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From Nature to the Skies: Exploring Bio-Inspired Polymer Coatings for Aerospace Advancements

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Abstract. The aerospace industry demands high-performance materials that can withstand extreme conditions and maintain efficiency in a variety of applications. Bio-inspired polymer coatings have emerged as a promising approach to meet these demands, by drawing inspiration from natural systems to develop new coatings that exhibit enhanced properties, such as self-cleaning, anti-icing, thermal management, and corrosion resistance. In this review, recent developments in the field of bio-inspired polymer coatings for aerospace applications are presented, covering a range of coatings and their respective properties. We discuss the recent developments and applications of bio-inspired coatings, with a focus on their advantages and challenges in aerospace applications. We also highlight the potential for future research and development in this field, including the integration of advanced technologies such as nanotechnology and additive manufacturing. The review aims to provide insights into the current state-of-the-art of bio-inspired polymer coatings for aerospace applications and to inspire further research in this rapidly growing field.

Keywords: aerospace coatings; bio-inspired coatings; polymer coatings; surface engineering

1. Introduction

Bio-inspired polymer coatings have emerged as a promising avenue for advancing the performance and durability of aerospace applications. These coatings draw inspiration from biological systems and organisms, ranging from plants and animals to microorganisms [1,2]. Taking inspiration from nature's ingenious designs and mechanisms, these coatings offer unique solutions to overcome challenges posed by the demanding aerospace environment and to replace previous solutions [3–5]. From reducing drag and turbulence to improving fuel efficiency and corrosion resistance, these coatings hold the promise of elevating aerospace technology to new heights, fostering innovation that mirrors the brilliance of nature's own engineering [6–8].

In general, bio-inspired polymer coatings can be categorized into bio-structuring, bio-mimicry, and bio-functionalization based on the specific mechanisms by which they draw inspiration from nature. Bio-structuring involves modifying the physical architecture of the polymer coating to replicate features found in nature [9]. The focus is on mimicking shapes, textures, or patterns observed in living organisms. Examples include coatings designed to imitate the microscopic structure of lotus leaves for super hydrophobicity and denticles on shark skin for enhanced hydrodynamics. Wei et al. [10] suggested additive manufacturing to develop bio-structures at different scales, including nano, micro, micro-macro, and macro levels. On the other hand, bio-mimicry coatings aim to imitate specific biological processes or functionalities observed in nature. This could involve replication mechanisms such as self-cleaning, color-changing, or anti-fouling properties. For instance, coatings inspired by the self-healing properties of certain plants might be developed to autonomously repair minor damage. Liu et al. [11] proposed a digital twin modeling method based on biomimicry principles that can adaptively construct a multi-physics digital twin of aerospace components machining process. Bio-functionalization involves introducing bioactive molecules or compounds into the polymer matrix of the coating [12]. These additives could provide antimicrobial properties, promote cell adhesion for biomedical applications, or facilitate specific chemical interactions. Coatings inspired by the adhesive proteins in mussels, for instance, might utilize bio-functionalization to enhance adhesion to various surfaces. Soler et al. [13] studied the optimum chemical modification and bio-functionalization procedures to develop antifouling and biomimetic functional coatings for optical sensor applications.

The aerospace industry demands coatings that can withstand extreme conditions, including high temperatures, corrosive environments, ice accretion, and mechanical stress [14]. Traditional coatings have limitations in terms of durability, maintenance, and protection. Recognizing the need for innovative approaches, researchers have turned to nature, which has perfected its own materials and coatings over billions of years of evolution. These coatings aim to replicate the unique properties and functionalities found in nature, offering a new paradigm for aerospace materials engineering [15,16]. According to Huang et al. [17], polymer coatings have shown potential in anti-icing in aircraft applications. The researchers also mentioned that several parameters such as coating material selection (fluoro- or silicone-based), material molecular structure, surface texture, and surface physical properties (dielectric constant or polarity) plays a vital role in designing polymer coatings for anti-icing purposes. Zhu et al. [18] conducted research on self-healing mechanisms for spacecraft coating applications. The coating system was designed with UV-responsive microcapsules embedded into silicon resin. The system heals the damage and cracks occur due to external stimuli and abundant UV radiation from space. By integrating bio-inspired concepts into polymer coating design and synthesis, researchers strive to enhance the performance, longevity, and sustainability of aerospace components [19,20].

