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Review

Advanced Laser Techniques for the Development of Nature-Inspired Biomimetic Surfaces Applied in the Medical Field

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Abstract: This review focuses on the innovative use of laser techniques in developing and functionalizing biomimetic surfaces, emphasizing their potential applications in the medical and biological fields. Drawing inspiration from the remarkable properties of various natural systems, such as the water-repellent lotus leaf, the adhesive gecko foot, the strong yet lightweight spider silk, and the unique optical structures of insect wings, we explore the potential for replicating these features through advanced laser surface modifications. Depending on the nature and architecture of the surface, particular techniques have been designed and developed. We present an in-depth analysis of various methodologies, including laser ablation/evaporation techniques, such as Pulsed Laser Deposition and Matrix-Assisted Pulsed Laser Evaporation, and approaches for laser surface structuring, including two-photon lithography, direct laser interference patterning, laser-induced periodic surface structures, direct laser writing, laser-induced forward transfer, and femtosecond laser ablation of metals in organic solvents. Additionally, specific applications are highlighted with the aim of synthesizing this knowledge and outlining future directions for research that further explore the intersection of laser techniques and biomimetic surfaces, paving the way for advancements in biomedical applications.

Keywords: biomimetic materials; surface functionalization; laser techniques

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1. Introduction

The convergence of nanotechnology and biomimicry has given rise to innovative materials that have the potential to revolutionize the medical field, particularly through the development of biomimetic coatings and the application of surface structuring techniques. These modified surfaces are engineered to replicate the structure (at the micro- and nanoscales) and functionality of natural biological systems, exhibiting remarkable properties such as mechanical strength, chemical resistance, and biological compatibility. Such attributes are critical in medical applications, where enhancing biocompatibility, minimizing infection rates, and promoting tissue integration are paramount [1,2].

By studying the adjustment of various organisms, researchers can leverage these insights to improve the performance of medical devices. Surfaces exhibiting specialized features, like textured patterns that enhance wettability, are tailored to specific performance enhancements, ultimately leading to more effective medical solutions [3].

Upon conducting an extensive review of recent literature and our research findings on anti-bacterial, anti-adhesive, anti-cancer, self-cleaning, anti-corrosion, and other capabilities inspired by nature, we have identified that surface functionalization (by surface structuring/patterning and coatings deposition) produced by advanced additive and laser-based techniques has great potential for medical applications.

This review offers a critical insight into the latest progress in the development of nano- or microstructured surfaces for medical devices, with a particular focus on the contribution of laser-based technologies in their fabrication.

The goal is to provide a comprehensive resource for researchers and practitioners looking to drive innovation in the biomedical device field. It outlines the current trends in laser technology used for designing surfaces inspired by nature, illustrating how the latest advancements can bridge the gap between the theoretical research and the practical application in medicine. Biomimetic surfaces present significant potential for industrial innovation, particularly within the biomedical sector, where optimizing surface properties is crucial for improved outcomes.

The image depicted in Figure 1 illustrates various natural systems that serve as the inspiration for laser-based surface functionalization, outlining their prospective medical applications. This encompasses a range of materials, from gecko-inspired adhesives designed for wound care to structures emulating bone for enhanced regeneration and drug delivery. Additionally, we explore surface designs derived from lotus leaves for anti-fouling purposes and butterfly wings for novel imaging techniques. The corresponding laser techniques such as Pulsed Laser Deposition (PLD), Matrix Assisted Pulsed Laser Evaporation (MAPLE), Two-Photon Lithography, Direct Laser Interference Patterning (DLIP), Laser-Induced Periodic Surface Structure (LIPSS), Direct Laser Writing (DLW), Femtosecond Laser Ablation of Metals in Organic Solvents (FLAMOS) and Laser-Induced Forward Transfer (LIFT) are also highlighted for their roles in advancing these innovations.

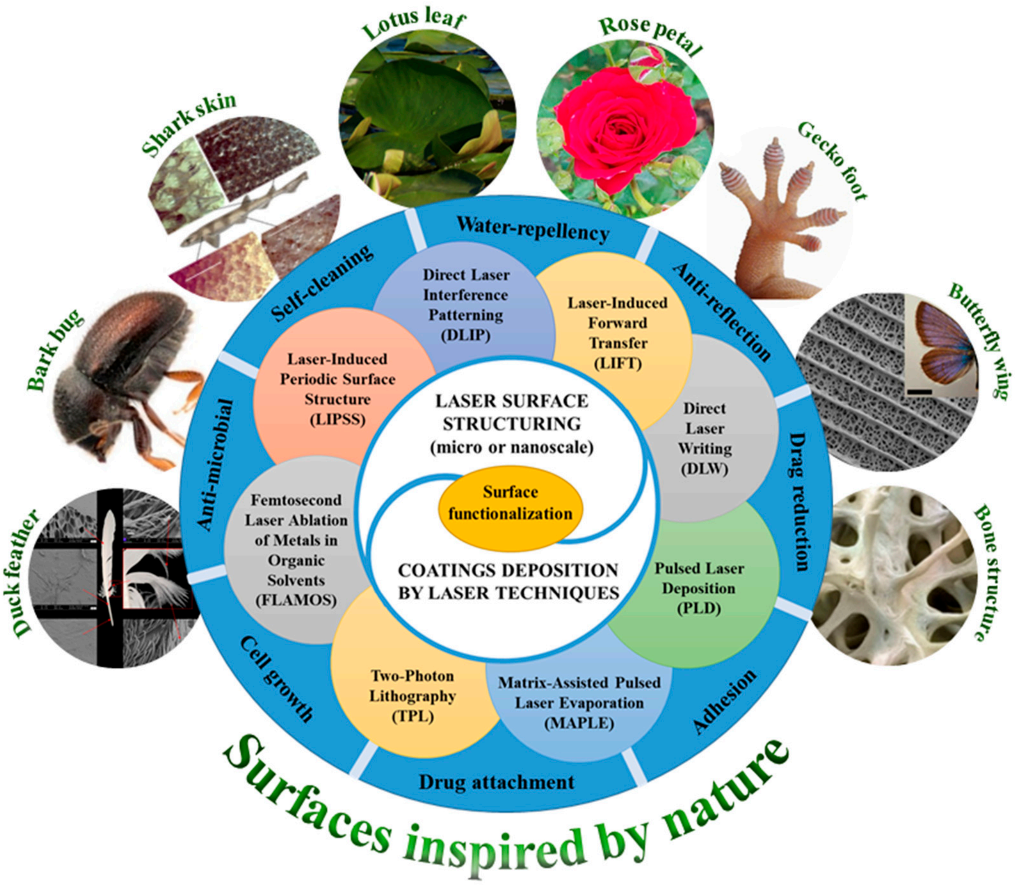

Figure 1. Surface functionalization by laser techniques to mimic natural systems [4–9].

As the integration of advanced laser techniques in the fabrication of biomimetic coatings and in the surface structuring process continues to evolve rapidly, there is an increasing need to consolidate existing research findings. The growing interest in this area is evidenced by the abundance of relevant publications, which points to the need for a thorough review that integrates laser techniques with the development of biomimetic surfaces. The literature reveals a specific interest in nature-inspired surfaces for medical applications while also indicating a broader discussion around biomimetic materials that emphasize the unique contributions of laser technologies. This underscores the necessity for advancing scientific dialogue on the substantial benefits of these techniques in the healthcare domain.

In brief, this review seeks to expound on the concept of biomimetic surfaces achieved by laser techniques, offering a detailed examination of their principles and various applications in medicine. By emphasizing the significance of these innovative surfaces, we aim to inspire further exploration into the intertwined fields of biomimicry, nanotechnology, and laser fabrication, ultimately fostering advancements that closely address the critical needs within the realm of the healthcare sector.

2. Biomimetic Coatings

Nature has always been an important source of inspiration in the technological and engineering fields. The term "biomimetic" is derived from the Greek word "bios", which means "life", and "mimetic", which means "to imitate". Biomimetics involves imitating nature in the fight against failure. It seeks to understand the principles of natural systems in order to create new engineering designs. The first patent for a biomimetic application dates back to 1952 and involved the design of a Velcro strip inspired by the interaction between a cocklebur fruit and a dog's fur [10]. Since then, many new applications have emerged from the observation of natural systems. The lotus effect and sharkskin have inspired new surface technologies to improve fluid flow dynamics, while bird and insect wings have been the motivation behind innovative aerodynamic designs. Materials science is another area in which biomimetics has played an important role, with potentially limitless applications in the medical industry. As the number of patients waiting for organ transplants greatly surpasses the number of organs available, there is a critical need for new types of implantable medical devices. Ideally, these devices should replicate the function of natural organs to the point of facilitating the body's own healing mechanisms and should eventually be resorbed and replaced by the body's own tissue [11].

Biomimetic coatings, also known as nature-inspired coatings, are surface coatings that are fabricated to mimic natural processes and structures found in living organisms. They are designed to replicate the functionalities and properties of natural materials, such as self-cleaning of the surface, water repellency, anti-fouling mechanism, drag reduction (for marine vessels), anti-corrosion, or anti-bacterial nature. The significance of biomimetic coatings lies in their potential to address various industrial and environmental challenges. For instance, they could lead to the development of more sustainable and eco-friendly materials, as well as innovative solutions for medical devices, architecture, and energy production. By drawing inspiration from nature, biomimetic coatings can provide a novel approach to material design and production that is both efficient and environmentally friendly [12]. The use of laser techniques for the fabrication of biomimetic coatings offers a promising opportunity for the development of advanced materials that can address various industrial and social challenges. This also contributes to the advancement of scientific knowledge and understanding of natural systems [13].

The integration of laser techniques in the fabrication of these coatings allows for precise control over surface textures and topographies, enabling the replication of complex natural structures at a micro and nanoscale [11]. The following section serves as an introduction to the extensive study of laser techniques used to create biomimetic surfaces inspired by nature. It aims to clarify the fundamental knowledge necessary for a thorough grasp of the topic. Furthermore, we will explore how nature has influenced the development of these surfaces, highlighting the remarkable diversity and efficiency of natural structures that serve as a model for innovative coating materials.

3. Overview of Advanced Laser Techniques Used for Nature-Inspired Biomimetic Surfaces Fabrication

3.1. Fundamentals of Laser Techniques

In recent years, laser technology has emerged as a powerful tool for enhancing biomimetic coatings and the structuring of surfaces in medical applications. It provides precise control over surface modifications and allows for tailored functionalities that meet specific requirements. Thus, such surfaces mimic natural biological surfaces to improve biocompatibility, reduce infection rates, and enhance integration with host tissues.

