the development of safer and more targeted nanomaterials, optimizing laser parameters for specific applications, and conducting thorough in vivo studies and clinical trials to validate the efficacy and safety of these innovative approaches.

9. Conclusion

The research landscape of laser-assisted antimicrobial nanotechnology reveals a highly promising and versatile field with significant potential to address the escalating global challenge of antibiotic resistance and the persistent problem of biofilm infections. This review has highlighted the diverse synthesis methods for antimicrobial nanoparticles using lasers, the various mechanisms of action through which these technologies combat microbes, and their wide-ranging applications in medical devices, wound healing, and the fight against drug-resistant bacteria. The synergistic combination of laser technology and nanotechnology offers unique advantages, including targeted action, multiple mechanisms of bacterial inactivation, and the potential to enhance the efficacy of conventional antibiotics. While challenges such as nanoparticle cytotoxicity and delivery limitations remain, ongoing research and development are actively addressing these issues. The future of this field is bright, with trends pointing towards the development of more biocompatible and targeted nanomaterials, the exploration of innovative combination therapies, and the refinement of laser-based techniques for a wide array of antimicrobial applications. As research continues to advance, laser-assisted antimicrobial nanotechnology holds the promise of revolutionizing the prevention and treatment of infectious diseases, ultimately leading to improved healthcare outcomes in an era of increasing antibiotic resistance.

Table 1: Comparison of Nanoparticles Used in Laser Antimicrobial Research

Nanoparticle Type	Laser Activation Wavelength (nm)	Primary Mechanism of Antimicrobial Action	Key Applications Mentioned in Research	Relevant Snippet IDs
Silver (AgNPs)	405 (Blue), NIR (808, 980)	PDT (ROS Generation), Photothermal Therapy, Ion Release	Wound disinfection, biofilm eradication, medical device coatings, multidrug-resistant bacteria	8
Gold (AuNPs)	NIR	Photothermal Therapy	Biofilm disruption, wound disinfection, medical implants	9
Palladium (Pd-NPs)	532, 1064	Ion Release, Membrane Disruption	Prevention of bacterial adhesion on titanium	3

Zinc Oxide (ZnO NPs)	UV	ROS Generation, Membrane Disruption	Antimicrob ial coatings	²⁷
Graphene (LIG)	Various	Membrane Stress, Oxidative Stress (ROS- independen t)	Antimicrob ial surfaces, water treatment, medical devices	³²

Table 2: Examples of Laser Parameters in Antimicrobial Nanotechnology Research

Nanop article Materi al	Laser Type	Wavel ength (nm)	Pulse Durati on	Fluenc e/Powe r Densit y	Applic ation	Releva nt Snippe t IDs
Palladi um (Pd)	Nd:YV O4 (Diode- pumpe d)	532, 1064	14 ns, 20 ns	0.26 mJ, 0.36 mJ	Synthe sis	³
Copper	-	-	-	-	Surface Texturi	³⁷

(Cu)					ng	
Silver (Ag)	NIR	808	-	0.5 W/cm ²	Activat ion (Photot hermal)	8
Graphe ne	-	-	-	1.25 W (proces sing power exampl e)	Synthe sis	32
Silver (Ag)	Diode	405	-	3.44 J/cm ² (energy density)	Activat ion (Photo dynami c)	14
Cyanob acterial Extract	-	-	-	32 min time, 10 cm distanc e (dose)	Enhanc ement of efficac y	15

Nickel Oxide (NiO)	Nd:YAG	1064	Nanosecond	Varied per pulse	Synthesis	⁴
Gold (Au)	Nd-YAG	1064	-	1000 mJ (energy), 1 Hz (frequency)	Synthesis	⁴
Silver (Ag)	Picosecond	-	-	-	Synthesis	⁴⁸
Gold (Au)	Nanosecond	-	-	-	Activation (Photothermal)	⁴⁰
ZnO	Nd:YAG	355	15 ns	-	Synthesis (PLD)	³⁸
Silver (Ag)	Red Laser	405	-	3.44 J/cm ² (energy density)	Activation (Photodynamic)	⁴¹

				)	c)	
Porphy rin (TAPP)	NIR	980	Contin uous	7.5 W/cm², 30 s (225 J/cm²)	Enhanc ement of PDI	20

Table 3: Summary of Key Findings from Studies on Laser-Assisted Antimicrobial Nanotechnology

Research Focus	Nanoparti cles Used	Laser Type and Parameters	Key Findings	Relevant Snippet IDs
MRSA Biofilm Treatment	Gold Nanopartic les (GNPs) coated with antibodies	Nanosecond pulsed laser	Synergistic 4- log reduction in viable bacteria when combined with gentamycin; biofilm dispersal.	40
Multidrug- Resistant Bacteria	Silver Triangular Nanopartic	Near- Infrared	Efficient killing of Gram-negative	8

Eradication	les (Tri-Ag)	(808 nm)	and Gram-positive MDR bacteria in vitro and in vivo; synergistic antibacterial effect via photothermal treatment.	
Wound Disinfection	Sugar-coated Gold Nanoparticles	Laser light	Rapid destruction of bacterial biofilms in vitro and in vivo (mice and rats) without antibiotics; outperformed conventional antiseptic and antimicrobial agents.	11
Wound Healing and Bacterial Load Reduction	Silver Nanoparticles from	Blue Laser (405 nm, 3.44 J/cm ²)	Significant improvement in wound	14

	Grape Seed Extract (GSE-AgNPs)		healing, 88.73% decrease in <i>S. aureus</i> bacterial load, enhanced immune response in mice.	
<i>Staphylococcus aureus</i> Inhibition	Palladium Nanoparticles (Pd-NPs)	Pulsed Lasers (532 nm, 1064 nm)	Immobilized Pd-NPs on titanium discs prevented <i>S. aureus</i> adhesion; significant antibacterial effect with good cytocompatibility.	3
Antibacterial Activity against <i>E. coli</i> and <i>S. aureus</i>	Laser-Induced Graphene Papers (LIGPs)	Laser processing at 1.25 W	Highest reduction rate of 92.8% for <i>E. coli</i> and 95.2% for <i>S. aureus</i> ;	32

			corrosion resistance demonstrated.	
Biofilm Inactivation of <i>S. aureus</i>	Porphyrin (TAPP)	NIR Laser (980 nm, 225 J/cm ²) followed by Visible Light	Synergistic 4.4-log CFU reduction when NIR irradiation preceded visible light PDI; increased PS accumulation and biofilm dispersal.	20
Enhanced Antibacterial Efficacy of Cyanobacterial Extracts	Aqueous Extracts of <i>Thermoleptolyngbya</i> sp. and <i>Leptolyngbya</i> sp.	Laser treatment (visible light)	Direct laser exposure of extracts significantly increased antimicrobial efficacy against <i>S. aureus</i> and MRSA; enhanced accessory	15

			pigment content.	
Photodynamic Antimicrobial Therapy against <i>E. coli</i> and <i>S. aureus</i>	Silver Nanoparticles from Grape Seed Extract (AgNPs-GSE)	Blue Laser (405 nm, 3.44 J/cm ²)	Effective photoinactivation of both bacteria; higher efficacy against <i>S. aureus</i> compared to <i>E. coli</i> ; concentration and time-dependent reduction in viability.	14
Antimicrobial Activity of NiO Nanoparticles	Nickel Oxide (NiO)	Pulsed Laser Ablation in Liquid Media (Nd:YAG, Infrared)	Synthesis of NiO nanoparticles with varying particle sizes by adjusting laser fluence; enhanced antibacterial activity against	4

			several pathogens.	
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