The development and application of bio-inspired coatings in aerospace presents exciting opportunities for innovation and advancement. This review paper aims to provide an overview of the current state of bio-inspired polymer coatings for aerospace applications. It will explore the various bio-inspired strategies, materials, and techniques employed in coating design, and discuss their potential benefits, limitations, and prospects.

2. Bio-inspired coatings for aerospace applications

Bio-inspired coatings are a relatively wide field of research that draws inspiration from the natural world to create innovative and highly functional coatings [21]. These coatings are designed to mimic the properties of natural surfaces, such as the self-cleaning abilities of lotus leaves or the adhesion properties of gecko feet [22,23]. By mimicking these natural systems, researchers can develop coatings that enhance the performance of aerospace materials, making them more durable, lightweight, and resistant to environmental factors such as corrosion and abrasion. Bio-inspired coatings have the potential to revolutionize aerospace materials design, leading to the development of safer, more efficient, and more sustainable aircraft and spacecraft. These coatings can be applied to a variety of aerospace components, from engine components, including bolted joints [24–26], and aircraft surfaces to satellite antennas and solar arrays. In recent years, researchers and industrialists have been working on innovations of bio-inspired coatings and technology to expand its range of applications and productivity. The following sub-sections aim to provide an overview of the advancements made available in bio-inspired coating technology which can be a potential alternative serving the aerospace industry.

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2.1. Sharkskin Inspired Coatings

Sharkskin (Figure 1) has a unique texture that reduces drag in water by minimizing flow separation and turbulence [27–29]. This bio-inspired texture has been replicated in coatings and applied to aircraft surfaces to reduce aerodynamic drag. By reducing drag, these coatings can improve fuel efficiency and increase the range of aircraft. Sharklet Technologies is a company that has developed a bio-inspired surface technology based on the microstructure of shark skin [30]. Their technology mimics the roughness and pattern of shark skin to reduce drag and improve aerodynamics on airplane wings and other surfaces.

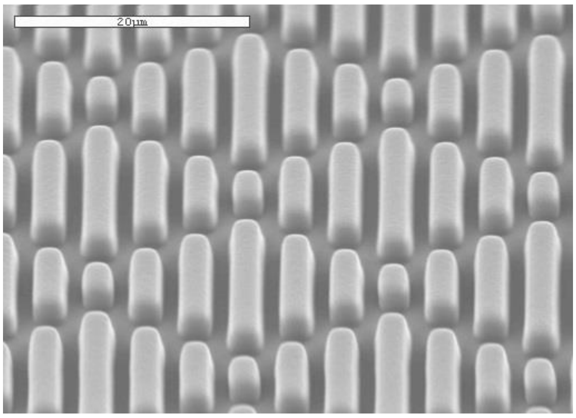

Figure 1. Sharklet micropattern [30,31].

Li et al. [32] used laser surface texturing to produce bioinspired shark skin texture on ceramic surfaces and coated with transition-metal-disulfide (WS_2). The surface modification exhibited reduced surface friction and shear stress when compared to those of only polished surface. Pan et al. [33] created a flexible composite film by incorporating stretchable silica hollow spheres with a unique shark scale-like pattern. This innovative film combines the colloidal crystal structure with polyperfluoroether acrylate-polyurethane acrylate. The outcome is a film that exhibits impressive resistance to wetting and fouling, making it highly effective in repelling liquids and preventing the buildup of unwanted substances. Liu et al. suggested 3D printing as alternative in preparing sharkskin inspired coatings by printing riblets and denticles on surfaces [34].