These laser techniques have advantages, including accurate control, high power density, and short duration of laser energy. Laser-assisted processing of material can improve the efficiency of coating fabrication and surface structuring by reducing variations, defects, and stress compared with traditional thermal flow-based techniques.

Despite the inherent capabilities of laser techniques, such as the accurate control over the heating procedure, localized heating effect, and adjustable energy flux density, the fabrication of functionalized surfaces using these methods presents challenges and requires specific guidelines in order to meet the demands of biomimetic coatings [14].

The term "laser" is derived from Light Amplification by Stimulated Emission of Radiation, and the laser is a coherent, monochromatic light produced by specific means, such as the optical resonant cavity, active medium, and driving energy. Characterized by coherence and one-dimensional radiation, laser energy has the ability to be concentrated onto a tiny point, which leads to the geometrical advantages of the laser technique: a localized and small heating area. As a result, the material can be quickly heated or melted by laser energy with precise control. Furthermore, the adjustable energy flux density of laser energy, in conjunction with different approaches to applying the laser energy, could lead to a range of methods for the coatings fabrication, satisfying targeted requirements [15].

Laser irradiation stands at the forefront of biomimetic surface fabrication, offering unparalleled capabilities in modifying surface properties with precision and efficiency. Laser irradiation for surface functionalization and activation involves altering surface chemistry and morphology by creating micro and nanostructures on surfaces to modify wettability, friction, and optical characteristics and also to enhance biocompatibility, promote cell adhesion, and facilitate specific biological interactions. As well, by irradiating biomaterial surfaces with laser pulses, researchers can create structures that mimic natural surfaces like the lotus leaf [16–18], rose petal [19,20], gecko foot [21,22], moth eye [23–25], butterfly wing [26], bark bug [27], duck feather [28], or shark skin [28,29], known for their self-cleaning, adhesive, anti-reflection, and water-repellent properties, respectively. Such biomimetic surfaces are particularly valuable in medical implants, where improved integration with surrounding tissues and a reduced risk of infection is critical [30].

Next, we will explore the basic principles of laser technology utilized for surfaces functionalization by biomimetic coatings and structuring in medicine. For example, laser ablation is a fundamental process used to modify the surface morphology and chemistry by structuring or biomimetic coatings synthesis. It involves the removal of material from the surface using laser pulses, which can be focused on micron-scale dimensions. By adjusting laser parameters such as pulse duration, energy density, and wavelength, researchers can precisely tune the surface (by laser structuring or by biomimetic coating deposition). This process creates hierarchical surface structures that mimic natural tissue interfaces, enhancing cellular adhesion and promoting tissue integration [31].

Surface functionalization via laser structuring enables precise spatial control over surface properties. Through techniques such as laser lithography or direct laser writing, researchers can create micro- and nanoscale patterns on surfaces. These patterns can influence cell alignment, guide neurite outgrowth, or control drug release kinetics from coated implants. Laser patterning also facilitates the incorporation of bioactive molecules or nanoparticles onto biomimetic coatings, enhancing their therapeutic efficacy and biological functionality. Laser-assisted techniques can facilitate the deposition of biomolecules onto biomimetic coatings with high spatial resolution and minimal thermal damage [32]. For example, Laser-Induced Forward Transfer (LIFT) enables the transfer of bioactive compounds, growth factors, or DNA sequences onto targeted regions of biomimetic coatings. This precise deposition method ensures controlled release kinetics and spatially defined bioactivity, which are essential for applications such as localized drug delivery or gene therapy [33].

Table 1 outlines the advantages and benefits of using laser techniques in surface structuring and coatings deposition, which have been proven to be superior compared to the conventional method. As already reported in the literature and sustained by the various cited studies reported in Table 1, the greatest advantage of laser techniques is the ability to process onto the substrate through a physical and/or chemical action, which facilitates the formation of a well-adherent coating by modifying the substrate surface. A consequence of these methods is the formation of tensile stress in the coating. This occurs as a result of the rapid cooling of the coating material. If the substrate has poor thermal conductivity, such as glass or ceramic, the stress can lead to cracking or delamination of the coating, making it unsuitable for its intended purpose. Therefore, the formation of a well-adherent coating by modifying the substrate surface is perhaps the greatest advantage of laser techniques in producing coatings on ceramic, metallic, and polymeric substrates. According to the authors, this is in stark contrast to the optical and thermal methods, in which coatings are subject to severe thermodynamic nonequilibrium during the growth phase. This has several implications; first, it induces some phase changes or interdiffusion between the coating materials and the substrate, thus undermining the protective or functional properties that the coating was initially designed for.

Table 1. Advantages and Limitations of Laser Techniques in Surface Functionalization.

Advantages	Limitations	References
PRECISION: Laser techniques allow for high level of accuracy, ensuring precise surface structuring or deposition of coatings.	COST: Laser deposition/structuring methods are expensive due to the need for high-end technical equipment.	[34]
SURFACE QUALITY: The technique results in excellent surface quality essential for medical purposes.	SKILL REQUIREMENT: Operation of laser equipment requires trained professionals, limiting its widespread use.	[35]
VERSATILIY: These techniques allow the processing of various materials, thus allowing the obtaining of biomimetic surfaces	EQUIPMENT SIZE: The equipment used for laser deposition/structuring is generally large and not suitable for small operations.	[36]
PROCESS CONTROL: Enable strict control of the structuring and deposition process resulting in surfaces with desired properties.	HEAT: Laser techniques produce high levels of heat which could cause damage to sensitive materials.	[37]
RAPID PROTOTYPING: Laser techniques enable fast fabrication for rapid testing and deployment.	COMPATIBILITY: Some materials may not be compatible with laser deposition/structuring techniques.	[38]
ENVIRONMENT FRIENDLY: Most laser techniques do not use harmful chemicals.	SCALABILITY: Scaling up the production could be challenging and expensive (factors such as cost, processing speed, and resolution may also impact the feasibility of laser patterning for certain applications). Also, the potential for thermal damage to the material being processed, limited depth of focus leading to difficulty in patterning complex structures, and restrictions on the types of materials that can be effectively patterned using laser technology.	[39]

The integration of laser-functionalized biomimetic coatings into medical devices, implants, and tissue engineering scaffolds is driven by their enhanced biocompatibility and tailored biological interactions. Laser technology enables the fabrication of biomimetic surfaces that promote cell adhesion, proliferation, and differentiation while minimizing immune response and inflammatory reactions. Moreover, the scalability and versatility of laser-based techniques facilitate their transition from laboratory research to clinical applications. This opens up possibilities for tailored approaches in personalized healthcare and regenerative treatments.

3.2. Types of Lasers Used for Surface Structuring and Coatings Fabrication

In the continuously expanding field of surface functionalization, the selection of laser technology is essential for replicating the functionality and structure of natural systems. Each type of laser brings distinct advantages in terms of precision, efficiency, and the ability to manipulate materials at the micro- and nanoscales.

Figure 2 provides a comprehensive overview of the most common lasers, including details about their specific wavelengths.

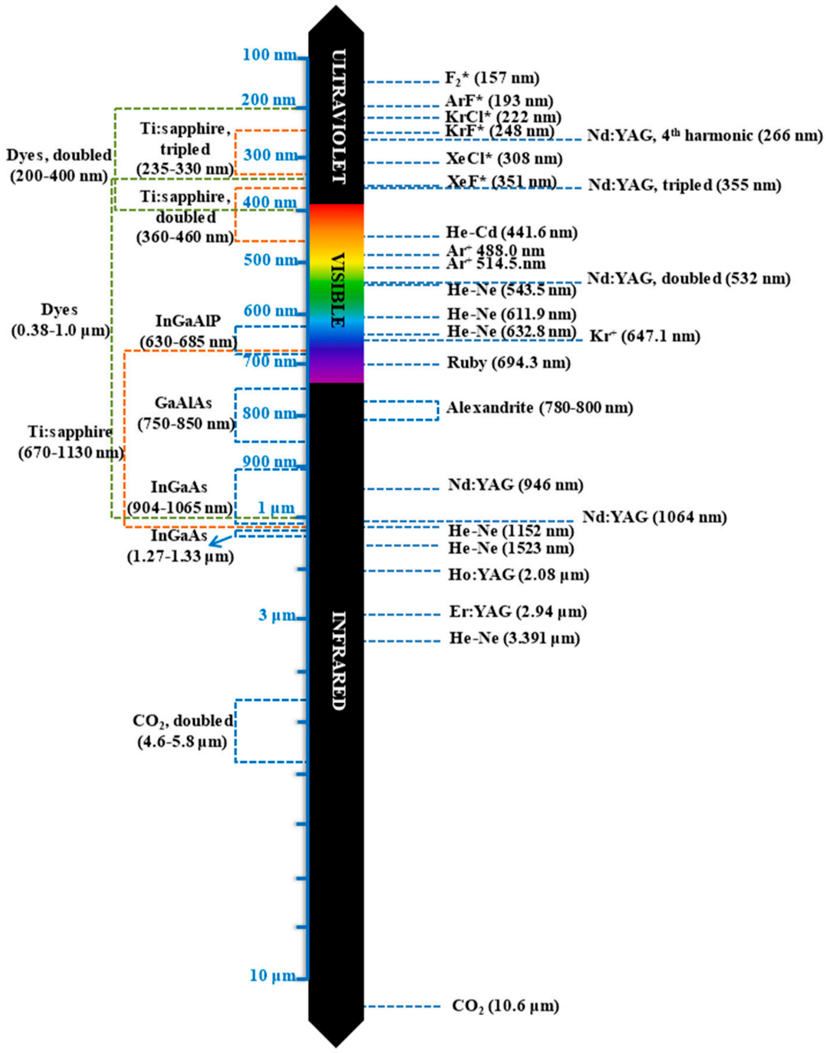

Figure 2. Overview of laser systems with their wavelength range [40–43].