The sharkskin-inspired coating's aerodynamic benefits extend beyond drag reduction. The unique texture of the coating also enhances the coating's anti-fouling properties, preventing the accumulation of contaminants, such as dirt, ice, or debris, on the surface [35,36]. This feature reduces maintenance requirements, optimizes fuel efficiency, and ensures the longevity of aerospace components, even in demanding operating conditions. Moreover, the sharkskin-inspired coating contributes to noise reduction during flight. The denticles on sharkskin create micro-vortices that effectively dampen the noise generated by turbulent airflow. By incorporating this feature, the coating helps minimize noise emissions during aircraft operations, providing a quieter and more comfortable travel experience for passengers and reducing environmental impact.

2.2. Lotus Leaf Inspired Coatings

The lotus-inspired superhydrophobic polymer coating creates a rough and textured surface at the microscale, interspersed with nanoscale structures. This intricate surface architecture traps air pockets, mimicking the lotus effect (Figure 2), which enables droplets of water or other liquids to effortlessly roll off the surface [37,38]. As a result, the coating exhibits exceptional water-repellent properties, preventing liquid accumulation, ice formation, and the adherence of contaminants, such as dirt, pollutants, and ice accretion [39].

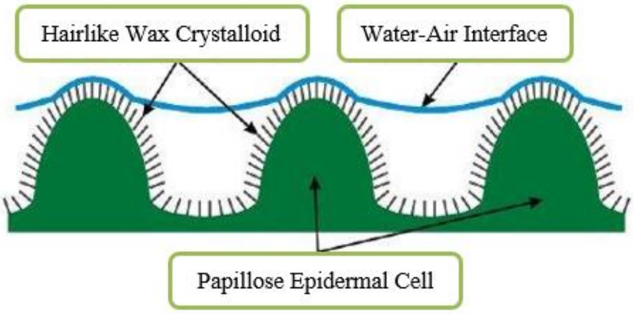

Figure 2. Hierarchical structure of lotus leaf surface [40].

Efforts have been taken by researchers in developing lotus leaf inspired hydrophobic coatings. Yang et al. [41] developed lotus leaf inspired superhydrophobic copper coating via facile pulse electrodeposition. The researchers claimed that the superhydrophobic coatings simultaneously exhibit excellent self-cleaning, corrosion resistance and mechanical properties. Li et al. [42] developed a hydrophobic waterborne polyurethane (PU) composite coating by reinforcing with graphene oxide and carbon nanotubes hybrids and nano-casting the surface with fresh lotus leaves. The lotus leaf bio-inspired coatings demonstrated improved tensile strength and hardness, increased contact angle and better corrosion resistance when compared to pure PU coating.

This innovative coating holds great promise for aerospace applications, offering a range of benefits. Firstly, its superhydrophobic nature reduces water and ice accumulation on critical aircraft surfaces, such as wings and fuselage, thereby minimizing drag and enhancing fuel efficiency. The reduction in ice formation and contamination also enhances the safety and performance of aircraft, particularly in adverse weather conditions. Moreover, the lotus-inspired coating's self-cleaning properties reduce the need for frequent maintenance, leading to significant cost savings and operational efficiency. By repelling contaminants, the coating minimizes the accumulation of dirt, insects, and debris, reducing the frequency of cleaning and maintenance cycles. Additionally, the bio-inspired coating exhibits excellent adhesion to various materials commonly used in aerospace, such as metals and composites, ensuring its long-term durability and reliability in challenging operational environments. It can withstand the harsh conditions of high-altitude flight, extreme temperatures, and exposure to UV radiation. Its application has the potential to revolutionize the aerospace industry, contributing to enhanced fuel efficiency, improved safety, and reduced environmental impact.

2.3. Gecko Inspired Coatings

In recent years, researchers have been captivated by the remarkable adhesive abilities of geckos and have sought to translate this natural phenomenon into innovative technologies [43,44]. Inspired by the gecko's unique ability to cling to various surfaces (Figure 3), gecko-inspired coating has been developed for aerospace applications, revolutionizing adhesion, and maneuverability in the field.