Among the various types of lasers developed, only a few have been used to modify surfaces and create coatings. These are in the ultraviolet (UV), visible, and near-infrared regions, which have sufficient photon energy to initiate the ablation and photodecomposition of the coating materials. UV lasers such as the excimer laser (e.g., ArF*—193 nm, KrF*—248 nm) and the frequency-quadrupled solid-state laser (e.g., Nd:YAG—266 nm) have shorter wavelengths and higher photon energy. They can be used to ablate a wide range of materials without causing significant heat damage, resulting in minimal heat-affected zones and reduced redeposition of the removed material. UV lasers are mainly employed for precise micromachining applications, utilizing photodecomposition to achieve material removal without generating excessive heat. Solid-state lasers, such as the diode laser (which can be either single-mode or multi-mode, with a very high power of up to 20 kW), push-pull, end-pumped Nd:YAG (wavelengths of 946 nm, 1064 nm) and Nd:YAP (1370 nm), Yb:YAG (1030 nm), and Yb:YLF (currently developed with a wavelength of 1047 nm), have longer wavelengths and lower photon energy. They can be conveniently absorbed by most materials. Solid-state lasers are commonly used to cut, weld, and surface-treat materials [44]. Ultraviolet, deep ultraviolet, and vacuum ultraviolet excimer-laser pulses have high peak power and can be absorbed efficiently over very short penetration depths. When the radiant energy is absorbed, it results in extremely high-temperature and pressure conditions in the irradiated material, which is driven out in the form of plasma. The highly energetic, short-wavelength excimer laser is particularly suited for this. Its pulse duration is very short, and the radiant energy is delivered in very narrow bandwidths. These features make the excimer laser more efficient in ablating materials than other lasers, creating minimal heat-affected zones and allowing a very high-precision removal of materials. Laser-surface interactions can be more complex than what is typically assumed for simple photodecomposition. When nanosecond or picosecond laser pulses on the order of tens or hundreds of picoseconds are used, shockwaves may be generated, contributing to the material removal. Additionally, the ablation of deeply absorbing metal coatings on poor absorbers necessitates a thermal process that extends beyond the pure plasma-driven ejection of material [45,46]. The use of various lasers, including femtosecond, excimer, and Nd:YAG lasers, provides the flexibility needed to achieve the desired effects on different materials. As the field progresses, the combination of laser patterning with advanced materials and real-time monitoring technologies promises to further enhance the capabilities and applications of biomimetic surfaces. The ongoing exploration of new biological inspirations and the continuous refinement of laser techniques will undoubtedly lead to innovative solutions that push the boundaries of surface engineering, offering significant benefits across numerous industries [47]. Femtosecond lasers are ultrafast lasers that emit pulses with durations in the femtosecond range (10^{-15} s), allowing for extremely precise ablation with minimal thermal damage. Femtosecond lasers are ideal for creating intricate nanostructures and are widely used in applications requiring high-resolution patterning. On the other hand, excimer lasers are commonly used for photolithography and surface modification. Their high photon energy makes them suitable for precise etching and surface activation [48]. Neodymium-doped yttrium aluminum garnet (Nd) lasers are versatile and can be used in both continuous and pulsed modes. They are effective for a wide range of materials and are often employed in industrial applications [49,50].

Table 2 provides an overview of the various laser-based techniques employed for surface functionalization by surface structuring or biomimetic coatings fabrication. This table outlines the functionalization type, the specific techniques, their applications, and laser types. Additionally, relevant references are provided to offer further reading and an in-depth exploration of each technique.

Table 2. Various laser-based techniques employed in surface structuring and biomimetic coatings fabrication.

Type of Surface Functionalization	Laser Technique	Applicability	Types of Lasers Used for Fabrication of Biomimetic Coatings	Ref.
Biomimetic coatings deposition	Pulsed Laser Deposition—(PLD) [51–53]	Implantable medical devices, wound healing, tissue engineering, drug delivery	Nd:YAG, UV Excimer (e.g., ArF* and KrF*)	[35,37,54–57]
	Matrix Assisted Pulsed Laser Evaporation (MAPLE) [51,58]			

Table 2. *Cont.*

Type of Surface Functionalization	Laser Technique	Applicability	Types of Lasers Used for Fabrication of Biomimetic Coatings	Ref.
Laser surface structuring (micro- or nanoscale)	Two-Photon Lithography [59]	Implantable medical devices (e.g., cardiovascular bare-metal stents [60], orthopedic applications [61]), tissue engineering, drug delivery	CO_2 UV Excimer, Diode laser	[62–65]; [21,66–70]; [71–73]
	Direct Laser Interference Patterning (DLIP) [74–76]			
	Laser-Induced Periodic Surface Structure (LIPSS) [77,78]			
	Direct Laser Writing (DLW) [79,80]			
	Laser-Induced Forward Transfer (LIFT) [81,82]			
	Femtosecond Laser Ablation of Metals in Organic Solvents—(FLAMOS) [83,84]			

3.3. Advanced Laser Processing for Nature-Inspired Biomimetic Surfaces Fabrication

3.3.1. Laser Surface Functionalization by Biomimetic Coatings

Surface modification, often accompanied by the change of the bulk material properties through physical or chemical alteration or covering with thin films of a different material, is generally part of surface engineering. Its objective is to enhance the performance and functionality of surfaces and substrates when they interact with the surrounding environment by developing new solutions to improve functional characteristics such as physical, chemical, mechanical, optical, and electrical properties, as well as wear resistance and wettability [85,86].

The laser is a versatile tool capable of fabricating a variety of thin films (nanocomposite coatings, amorphous, nanocrystalline, polycrystalline or monocrystalline films, as well as multilayers or superlattices), starting from simple, complex or multi-component materials. By directing a laser beam to heat a target within a vacuum, atoms can be evaporated and deposited onto a substrate (Figure 3a). Additionally, lasers can be used to initiate chemical reactions, leading to the deposition of dispersed products [87,88].

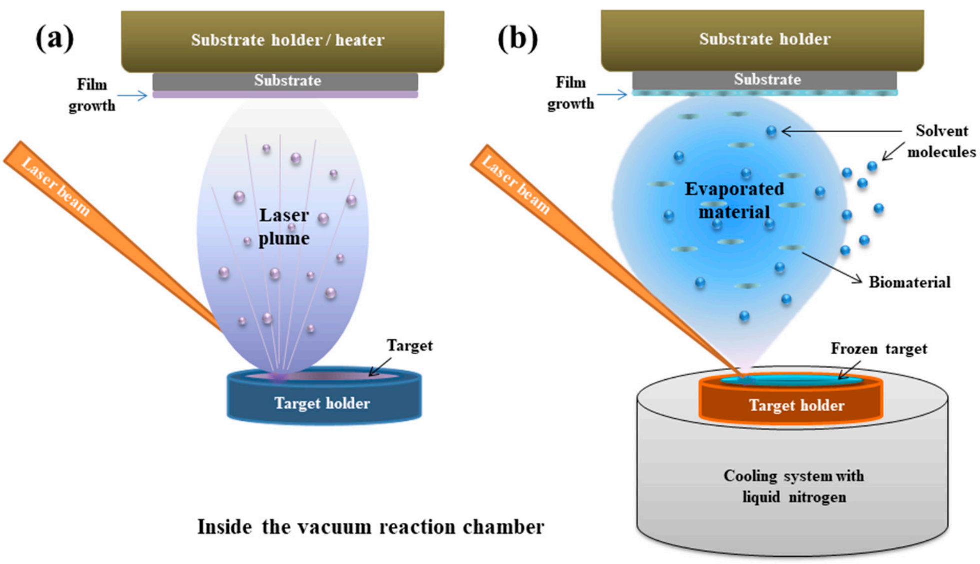

Figure 3. Laser Ablation (**a**) and evaporation (**b**) processes.

By adjusting laser parameters such as energy density and pulse duration, researchers are able to effectively control the morphology and roughness of the coated surface [34,35,89]. Nanosecond, sub-nanosecond, and femtosecond lasers are capable of minimizing the level of thermal damage to the material. The extremely low ablation threshold in the laser spectrum, measuring several MW/cm^2, allows absorbed light energy to be transformed into mechanical energy, disintegrating the micropart of the material. It also follows that various physical processes are involved in ablation. When short pulses are used near the matrix materials, an efficient interaction between radiation and substance is formed, corresponding to high photon energy. Near the surface layer, multiple electronic excitations of atoms and ions enable the process of electronic emission in general [90].

The results of laser ablation experiments suggest that the frequency and the time between pulses significantly affect the characteristics of the obtained materials. The atmosphere during the laser ablation process also profoundly impacts the properties of coatings. In addition, irradiating the target with a specific wavelength can often improve the deposition quality. Despite the complexities involved, high-quality products can be achieved through careful manipulation of these variables [39].

Several parameters can modify the features of the deposit obtained by laser ablation. These include the fluence of the laser, the number of pulses, the frequency of the laser (i.e., the frequency with which the pulses are emitted), the pulse duration, the atmosphere in which the ablation occurs, the composition of the target material, and the specific wavelength of the laser. The energy absorbed by a metallic particle, for example, is different from the one absorbed by a metallic matrix. These parameters can modify the roughness and composition of the obtained surface, the chemical state of the elements in the film, and the structure of the coating resulting from laser ablation [91].

The field of short-pulse quantum materials processing is rapidly advancing, with excimer lasers playing a crucial role. Despite notable progress in understanding the ablation process for biomimetic coating growth, there are still many unexplained phenomena that require further investigation. Both theoretical and experimental research has primarily focused on the impact of the ablation process on the final bio-integrative biomimetic coating. The combined study of excimer-aided coating deposition and laser-induced ablation, although not extensively studied in combination to date, holds significant potential for future materials-based design. UV excimer and UV excimer-like sources, including attenuated microfocus lines, may find applications ranging from optical diagnostics through wet and dry excimer-aided patterning of functional coatings and devices. They also have the potential to produce durable inorganic coatings tailored for demanding large-scale applications. The future directions and innovations in laser ablation for biomimetic coatings focus on pushing technological boundaries and maximizing the potential of this transformative technique. The comprehensive examination of the refinement in laser ablation parameters, such as energy levels, pulse duration, and repetition rates, holds the potential to tailor the process to achieve the desired coating properties, including enhanced adhesion, controlled surface roughness, and improved durability. This fine-tuning approach opens up endless possibilities for creating biomimetic coatings with unprecedented accuracy and performance. In addition to optimizing parameters, the future also shows promise for the development of novel laser systems [92]. These systems could significantly augment the ablation process by integrating advanced functionalities, such as multi-beam configurations, adaptive optics, and real-time monitoring sensors. This fusion of cutting-edge technologies would not only expand the range of achievable coatings but also enhance the efficiency, reliability, and control over the entire process. Moreover, there is a growing interest in exploring new materials for laser ablation coatings, particularly those with superior biocompatibility and bioactivity. By expanding the selection beyond traditional options like hydroxyapatite and titanium dioxide, researchers aim to unlock unexplored avenues in the synthesis of coatings that mimic the intricate structures and functionalities found in nature. The incorporation of biomimetic properties, such as self-healing capabilities or controlled release of therapeutic agents, could potentially revolutionize various medical and industrial applications. Furthermore, ongoing efforts are directed toward harnessing the power of laser ablation for creating hierarchical coatings, wherein multiple scales of surface features are precisely engineered [93]. By combining micro-, nano-, and sub-nanostructures, researchers aspire to replicate the complexity and functionality found in natural systems, such as lotus leaves or gecko feet. These hierarchical coatings offer unique advantages, including improved wettability, anti-fouling properties, and enhanced biocompatibility, with far-reaching implications across various fields, ranging from energy management to biomedical devices.