Singh et al. [45] studied gecko feet inspired surface in a unique approach by developing reprintable coatings for papers which can be cleaned and reused up to 50 cycles. The coating is prepared by by casting cross linkable silicone films on a porous template. Kerst et al. [46] investigated the adhesive performance of gecko inspired adhesive when polymer coating is added as surface treatment. The addition of coating significantly improved the shear properties of the adhesive.

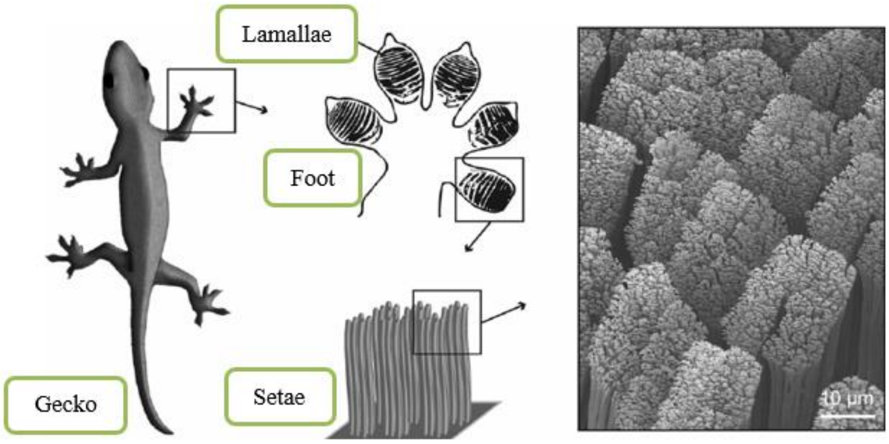

Figure 3. Microstructure of Gecko foot [47].

The gecko-inspired coating is designed to mimic the structure and functionality of the tiny hairs, known as setae, found on a gecko's feet. These setae possess microscopic structures called spatulae, which allow geckos to create strong adhesive forces through van der Waals interactions [48,49]. This natural adhesion mechanism has been harnessed to create a coating that can enable spacecraft, satellites, and other aerospace components to adhere to surfaces in a secure and reversible manner. Researchers have studied the adhesive properties of gecko feet, which can stick to walls and ceilings without leaving any residue. By mimicking the microstructure of gecko feet, researchers could develop adhesives that can stick to smooth surfaces without using traditional adhesives or fasteners. This could be useful in aerospace applications for attaching components or sensors to surfaces without damaging them.

2.4. Butterfly Wing Inspired Coatings

The wings of some butterflies like *Morpho aega, Pachliopta aristolochiae* and *Monoptera* are covered in tiny scales that give them their distinctive colours and patterns. The vibrant and iridescent colors found on butterfly wings are a result of nanostructures that manipulate light [50]. Researchers have developed bio-inspired materials that replicate these nanostructures, enabling the creation of coatings that exhibit vivid and angle-dependent colors [51,52]. Such coatings can be used for aesthetic purposes in aerospace design or for functional applications like anti-counterfeiting measures on aircraft components. Cypris Materials creates structural colour coatings that reflect UV and infrared light eliminating the need for toxic chemicals or dyes. These coatings are designed to replicate the naturally occurring nanostructures that produce the brilliant colours observed in butterfly wings.

Zhao et al. [53] inspired the *Morpho aega* wing geometry to fabricate synthetic scale arrays comprising thin, curved CNT microstructures coated with a hydrophobic polymer. The coating exhibited anisotropic liquid adhesion and can be applied for self-cleaning surfaces, microfluidics, and phase change energy conversion. Ding et al. [54] developed polymer-based antireflection films based on the window-like optical structure of the butterfly *Monoptera*. The bio-inspired film demonstrated broader-band antireflection compared to plain and flat PDMS films.