Pulsed laser deposition is a very well-known technique based on laser ablation which allows the fabrication of biomimetic coatings. This method presents notable advantages such as high adhesion, absence of contamination and pores, and precise transfer of target composition stoichiometry. These plasma plumes are then applied to a substrate as thin films, with the process being conducted either in the presence of a background gas or under extremely high vacuum conditions [35,94,95].

An alternative to the laser ablation process is laser-assisted evaporation (Figure 3), which can also produce high-quality thin films. It can be highly beneficial in reproducing the precise chemical composition of source materials in multi-element compounds [96].

Matrix-assisted pulsed laser evaporation has emerged to surpass the limitation due to the stress caused by direct ablation, when dealing with delicate materials. MAPLE offers a solution to the photochemical damage caused by direct UV laser interaction with organic or biomaterial targets by using a frozen target composed of the material to be deposited and a high vapor-pressure solvent. The technique involves dissolving the organic compound in a matrix, freezing the solution forming a laser target, and selectively transferring desorbed compounds to the collector based on a user-defined pattern. The low-fluence laser pulse predominantly interacts with the volatile solvent, leading to its evaporation. MAPLE allows for the deposition of a wide range of organic and polymeric compounds with minimal damage during the conversion from condensed to vapor state. Additionally, MAPLE provides excellent control over several coating parameters, including thickness, roughness, and homogeneity, and offers the advantage of being a dry physical vapor technique which does not involve heating or denaturing of biological materials. It is a promising method for applications in drug delivery, tissue engineering, and other biomaterial processing fields [97–100].

The future directions and innovations in laser ablation/evaporation for biomimetic coatings have the potential to significantly reshape surface engineering. Through a relentless pursuit of technological advancements, fine-tuning parameters, developing advanced laser systems, exploring new materials, and expanding the concept of hierarchical coatings, scientists and engineers are paving the way for creating functional surfaces that closely resemble nature.

3.3.2. Laser Surface Functionalization by Surface Structuring

Ongoing research indicates that the synergy between advanced laser technologies and biomimetic design principles is poised to drive innovations that transform how surfaces are engineered for diverse applications. By combining the principles of nature with cutting-edge laser techniques, scientists and engineers are paving the way toward a future where biomimetic surfaces play a pivotal role in enhancing performance, functionality, and sustainability across various industries. This dynamic field continues to evolve, promising exciting possibilities for creating next-generation biomimetic surfaces that not only emulate but also surpass the natural world's ingenuity [101].

By exploring different parameters such as energy density, pulse duration, and wavelength, researchers can tailor the structuring characteristics to achieve biomimetic properties crucial for applications ranging from biomedical devices to renewable energy technologies [102].

Scientists aim to improve the performance of surfaces in various applications by replicating biological structures with laser irradiation, from enhancing solar panel efficiency to improving the durability of industrial components [103]. However, challenges arise in optimizing laser irradiation for biomimetic surfaces: There is a complexity in parameter optimization. The intricate interaction between laser parameters (fluence, pulse duration, repetition rate) and their impact on structuring properties requires comprehensive understanding and optimization. Another challenge is the depth of modification: Laser irradiation typically affects only the surface layer of the substrate, limiting its application to superficial coatings rather than bulk modifications. Current research in laser irradiation for biomimetic coatings is focused on expanding the scope of applications and refining techniques [104,105].

As the mechanisms, laser surface structuring operates either by directing laser beams onto a material surface, which absorbs the laser energy and undergoes localized melting, ablation, or photochemical reactions or by growing/deposition of biomolecule patterns without degradation (Figure 4).

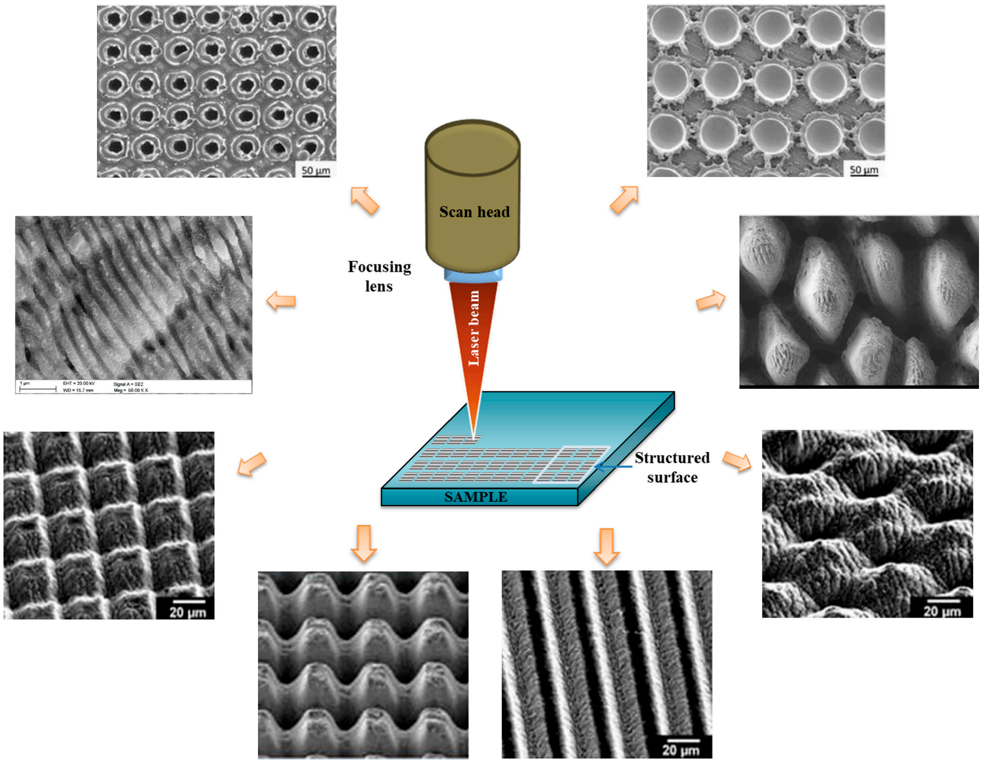

Figure 4. An example of laser surface structuring and some SEM images of as-obtained structures [106–109].

As the mechanisms, laser surface structuring operates either by directing laser beams onto a material surface, which absorbs the laser energy and undergoes localized melting, ablation, or photochemical reactions, or by growing/deposition of biomolecule patterns without degradation. The parameters of the laser, such as wavelength, pulse duration, and energy density, can be finely tuned to control the size, shape, and arrangement of the patterns created. This ability to precisely manipulate surface characteristics is essential for developing biomimetic surfaces that emulate natural textures and functionalities [110].

In biomimetic applications, laser patterning is used to create surfaces that exhibit specific properties such as hydrophobicity, adhesion, and optical performance. For instance, the creation of superhydrophobic surfaces—those that repel water effectively—is inspired by natural structures like lotus leaves. By using laser patterning to etch micro- and nanoscale features onto a material, researchers can produce surfaces that mimic the intricate texture of lotus leaves, resulting in coatings that are highly water-repellent and self-cleaning [111].

However, challenges remain in optimizing laser structuring for biomimetic surfaces. Designing patterns that accurately mimic natural structures can be complex and requires a deep understanding of both biological systems and laser-material interactions. High-precision lasers and associated equipment can be expensive, which may limit accessibility for some research and industrial settings [111].

Different techniques involving laser structuring for biomimetic surfaces were developed and have the ability to create detailed and complex patterns at micro- and nanoscales with high repeatability and applicability to a wide range of materials, including metals, polymers, and ceramics [112].

Two-photon lithography is a technique used to directly fabricate complex three-dimensional (3D) micro- and nanostructures with submicron resolution where the crosslinked volume is restricted to the volumetric spatial location defined by the laser focus point to generate 3D pattern [113]. TPL uses a high-powered laser and a two-photon photo-initiator resin, which cures in specific areas by a chemical reaction when two or more photons travel through the resin simultaneously [114]. A great number of process parameters can effectively change the final structure, in terms of dimensional accuracy (e.g., the speed of translation stages, writing power, slicing thickness), optical transparency (e.g., gray value and amplitude of the signal), shape and porosity (e.g., packing density, exposure combinations, voxel overlap, slicing thickness). The change of one parameter may affect the photopolymerization process or resin properties, and the possibility of changing other parameters to obtain a different structure may be required [115,116]. This can be most commonly used to produce micro-sized fluidic channels and micro-grooves with a feature size of 1 µm, and has been an invaluable method of microfabrication, packet-switches, photonic waveguides, collimating filters, and even sensors in the literature [117]. TPL was also used in the medical discipline, as evidenced by its usage in creating microneedles. In contrast to that, an efficient delivery system for a mathematical product can be developed by micro-injection through the use of hollow microneedles [118,119].

Direct Laser Interference Patterning is a cutting-edge technique used for fabricating surface periodic structures without the need for molds or masks, which provides macro and micro-structuring on organic, inorganic, and biological surfaces. This method involves creating an interference pattern by overlapping two or more coherent laser beams, which is then directly applied to the material surface. The laser intensity at the interference maxima positions allows for the patterning of polymers, metals, ceramics, and coatings. The structuring process is conducted in ambient air and is compatible with sterile conditions [120]. It combines the benefits of the laser interference phenomenon such as breaking the diffraction limit due to high-spatial frequency components, direct photocharacteristics in various materials, high-speed fabrication, etc. [121]. The operating principle of DLIP is based on ablative removal of the material (e.g., nickel, aluminum, stainless steel), but also on melting [74]. DLIP can provide advanced surface functionalities including directed surface wettability by changing the laser pulse duration, hardening and decreasing the absorptance of two- and three-DLIP surfaces, black universal absorber down to almost zero reflectance up to the red/near-infrared wavelengths range by only incorporating the DLIP black parts in a multilayer absorber design. Also, DLIP patterns in metals might improve electrode efficiencies by scattering and local field enhancements between the DLIP bands. These remarkable features make DLIP a powerful technique in a broad range of applications from anti-fogging, anti-biofouling, passivation, and wettability to photovoltaic, plasma facing components, and optics applications [60,121–123].

In the biomedical field, DLIP has been used for surface structuring of biomedical implants to enable functionalization or other blood-purification applications. Another modality is the structured ablation of DLC-films in gear application, again in the biomedical segment. An interesting application for high-performance automotive adhesives goes together with surface activation or priming to provide good anchorage in the steel or plastic pieces to be bonded. The method is already reasonably well understood by the scientific community, and its advantages, but still needs some in-depth studies, especially in high-volume production applications [76].