The benefits of these materials when compared to conventional coatings are its non-toxic characteristics, reduced cost, and reduced usage of energy upon manufacturing. Researchers also studied the frost formation process on butterfly wing and the hydrophobic durability mechanism of butterfly wing [55]. The findings provide an experimental basis for the design of new and durable anti-icing surface coatings to suppress frost/ice growth, which could have industrial applications. The coating that mimics the structure of butterfly wings could also reduce drag and improve aerodynamics on airplane wings.

2.5. Spider Silk Coatings

Spider silk (Figure 4) is a strong, lightweight, and flexible material that has potential in aerospace applications. The spider silk-inspired polymer coating exhibits lightweight properties, making it highly advantageous for aerospace applications where weight reduction is critical [56–59]. The coating's thin and lightweight nature minimizes the added mass while providing significant strength and protection advantages, enabling aerospace systems to achieve improved efficiency and fuel economy. Researchers have studied the structure of spider silk to develop new coatings that could be used to protect aerospace components. For instance, spider silk coatings could be used to reinforce airplane wings or to protect them from impacts or vibrations. The coating is designed to mimic the complex hierarchical structure of spider silk, which consists of aligned fibers at the molecular, nano, and microscale levels. This structural arrangement imparts exceptional tensile strength and toughness to the coating, enabling it to withstand high stress and mechanical loads.

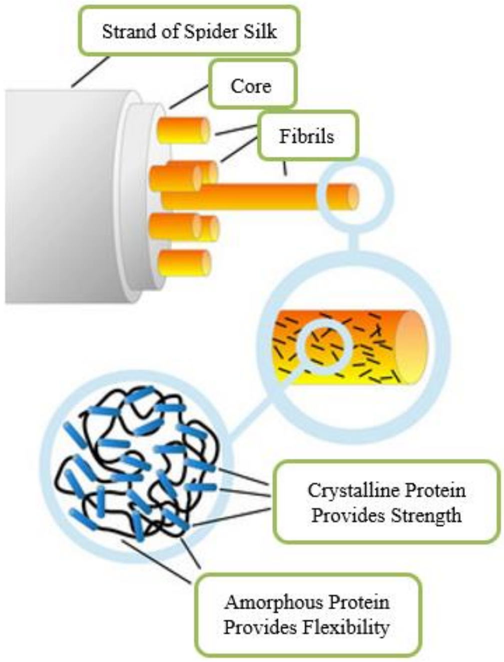

Figure 4. Hierarchical structure of spider silk [60,61].

Koga et al. [62] have created a biopolymer film using a blend of spider silk-like peptides and flexible polypropylene glycol. These peptides consist of hydrophobic segments that can form β-sheet structures. The team discovered that the mechanical characteristics and self-healing capabilities of the microfilms were influenced by both the type of peptide block used and its length. After first decoding spider DNA, researchers realised that by taking the animal's specific genetic code for producing silk and introducing it to bacteria, they could artificially reproduce an identical material [63]. Wu et al. [64] used genetic engineering to create bioinspired spider silk hydrogel. By utilizing *Escherichia coli* (*E. coli*) as a host for heterologous expression, the researchers produced a self-assembled hydrogel from the recombinant spider silk through dialysis process. This hydrogel exhibited remarkable properties, including a storage modulus of around 250 Pa, displaying both autonomous self-healing abilities and exceptional sensitivity to strain.

The spider silk-inspired coating exhibits excellent flexibility and elasticity, similar to natural spider silk. It can adapt to dynamic conditions and absorb impact energy, ensuring the integrity and longevity of aerospace components. This flexibility allows the coating to endure deformation without compromising its protective properties, making it suitable for applications that experience vibrations, shocks, or sudden changes in forces.