Laser-Induced Periodic Surface Structure is a typical laser structural modification which can have a significant impact on various properties of materials [124,125].

LIPSS generation is found to be deeply dependent on the laser wavelength, pulse duration, fluence, repetition rate as well as polarization. Additionally, the chemical aspect must also be taken into account, which corresponds to the contribution of local defects, such as temperature gradients, superficial inhomogeneities, or grain boundaries. Two types of LIPSS, LIPSS with increased heights and LIPSS with similar heights, can be found. Furthermore, LIPSS tends to be more periodic and smoother with the help of surrounding gas or environmental conditions. Laser-induced plasmonic is the primary process for melting/ablating the material from the surface into the vapor, which is then used to generate LIPSS. The material properties related to the formation of LIPSS include crystallographic orientation and pre-treatment. All these mechanisms provide an available fundamental to further control their generation and use them in various applications [126–128].

Direct laser writing (DLW) is a 3D additive technique, best used for creating highly precise features and components [129]. The precision of this process is outstanding and is useful in applications like the fabrication of 3D micro-optical and photonic elements and the manipulation of biological materials. Over the decades, the DLW technology, especially the resolution, has improved significantly. Instead of the traditional lens, solid-immersion-lens, and oil-immersion-lens-based DLW writing systems, a recently proposed air-fluid-damped-lens-based axial-scanning framework shows high-quality micropatterning capabilities that are an efficient alternative to the traditional DLW [130].

Some applications include 3D and 4D printing, robotics, microfluidics and nanofluids; anatomy, orthopedics, drug delivery and orthodontics; cow-print contact lenses, nanodiamonds with fluorescent web-shaped defects; biofabrication and regenerative medicine; nanomanufacturing; quantum mechanics; the making of dielectric waveguides and lasers; the extension of the decay of superwhole photons; a new backpack-powered exosuit; and the fastest on-chip coherent waveguide electro-optic modulator demonstrated to date [131–133].

LIFT is one technique used to transfer thin layers of material from a donor substrate to a receiver substrate using laser pulses.

This technique is particularly useful for depositing delicate materials, such as polymers and several types of biological materials (e.g., proteins, genes, viral particles, bacteria, mammalian cells) onto target surfaces to replicate specific biological functionalities [134].

The LIFT technique is granted even more importance in the case of biomimetic surfaces, as these are organic–inorganic surfaces that mimic the structure and properties of hard and soft tissues. Candidate applications for LIFT fabricated surfaces are in the biomedical field, especially for improving the lifetime and quality of multiple materials: bioactive glasses and ceramics, bioactive composites, bioresorbable polymers, metals, and alloys implants or prosthesis [135]. Moreover, LIFT offers a non-contact and maskless approach to material deposition, minimizing the risk of contamination and damage to sensitive biological samples.

Femtosecond laser ablation of metals in organic solvents (FLAMOS) offers several advantages for medical applications (e.g., medical device fabrication, tissue engineering, and drug delivery systems). Firstly, the ultrafast nature of femtosecond lasers allows for precise and controlled material removal with minimal heat-affected zones, reducing the risk of damage to surrounding tissues [83,84].

Furthermore, the use of organic solvents in FLAMOS can provide a conducive environment for biofunctionalization of metal surfaces, enabling the attachment of biomolecules or drugs for targeted medical treatments. The ability to tailor the surface properties of metal substrates through FLAMOS opens up new possibilities for enhancing biocompatibility and promoting specific biological responses [83].

The research and development in this field are expected to unlock new possibilities for medical applications of femtosecond laser ablation of metals in organic solvents [84].

Future directions in this field involve pushing the boundaries of technological advancements to unlock new possibilities in surface engineering. By continuing to refine laser parameters, develop innovative materials, and integrate cutting-edge technologies, researchers aspire to create biomimetic surfaces that not only mimic but surpass the functionalities found in nature. These advancements hold promise for revolutionizing industries such as healthcare, aerospace, and renewable energy, where enhanced surface properties are crucial for performance and sustainability.

One notable example of a biomimetic surface that has been fabricated using laser irradiation for surface structuring was inspired by shark skin. Sharks are known for their ability to swim efficiently due to their denticles, which are small, tooth-like structures that reduce drag by altering water flow over their skin. Researchers have replicated these denticles on surfaces using laser patterning techniques. By employing femtosecond lasers, they create microstructures that mimic the geometry and spacing of shark skin denticles. These biomimetic coatings exhibit reduced drag, making them suitable for applications in marine vessels and underwater robotics where improved hydrodynamics are essential [136].

Another intriguing application involves biomimetic surfaces inspired by butterfly wings, which exhibit vibrant colors and self-cleaning properties due to their micro- and nanostructured surfaces. Researchers employ laser irradiation to replicate these intricate structures on various substrates, enhancing optical properties such as anti-reflectivity and coloration. By precisely controlling laser parameters, including wavelength and pulse duration, scientists can recreate the complex patterns found on butterfly wings. These structures find applications in optical devices, where improved light management and durability are required [137].

A remarkable example is also the biomimetic surface achieved through laser structuring, inspired by the adhesive capabilities of gecko feet. Geckos can climb smooth vertical surfaces thanks to the microscopic setae on their feet, which create van der Waals forces with the substrate. Researchers have used femtosecond lasers to pattern synthetic surfaces with similar microscopic structures, resulting in coatings that exhibit strong adhesion properties without the need for additional adhesives. These gecko-inspired surfaces have potential applications in robotics, where reversible and controllable adhesion is valuable [67].

The development of anti-reflective surfaces inspired by the eyes of moths is another notable application. Moth eyes have a natural nanostructured surface that minimizes reflection, enhancing their ability to see in low light. By employing excimer lasers to create similar nanostructures on glass and polymer surfaces, scientists have developed functionalized surfaces that significantly reduce reflection and improve light transmission. These moth eye-inspired surfaces are particularly useful in optical devices, such as lenses and solar panels, where reduced reflection can enhance efficiency and performance [138].

4. Medical Applications of Nature-Inspired Biomimetic Coatings and Laser Structured Surface

Nature-inspired biomimetic coatings have become increasingly significant in the medical field due to their ability to enhance the functionality and biocompatibility of medical devices and implants. These coatings, which mimic the properties and structures found in natural organisms, offer several advantages, including improved biointegration, anti-microbial properties, and enhanced mechanical performance [139].

One prominent application is in orthopedic and dental implants. Biomimetic coatings and laser-structured surfaces inspired by natural bone structure can improve the osseointegration of implants, ensuring that they bond more effectively with the surrounding bone tissue. For instance, laser surface functionalization by coatings deposition and surface structuring, that mimic the composition and nano-architecture of bone, can promote the growth of new bone cells around the implant, reducing the risk of implant failure and enhancing recovery times [140–144].

In cardiovascular devices, biomimetic coatings and laser-structured surfaces are used to enhance hemocompatibility and reduce the risk of thrombosis. By mimicking the surface properties of natural blood vessels, these functionalized surfaces can minimize platelet adhesion and activation, leading to safer and more effective stents and vascular grafts. For example, coatings inspired by the slippery surfaces of certain plants can create a non-stick surface that resists blood clot formation [145–149].

Biomimetic surfaces also find applications in wound healing. Surfaces inspired by the natural extracellular matrix (ECM) can support cell attachment, proliferation, and differentiation, accelerating the healing process. These functionalized surfaces can be used on wound dressings and tissue engineering scaffolds to provide a conducive environment for tissue regeneration and repair [150–152].

Moreover, anti-microbial biomimetic coatings and laser-structured surfaces, inspired by natural surfaces such as shark skin, lotus leaf, or bone-like structures can prevent bacterial colonization on medical devices. Such surfaces have microscopic patterns that disrupt bacterial attachment and growth, significantly reducing the risk of infections associated with medical implants and surgical instruments [153–157].

In the realm of drug delivery, biomimetic coatings and laser-structured surfaces are used to create smart systems that can respond to specific physiological conditions. For example, coatings that mimic the pH-sensitive properties of certain natural tissues can release therapeutic agents in response to the acidic environment of a tumor, providing targeted treatment while minimizing side effects [59,158–162].

Overall, the application of nature-inspired biomimetic coatings and laser-structured surfaces in medicine represents a cutting-edge approach to improving the performance, safety, and efficacy of medical devices and therapies. By harnessing the principles observed in nature, these surfaces offer innovative solutions to longstanding challenges in the medical field, paving the way for advanced treatments and improved patient outcomes [163].

To further explore the intersection of biomimicry and medical advancements, Table 3 highlights several surfaces inspired by nature and their corresponding medical applications. These examples illustrate how mimicking the structures and functions found in nature can lead to innovative solutions in healthcare.

Table 3. Nature-Inspired Surfaces and Their Medical Applications.

Biomimetic Surfaces	Medical Application as Nature-Inspired Biomimetic Surfaces	References
Gecko-inspired Surfaces	Geckos' ability to stick and unstick their feet on surfaces has inspired the development of surfaces with similar properties. These could be used for bandages, wound healing dressings, or to create bio-adhesive materials for medical equipment or wound closure.	[22,164–169]
Spider Silk-inspired Surfaces	Extremely strong and lightweight, spider silk-inspired surfaces have been studied for potential use in sutures, ligament/tendon repair, or as a medium for drug delivery.	[170–175]
Lotus Leaf-inspired Surfaces	The water-repellent and self-cleaning properties of lotus leaf have inspired the development of laser structured/patterned surfaces with anti-fouling, bacteriostatic effect for implants functionalization, or to reduce microbial contamination on various medical tools.	[89,155,176–181]
Insects Wing-inspired Surfaces	The structure of butterfly wings can be mimicked to develop surfaces with unique optical properties. These structures could be used in medical imaging and sensing applications, or for creating visually appealing prosthetics or therapeutic devices.	[89,182–187]
Tissue-like-inspired surfaces	The laser-structured surfaces and the biomimetic coatings based on synthetic or natural origin apatite (e.g., bovine, marine-derived hydroxyapatite, mussels), polymers, etc., emulate the unique structural and functional properties found in nature, leading to innovations in the biomedical fields. Laser induced 3D micro-channels or cavities of various shapes and sizes, enables the development of vascular networks that closely resemble those found in living organisms.	[51,58,149,188–194]

We will examine specific case examples (Figure 5) following our comprehensive discussion of bio-inspired materials and their associated laser techniques.