2.6. Mussel Inspired Coatings

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Mussels can attach themselves to various surfaces, such as rocks or ship hulls, in wet and turbulent environments (Figure 5). This ability is attributed to the unique structure and chemistry of the adhesive proteins they secrete. The key novelty of this mussel-inspired coating lies in its ability to create strong and durable bonds between different materials, including metals, composites, ceramics, and polymers [65]. Researchers have studied the structure of this adhesive to develop new materials that can stick to wet or underwater surfaces [66,67]. The polymer coating contains bio-inspired chemical functional groups, such as catechol and amine moieties, which facilitate adhesion by forming strong molecular interactions with the substrate surface [68,69]. The mussel-inspired coating exhibits exceptional adhesion under both dry and wet conditions, making it particularly valuable for aerospace applications that encounter moisture or humidity. Unlike traditional adhesives, which may lose their effectiveness in the presence of water, this coating maintains its bonding strength and integrity, ensuring reliable performance even in challenging environments.

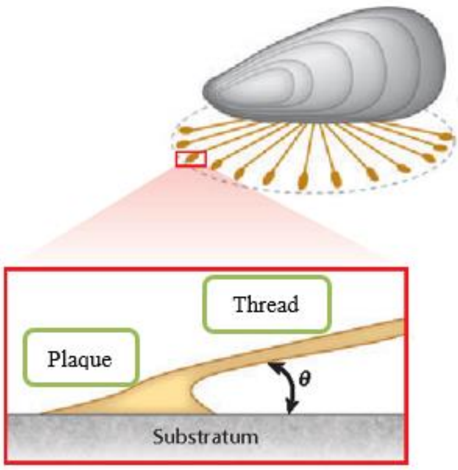

Figure 5. Adhesive structure of mussels [70]**.**

The versatility of the mussel-inspired coating extends beyond adhesion. It can also serve as a protective barrier, shielding aerospace surfaces from corrosion, abrasion, and environmental degradation. The coating forms a robust and impermeable layer that acts as a shield against moisture, chemicals, and other detrimental factors, thereby extending the lifespan of aerospace components and reducing maintenance requirements. Additionally, the mussel-inspired coating exhibits self-healing properties, another unique feature derived from mussel adhesive proteins. When the coating is damaged or scratched, the mussel-inspired chemistry enables it to autonomously repair the damaged area, restoring its protective and adhesive properties. This self-healing capability enhances the coating's longevity and minimizes the need for frequent repairs or replacements. Its strong adhesion, durability, protection, and self-healing capabilities make it an invaluable tool for ensuring reliable performance, extending component lifespan, and reducing maintenance efforts in the aerospace industry.

One area of focus is the development of new polymeric coatings that can address specific challenges faced in the aerospace industry, such as ice formation, contamination, drag, corrosion, thermal management, and fouling. Table 1 summarizes the potential applications of bio-inspired coatings in the aerospace industry.

Table 1. Potential applications of bio-inspired coatings in the aerospace industry.

Type of Coatings	Description	Bio-inspiration	Aerospace Applications
Anti-Fouling Coatings	Marine organisms, like barnacles and algae, often attach themselves to submerged structures, causing increased drag and fuel consumption. Bio-inspired anti-fouling	Sharkskin [74,75] Butterfly wings Lotus leaves	- Engine Components