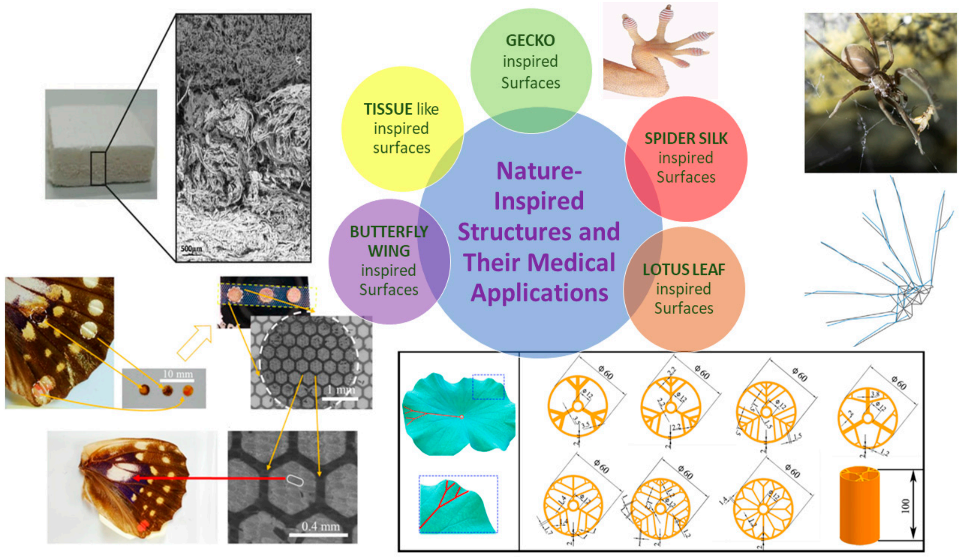

Figure 5. Applications of selected nature-inspired surfaces for medical purposes, showcasing their unique properties [195–198].

So, in the upcoming sections, we explore the innovative applications of selected nature-inspired surfaces for medical purposes, showing their unique properties with significant benefits for wound care, bio-adhesive surfaces, and/or medical equipment.

4.1. Case Examples of Gecko-Inspired Surfaces for Medical Applications

The exploration of laser technology in developing gecko-inspired surfaces presents promising possibilities in the field of biomimetic materials. The remarkable ability of the gecko to climb on a variety of surfaces (smooth or rough) is due to the fine keratinous hair-like structures, called setae, which are found on the toes. These microscopic structures, which range in length from 30 to 130 µm and with a diameter of 5 µm, are further divided into hundreds of smaller nanoscale end structures, called spatulae. Geckos' adhesion capacity primarily arises from the capillary force, including the Laplace force, surface tension, and solid-to-solid interaction. Each spatula generates small van der Waals forces due to molecular attraction between the spatula and the substrate surface forces that are strong enough to support the gecko's weight, thus allowing for effective adhesion and detachment, as required [165,199–201].

Through the precise application of laser engraving and surface texturing, researchers can create patterned surfaces that closely resemble the hierarchical architecture of gecko setae. This process involves fine-tuning laser parameters to achieve specific heights, shapes, and interspacing of microstructures that replicate the unique adhesion seen in gecko feet. Additionally, laser-driven deposition methods can potentially integrate materials that enhance the adhesion properties, allowing the development of surfaces with adjustable adhesion characteristics for diverse applications, from climbing robots to medical devices that require secure yet reversible adhesion. Moreover, the scalability and precision of laser technology facilitate the manufacturing of large-area gecko-inspired surfaces, paving the way for incorporating these innovative materials into commercial products. Thus, the use of laser technology not only deepens our comprehension of natural adhesion mechanisms but also leads to the development of smart surfaces with practical applications in various industries.

Laser technology plays a pivotal role in enhancing the properties of gecko-inspired surfaces, making these surfaces highly suitable for various medical applications. By employing laser structuring techniques, researchers can precisely replicate the nanoscale topography of gecko setae, resulting in improved adhesion, self-cleaning capabilities, and durability for medical devices.

Several properties of gecko-inspired surfaces make them potentially useful in medical devices. Overall, gecko-inspired surface adhesion, self-cleaning, and durability make them valuable for medical applications, offering improved performance and cost efficiency [202].

1. Adhesion

The adhesion of gecko-inspired surfaces is one of the most critical properties that allow devices to securely attach to tissues, organs, or bones, ensuring stability and reliability during medical procedures. For instance, accurate intraocular pressure measurements require a tonometer to be securely fixed [203], while proper adhesion enhances the efficacy of drug delivery devices for the small intestine or colon. By leveraging laser technology, one can strategically design customized surface patterns to enhance van der Waals forces, leading to superior adhesion compared to conventional methods. While these forces are individually weak, they can produce substantial adhesion when integrated with specially designed micro- and nanostructures that simulate the gecko's setae—tiny hair-like projections that enhance the surface contact area. These adhesives fall into two main categories: dry adhesives, which depend solely on physical mechanisms, and wet adhesives, which incorporate structural features alongside chemical bonds for increased versatility [204].

2. Self-Cleaning

Self-cleaning surfaces can significantly enhance the efficiency of medical devices used inside the body by preventing contamination from body fluids, cells, proteins, and bacteria. This property is particularly beneficial for devices like catheters, endoscopes, and medical tools, where maintaining a sterile surface is crucial. Laser-induced surface structuring can create micro- and nanostructures that promote self-cleaning features, thereby minimizing infection risks and facilitating patient recovery by reducing reliance on harsh antiseptics and frequent dressing changes [205,206].

3. Durability

Durability is another key-factor that can be improved by surface functionalization using laser techniques (coatings deposition or surface structuring), which prolongs the life of medical devices while reducing overall costs [205,207]. The capacity to create precise patterns and structures on surfaces not only improves mechanical resilience but also ensures consistent performance over time in various physiological environments.

Gecko-inspired adhesives for medical applications encompass a spectrum of uses facilitated by laser technology. They can provide a novel alternative to sutures or staples, especially for patients with delicate skin, such as the elderly or neonates. Additionally, these adhesives can be applied to internal medical devices, like endotracheal tubes and urinary catheters, to prevent unintended migration. Externally, gecko-inspired adhesives effectively secure devices like hearing aids or glucose monitors while offering temporary fixes for traumatic injuries, as they minimize skin irritation [22,165,208].

Implants present another significant medical application necessitating strong tissue adherence; their effectiveness diminishes if they become dislodged. Utilizing laser-assisted methods to integrate semiconductor microdevices onto unconventional substrates allows for the development of bio-integrated electronics. A promising solution presented by Jeong et al. [207] involves natural gecko setae arrays that can switch adhesion on and off, enabling manipulation of thin microscale semiconductor materials onto diverse surfaces, including those of plants and insects. Key components of these adhesives include micro- and nanoscale designs that maximize the surface area, flexible polymers that adapt to various surfaces for better grip, and self-cleaning features that maintain effectiveness in dirty environments. Notably, gecko-inspired adhesives possess reversible adhesion properties, facilitating easy removal without leaving residue—an advantage for industrial and biomedical applications.

Technologies utilizing biodegradable polymers, such as poly(glycerol-co-sebacate acrylate) (PGSA), combined with laser-based fabrications, create adhesives with tailored mechanical properties capable of adapting to tissue deformation while maintaining strong bonds. Researchers have investigated various polymers and nanomaterials, such as carbon nanotubes, that can be applied in settings ranging from wall-climbing robots to tissue adhesives and medical tapes. Studies indicate that adhesion performance is notably influenced by factors like fiber aspect ratio, tip shape, and hierarchical structures significantly impact. Ongoing research strives to optimize these nanostructures, enhancing properties and functionalities to ensure their practical application. Mahdavi et al. developed a gecko-inspired adhesive using PGSA and a nanotopography surface. A fabrication procedure for manufacturing tissue adhesives was developed that avoids high-temperature and harsh chemical conditions that are amenable to a variety of materials. Silicon templates were prepared using the microfabrication techniques of photolithography and reactive ion etching. To create the nanopattern, linear PGSA polymer was cast on nanomold cavities without using a high vacuum, and then cured by UV light in less than 5 min at room temperature. To study how the pattern dimensions affect PGSA adhesive properties, pillar arrays were patterned in PGSA with tip pillar diameters ranging from approximately 100 nm to 1 μm and pillar heights from approximately 0.8 to 3 μm. Tissue adhesion was optimized by varying the nanopattern dimensions and adding a thin layer of oxidized dextran to increase adhesive strength on tissue surfaces. This adhesive has the potential to seal wounds and replace sutures or staples [202,209].

One of the most widely recognized techniques for producing fibrillar adhesives is soft lithography. This process involves various pattern-replication methods that utilize an elastomeric mold [210]. This mold acts as a negative imprint of a micro- or nanostructured rigid master, which is formed by casting and thermally curing a liquid prepolymer, commonly poly(dimethylsiloxane) (PDMS), onto the master. The resulting PDMS replica is considered the final patterned surface, but it can also function as a mold or stamp for subsequent replication of other polymeric materials. The elastomeric properties of the PDMS stamp allow for easy detachment from the master, even when dealing with complex and delicate structures, such as high-aspect-ratio fibers [211]. Additionally, its low interfacial free energy and chemical inertness contribute to a reduction in mold adhesion.

For soft molding to be effective, access to masters with the desired geometry is essential. The masters used for bioinspired fibrillar adhesives typically consist of arrays of holes with specified dimensions, often fabricated by photolithography [212]. Other methods for creating these masters include indenting melted wax with an atomic force microscope tip [213] or employing laser ablation on metallic surfaces [214]. Photolithography utilizing epoxy-based SU-8 photoresist has been particularly effective for producing uniform model surfaces, enabling the characterization and quantification of different geometric parameters on adhesion [205].

Numerous empirical studies, theoretical approaches, and synthetic replicas have contributed to a deeper comprehension of how geckos' abilities affect their shape, size, and scale [215,216]. Key factors such as tip geometry [217], fiber aspect ratio [218], tilt angle [219,220], and structural hierarchy [221] significantly determine the material and structural characteristics of individual fibers [222]. These properties have profound implications for various behaviors, including self-cleaning [206], adhesion [212], friction [223], repeatability [224], and occasionally biodegradability [225]. The endeavor of replicating the structure of gecko feet using two primary materials, namely polymers [226] and carbon nanotubes [16], has revealed considerable potential in various practical applications, such as wall-climbing robots [227], tissue adhesives [228], medical tapes [229], semiconductor carriers [229], and transfer printing [230], among others [231].

Noteworthy are the benefits of micropatterned adhesives which can interact solely with the mucous layer, preserving the integrity of the colonic epithelium, unlike conventional endoscopes. In a related approach, Glass et al. [232] developed a three-legged anchoring system that enhances the performance of existing passive capsule endoscopes. Their findings revealed that dry PDMS-based micropillars could boost friction by 50%–100% compared to unstructured materials, as evidenced through in vitro tests on fresh porcine small intestine samples. Furthermore, when the pillars were coated with a thin layer of silicone oil, frictional properties improved by up to 400% over flat surfaces. The structures were evaluated in a simulated intestinal environment, confirming their potential application within the human body. Notably, the researchers designed a prototype robot, which weighed just 10 grams, that is capable of navigating through the simulated intestinal material. The emergence of mucoadhesive interfaces that provide effective adhesion has led to the creation of new endoscopes that are far less invasive for patients, greatly reducing the likelihood of serious complications during procedures. This progress is facilitated by the adhesives' specific interactions with the mucous layer rather than the colonic epithelium. Additionally, these endoscopes can be engineered to be much smaller compared to earlier models, allowing them to navigate tight turns within the colon, thus minimizing the risk of structural damage. The examples provided highlight the immense potential of bioinspired fibrillar adhesives in the life sciences, indicating that future research may not only improve existing applications but also unveil numerous unexplored possibilities [232–234].

Additionally, another multi-adhesion mechanism has been documented for gecko-inspired adhesives. Unlike mussel-inspired bioadhesives that operate through functional groups replicated by mussel foot proteins, gecko-inspired bioadhesives primarily rely on interface features and chemical bonding. The adhesive properties of geckos often stem from simple physical interactions, where nanoscale fibers are organized into microscale pillars, which are then structured into macroscale columns. This hierarchical arrangement enables the adhesive to establish numerous contact points with the substrate, enhancing van der Waals interactions and improving adhesion to the surface [235].

Frost et al. [209] developed a chitosan-based adhesive featuring a nanopillar-modified surface to enhance adhesion strength. Nano-structured chitosan-based hydrogels demonstrated superior tissue adhesion compared to flat-structured adhesives. This improved adhesion is primarily due to van der Waals forces and electrostatic interactions between the nanopillars and the tissue. However, the adhesion strength of gecko-inspired patterned adhesives significantly decreased in wet conditions. To overcome these issues, various surface treatments have been explored, and gecko adhesives have been integrated with other adhesive types.

In addition, Lee et al. [236] synthesized a biomimetic adhesive by integrating mussel-mimetic and gecko adhesives, which resulted in a notable improvement in the detach–reattach cycle. Furthermore, the underwater adhesive strength of this hybrid formulation was found to be comparable to that of gecko adhesives under dry conditions. However, challenges remain in the development of gecko-inspired adhesives for medical applications, particularly with respect to regulatory hurdles, including comprehensive biocompatibility testing. The definition and consistent characterization of gecko-inspired adhesives across their diverse applications complicate the regulatory approval process.

Additionally, scaling up production for mass medical use is a significant challenge due to the time-intensive nature of current fabrication techniques, such as lithography. Ensuring biocompatibility is vital, with ongoing research focused on optimizing mechanical properties and adhesion performance, leveraging laser technologies to refine the physical characteristics of these innovative materials [205].

4.2. Example Cases of Biomimetic Surfaces Based on Spider Silk-Inspired Materials

Spider silk is renowned for its strength, elasticity, and lightness. Biomimetic coatings inspired by spider silk aim to replicate these properties, offering potential applications for stronger, more flexible, and lighter structures in various industries [173].

Coatings are crucial in medical applications, modifying device functions to improve outcomes. They can make devices biocompatible, prevent infections, and enhance mechanical properties. Examples include anti-thrombogenic coatings for cardiovascular surgery and protective layers on pharmaceutical capsules for controlled drug release. Applying coatings is often more cost-effective than developing new materials [237]. For instance, the longevity of a hip prosthesis depends on the wear rate and the effectiveness of its coating. Successful coatings can also reduce postoperative infections, such as preventing the spread of microorganisms when a catheter is inserted [238,239].

Spider silk, a protein polymer, has a tensile strength comparable to high-grade alloy steel and high toughness. It is low in toxicity and is produced with water, and transgenic studies aim to generate recombinant spider silk for high-strength fibers and structural proteins for medical use. These polymers, which possess mechanical properties akin to synthetic materials, present an opportunity for new biomaterials that combine biocompatibility, biodegradability, and mechanical functionality. Native spider silk and spider silk-inspired materials are being investigated as novel coatings for medical implants, addressing issues of incompatibility between implant materials and body tissues [173].

Bioengineering has emerged as a promising field in materials science, driven by interest in biocompatible materials. Researchers are modeling new materials in nature, experimenting with protein-based polymers used by animals for structural support. They offer a potential source of new biomaterials combining biocompatibility, biodegradability, and mechanical functionality [174].

Spider silk coatings offer biocompatibility, biodegradability, and controlled drug release. They can be marketed as temporary solutions, reducing complications associated with implant removal. Bioactive agents incorporated into silk matrices provide sustained release, enhancing the effectiveness of medical devices. Studies have shown spider silk's potential for anti-inflammatory and anti-microbial applications, representing a significant advancement over traditional coatings [240]. Persistent wounds like venous ulcers, pressure ulcers, and diabetic foot ulcers pose a considerable challenge due to extended treatment durations and associated expenses. Utilizing spider silk coatings presents a cost-effective alternative to expensive growth factors by promoting cell adhesion, spreading, and migration, accelerating wound healing. Spider silk proteins exhibit stability and enable sustained release from a matrix, making them cost-effective for chronic wound therapies. Studies show spider silk scaffolds enhance re-epithelialization and wound closure compared to traditional dressings [237].

Implantable devices often risk infection, which can lead to severe complications like sepsis. Spider silk coatings can reduce infection risk by releasing anti-microbial peptides over time. Studies have shown silk matrices can immobilize and release anti-microbial agents effectively. Spider silk coatings may also prevent blood clotting on devices like stents and artificial valves by repelling platelets, a feature demonstrated in spider silk film studies [240].

Miroiu et al. conducted a study to develop thin films suitable for use as coatings on metallic medical implants. These films consist of hydroxyapatite, a key component of bones, and silk fibroin, a natural biopolymer, added to enhance the surface properties. The researchers produced hydroxyapatite (HA), silk fibroin (FIB), and composite HA–FIB films using MAPLE to assess their physical and biological performance as coatings on metallic prostheses. An excimer laser source (KrF*, with a wavelength of 248 nm and pulse duration of 25 ns) operating at a 10 Hz repetition rate was employed in the process. Osteosarcoma SaOs-2 cells cultured for 72 h on FIB and HA–FIB films exhibited increased viability, good spreading, and normal cell morphology. The well-elongated, flattened cells are indicative of an appropriate interaction with the MAPLE FIB and composite HA–FIB coatings [241].

Coatings made of composite silk fibroin–poly(3-hydroxybutyric-acid-co-3-hydroxyvaleric-acid) (SF–PHBV) were deposited onto titanium substrates using MAPLE. These coatings were studied to understand their properties and degradation behaviors in simulated body fluid at 37 °C, as an initial step towards their potential use in localized controlled release for tissue regeneration applications. SF and PHBV are natural biopolymers known for their excellent biocompatibility, but they differ in terms of biodegradability and tensile strength. By combining the two polymers in a composite, it was hoped that there would be improvements of their properties for use as coatings in biomedical applications. Analysis using FTIR showed that the main absorption characteristics of both polymers were present in the spectra, confirming the transfer of stoichiometry from the targets to the coatings. By adjusting the SF:PHBV ratio, it was possible to achieve distinct drug-release patterns, allowing for the controllable tuning of the coatings' degradation rates, from rapid–release formulations with a higher SF content to prolonged sustained releases when the PHBV content was higher [242].

4.3. Example Cases of Lotus Leaf's Inspired Surfaces

Lotus leaf-inspired biomimetic surfaces are gaining attention for their superhydrophobic and self-cleaning properties, which offer significant advantages in various infrastructural applications [178].

Modifying existing materials with superhydrophobic coatings or by surface structuring has shown promise, particularly in enhancing the performance of medical implant devices. Despite challenges in the cost-effective production of micro/nanostructures, these coatings aim to improve biocompatibility and prevent infections associated with implants [243,244].

Inspired by natural surfaces like lotus leaves, cicada wings, and swan feathers, researchers are replicating micro/nanostructures to enhance the protective functions of medical implants. These surfaces aim to minimize the need for secondary procedures due to device failure, thereby reducing infection risks [245].

Developing non-toxic, water-resistant, and self-cleaning surfaces for medical devices holds immense promise in the healthcare industry. Such surfaces can resist protein absorption and organism adhesion, potentially lowering procedure costs, improving patient recovery, and enhancing device longevity [178].

Techniques such as laser etching and anodization are utilized to create micro/nano roughness on biocompatible materials, followed by hydrophobic coating applications. This approach ensures stable, biocompatible surfaces that can improve the functionality of medical devices [246].

Lotus-inspired superhydrophobic surfaces effectively inhibit bacterial adhesion, which is crucial for preventing infections associated with medical implants. These surfaces mimic natural self-cleaning mechanisms, which reduce microbial attachment and biofilm formation [178].

In another study conducted by Hanh Vu Thi Hong and colleagues [247], the anti-icing performance of a hierarchical slippery polymer thin film that is inspired by structures of the lotus leaf and Nepenthes pitcher plant was explored. The polymer solution was blended with the lubricant at an optimal concentration to achieve slippery characteristics. A combination of dry etching and spin-coating techniques was used to generate a uniform polymer microstructure on the thin film, followed by the generation of a polymer nanostructure through the plasma-etching method using carbon tetrafluoride (CF4) gas. The anti-icing efficiency was then compared with that of the non-functional samples to demonstrate the advantages of combination in all criteria [247].

Cheng et al. demonstrated the self-cleaning effect of micro- and nanostructures by comparing untreated lotus leaves with annealed lotus leaves. Annealing at 150 °C for 1 h eliminated all nanocrystals on the surface, while microstructures (5–10 μm height) remained. The untreated lotus leaf had a higher contact angle ($142.4° \pm 8.6°$) compared to the annealed leaf (126.3°), and the smooth wax surface had a contact angle of 74°. This indicates that the presence of nanostructures increases the contact angle of the surface.

The study also suggests that the microscale bump pattern significantly influences hydrophobicity, increasing the contact angle by 70%, while the nanocrystals have less impact, increasing the hydrophobicity of the surface by 13%. The resistance of taro and lotus leaves toward biological and non-biological particles is due to the physiochemical interaction between the cell and the surface roughness of the leaf. This behavior has increased research interest in applications such as self-cleaning paint, clothes, windows, bio-repellent coatings, and low-friction surfaces [248].

Lotus-inspired biomimetic surfaces offer significant advancements across various medical applications, providing solutions for implantable devices, catheters, surgical instruments, wound dressings, and drug delivery systems [249].

Self-cleaning surfaces on implants promise to reduce infection rates and the need for costly re-operations due to device failure. These surfaces, resistant to wear and bacteria adherence, significantly enhance implant longevity and patient outcomes [178].

The integration of lotus-inspired surfaces in medical devices represents a paradigm shift towards safer, more effective treatments. By mimicking nature's self-cleaning properties, these innovations contribute significantly to infection prevention, treatment efficacy, and patient care in modern medicine [243].

4.4. Example Cases of Insects Wing-Inspired Surfaces

The application of laser technology in developing insect wing-inspired surfaces is a fascinating aspect of biomimicry, providing valuable insights into the performance characteristics of natural materials. Insects such as butterflies and moths possess wings that are not only lightweight and resilient but also exhibit unique micro- and nanostructures that can influence optical properties and hydrophobicity. These structural features are essential for functions like flight efficiency, making them ideal candidates for functional surface design. Employing laser techniques, scientists can reproduce complex surface structures at various scales to develop synthetic wings or surfaces with similar functional attributes. Through focused laser ablation, selective laser melting, or two-photon polymerization, one can engineer microscale textures that control liquid and light interactions, mirroring those of insect wings. The fabrication of hierarchical patterns can enhance a surface's anti-reflective and dirt-repellent properties, contribute to advancement in materials' energy efficiency, and promote water management solutions. Additionally, the ability to adjust laser parameters allows for customized surface properties, empowering researchers to investigate a wide array of applications, from self-cleaning surfaces to enhanced drag reduction in aerospace designs. By advancing our capability to mimic these intricate insect structures through laser technology, we unlock new pathways for innovation in material science, with implications that extend into environmental sustainability and energy conservation. Thus, the integration of laser technologies with biomimetic design not only bridges the gap between natural phenomena and engineered solutions but also propels us toward the development of smart, adaptable materials inspired by the natural world.

Butterfly wing-inspired surfaces have garnered interest across various fields due to their unique properties, particularly in optics and material science. Mimicking the structural coloration and sensitivity found in butterfly wings holds promise for numerous medical applications [250].

The intricate structural coloration of butterfly wings arises from the microscale 3D shapes of their scales (ridges, cross-ribs, and solid holes), which manipulate light through optical interference and angular reflection. This unique feature has inspired the development of artificial 3D photonic materials with enhanced durability and environmental stability. Recent advancements in laser technology, particularly in laser engraving and laser sintering, have the potential to revolutionize this area. By employing these precise laser techniques, researchers can create highly accurate and reproducible micro-patterns that mimic the complex designs of butterfly wings. Such capabilities can facilitate rapid prototyping of photonic structures that exhibit desired optical properties for applications ranging from iridescent textile apparel to efficient solar cells and high-speed infrared imaging devices.

One of the most significant advancements in this field is the ability to replicate butterfly wing structures in thin film materials, particularly in the realm of medical coatings. Through laser-assisted fabrication, researchers can achieve unparalleled precision in replicating the photonic structures of butterfly wings, enabling the creation of coatings for wound dressings and medical instruments that are sensitive to pH changes. This innovation facilitates real-time monitoring of wound conditions, aiding in chronic wound management and enhancing healing rates. Future research may leverage cutting-edge laser-based techniques to further refine the fabrication methods of these artificial photonic materials, optimizing their mechanical and chemical properties specifically for medical applications [251,252].

Additionally, the super-hydrophobic properties of insect wing scales, which have inspired the creation of durable anti-microbial surfaces, could significantly benefit from the precision and versatility of laser technology. Laser texturing can be used to manipulate surface topographies on micro- and nanoscales, creating surfaces that effectively prevent bacterial adhesion on medical devices, such as catheters, thereby mitigating the risk of infections. By incorporating materials like chitin and chitosan in conjunction with laser-processed designs, researchers aim to develop surfaces that resist fouling and bacterial contamination more efficiently [253].

Utilizing butterfly wing-inspired surfaces, researchers have developed drug-eluting patches for targeted drug delivery. These patches, composed of layers mimicking the wing scale microstructure, control drug release kinetics and enhance therapeutic efficacy. The integration of laser micromachining techniques into the development process could allow for increased precision in creating drug-delivery systems, showing promise in treating coronary artery disease and other localized medical conditions, while minimizing systemic side effects [254].

The nano-architectures of dragonfly wing scales also provide a blueprint for advanced tissue engineering scaffolds. By applying laser technologies, such as selective laser sintering, researchers can fabricate biomimetic scaffolds that not only support cell growth but also promote differentiation in regenerative medicine applications. By replicating the physical and chemical properties of butterfly wings and leveraging the fine control offered by lasers, researchers envision more effective strategies for tissue repair and regeneration [255].

One study [256] demonstrated the potential of combining laser technology with 3D printing to create bionic-patterned zirconia, mimicking patterns found on lotus leaves, butterfly wings, shark skin, and gecko feet. This research analyzed the micro-pattern features and the quality of 3D printing, investigating how these biomimetic patterns influenced the behavior of gingival fibroblasts. The findings indicated that the 3D printing process successfully produced zirconia with various microscale bionic patterns, particularly those resembling gecko feet or lotus leaves, which were found to enhance cell growth and spreading. The addition of laser techniques to this process could refine control over patterns, further improving adhesion, proliferation, and gene expression of gingival fibroblasts, thus promoting soft tissue integration [256].

Overall, butterfly wing-inspired surfaces represent a frontier in medical innovation, offering solutions in anti-microbial coatings, drug delivery systems, and tissue engineering. Future research will increasingly focus on refining these biomimetic technologies through the implementation of advanced laser technology to effectively address current medical challenges—ultimately paving the way for enhanced therapeutic interventions and improved patient outcomes [257].

4.5. Example Cases of Other Nature-Inspired Surfaces

Concepts of chemistry, physics, and engineering have traditionally influenced the design of materials. Biomimetic mineralization seeks to improve the biocompatibility and performance of biomaterials used in bone-related applications. Calcium phosphates, also known as CaPs, show promise in mimicking bone structure and composition. These materials have demonstrated biocompatible behavior with various cell types found in calcified tissues.

Researchers have been exploring natural processes to produce biologically identical CaP coatings that mimic bone apatite. Recently, there has been a focus on biomimetic preparation of CaP coatings, especially for application on the surface of biodegradable polymers.

Furthermore, novel biomimetic coating routes have been developed to produce CaP layers on orthopedic implants and tissue engineering scaffolds. While there are various biomimetic coating routes available in the literature, these methodologies have not yet been introduced in industrial or clinical practice. However, it is believed that by continuing to learn from nature, these advancements will eventually make their way into practical applications [258].

In a study conducted by Visan et al., the MAPLE technique was used for depositing biomimetic nanocrystalline apatite coatings on titanium substrates, with potential application in tissue engineering. The nanometric, poorly crystalline apatite powders used for the preparation of the MAPLE target were synthesized through a biomimetic process involving double decomposition. A KrF* excimer laser source (248 nm, $\tau_{FWHM} \leq 25$ ns) was employed for the deposition of thin films. Analyses revealed the presence of labile non-apatitic mineral ions in the synthesized powders, associated with the formation of a hydrated layer at the surface of the nanocrystals. The results showed that the structural and chemical nature of the nanocrystalline apatite was well-preserved, with the perpetuation of the non-apatitic environments also observed. The study indicated that MAPLE is a suitable technique for the transfer of delicate materials such as biomimetic hydrated nanohydroxyapatite [58].

Another research presents the synthesis of chitosan/biomimetic apatite thin films using a gentle method of temperature and pressure known as combinatorial MAPLE. By using a KrF* excimer laser source (λ = 248 nm, τ_{FWHM} = 25 ns), two different material targets were simultaneously vaporized to grow the films. The use of the C-MAPLE technique in this research has shown great promise as a practical and effective way to create biomimetic and bioactive anti-microbial coatings for orthopedic implants. These coatings closely mimic the composition of natural bone extracellular matrix, which includes water, minerals, fibrous proteins, and proteoglycans. This creates an ideal environment for bone cells to thrive, while also protecting against microbial infection [259].

Another study introduced the MAPLE technique for depositing thin films of mussel adhesive protein (Mytilus edulis foot protein-1). While synthetic adhesives have been widely used in various industries for decades, concerns regarding their environmental and health effects have prompted a search for natural alternatives. One such substitute is marine mussel adhesive protein, which is a formaldehyde-free natural adhesive with excellent adhesion properties. The results indicate that MAPLE does not significantly alter the chemical structure of foot protein-1 and offers better control over film thickness and roughness compared to conventional solvent-based techniques. These findings open up potential applications of MAPLE-deposited mussel adhesive protein thin films in electronics, medicine, and marine industries [188].

Novel biomaterials with potential for bone regeneration, sourced from abundant and cost-effective marine origins, have been studied. Thin films made from marine-derived hydroxyapatite (MdHA), obtained from fish bones and seashells, were produced using pulsed laser deposition (PLD) technology. Alongside physical, chemical, and mechanical analyses, the deposited MdHA films underwent in vitro assessments for cytocompatibility and anti-microbial properties. Examination of the MdHA film morphology revealed rough surfaces that promote cell adhesion and support implant anchorage. The PLD films displayed minimal cytotoxicity on various cell types and exhibited significant anti-microbial effects, with notable reductions in bacterial and fungal growth compared to the control. The combination of good biocompatibility, anti-microbial efficacy, and cost-effectiveness from sustainable sources makes MdHA materials a promising option for innovative coatings on metallic dental implants [156,190].

5. Conclusions

The purpose of this review is to develop a fundamental understanding of laser surface functionalization and to apply this knowledge in the fabrication of advanced biomimetic coatings and patterning through the use of laser surface modification techniques. Inspired by natural surface phenomena observed in lotus leaves, insect wings, and gecko skin, an emphasis was placed on mimicking nature to create surfaces with superhydrophobic, anti-microbial, anti-reflective, and haemocompatible properties. Specific laser surface modification techniques were tailored to the texture and architecture of the surfaces. These techniques have the advantage of allowing the researchers to adapt the surface chemistry and topography of the coating/surface independently, and to create surface gradients and patterns, all of which are important in creating more biomimetic surfaces. In addition, laser techniques allow surface modification of the coating alone, without affecting the bulk material, in cases where it is desirable to separate the functions of the two materials.

The versatility and extensive capabilities of laser surface modification techniques pave the way for innovative research in this field and shape the progress of future studies on nature-inspired biomimetic surface functionalization for medical applications.

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