	polymer coatings can be developed to prevent the attachment of organisms to aircraft surfaces, reducing maintenance requirements and improving performance [71–73].		- Propellers and Rotors
Anti-Icing Coatings	Ice accumulation on aircraft surfaces can affect aerodynamic performance and increase fuel consumption. Polymer coatings that mimic the microstructure of lotus leaves or insect wings, which have water-repellent properties, can be applied to aircraft surfaces. These coatings reduce ice adhesion and promote easy ice removal, improving flight safety and efficiency [76,77].	Lotus leaves [78] Cicada wings [79,80] Gecko feet [81]	- Aircraft Wings - Sensors and Avionics - Windshield and Windows
Anti-Microbial Coatings	In environments where cleanliness and hygiene are critical, such as in aerospace interiors or medical transport aircraft, bio-inspired anti-microbial coatings can be applied. These coatings mimic the properties of natural antimicrobial substances and help inhibit the growth of bacteria, viruses, and fungi, reducing the risk of contamination and improving cabin air quality [82–84].	Spider Silk [85] Sharkskin Chitosan [86,87]	- Aircraft Interiors - Ventilation Systems - Food Storage and Preparation Surfaces
Anti-Reflective Coatings	Certain organisms, like moths and butterflies, have evolved unique structures on their wings to minimize reflection and enhance light absorption [88–90]. Bio-inspired anti-reflective coatings can be used on aircraft windows, camera lenses, and optical sensors to reduce glare, improve visibility, and enhance optical performance.	Moths [91] Butterfly wings [92] Rose petals [93]	- Satellite Optics - Optical Telescopes and Observatories - Satellite Solar Panels
Corrosion Resistance Coatings	Polymer coatings can be designed to provide enhanced corrosion resistance by emulating the protective properties of natural materials [94]. For example, applying coatings that mimic the structure of mollusk shells or coral skeletons can provide a barrier against corrosion and extend the lifespan of aerospace components exposed to harsh environments [98].	Mollusk shells [96] Coral skeletons [97] Mussel	- Fuel Tanks and Pipelines - Undercarriage and Landing Gear
Drag Reduction Coatings	The surface texture of shark skin has inspired the development of coatings that reduce aerodynamic drag. These coatings mimic the microscopic riblets found on shark skin, which decrease drag by reducing the size and intensity of turbulent air flow over the surface. Applying such coatings to aircraft wings and bodies can lead to improved fuel efficiency and increased range.	Sharkskin European Sea Bass scales [98] Pufferfish skin [98]	- Aircraft Wings and Fuselage - Rotorcraft and Rotor blades
Heat Shielding Coatings	For spacecraft and re-entry vehicles, heat shielding is crucial during atmospheric re-entry. Bio-inspired coatings can be developed to mimic the heat resistance and thermal insulation properties of materials like the silica shells of diatoms. These coatings help protect the vehicle from extreme temperatures and ensure the safety of the crew and payload.	Diatom frustules [99]	- Launch and Re-entry Vehicles - Exhaust Systems
Noise Reduction Coatings	Surface microstructures with noise reduction properties has inspired the development of bio-inspired coatings that reduce aerodynamic noise . These coatings can be applied to aircraft surfaces to suppress noise generated during takeoff, landing, and high-speed flight, leading to quieter operations and improved passenger comfort.	Riblet [100] Mushroom-like microstructure [100]	- Aircraft Engines - Air Traffic Control Towers

Self-Cleaning Coatings	Aerospace components often encounter dust, dirt, and other contaminants during flight. Self-cleaning polymer coatings inspired by the lotus effect, or the self-cleaning ability of butterfly wings can be applied to aircraft surfaces. These coatings repel dirt particles and allow rain or airflows to remove contaminants, reducing maintenance needs and improving aerodynamic efficiency.	Lotus leaves Butterfly wings Fly eye [101]	- Satellite Optics - Satellite Solar Panels -Windows and Windshields
Self-Healing Coatings	Self-healing coatings inspired by mussel and tree frog toe can be applied to various aircraft structures and components, such as turbine blades, wings, fuselage, and control surfaces [102]. These coatings can help mitigate the effects of wear, fatigue, and environmental damage, thereby extending the service life of critical aerospace components. By autonomously repairing cracks, scratches, or delamination, these coatings ensure structural integrity and reduce the need for frequent inspections and maintenance.	Mussel [103,104] Tree frog toes [105,106]	- Windows and Windshields - Fighter Jet Skin
Solar Energy Harvesting Coatings	Bio-inspired coatings can be used to improve the efficiency of solar panels installed on aircraft. By emulating the light-trapping structures found in plant leaves or photosynthetic bacteria, these coatings can enhance light absorption, optimize energy conversion, and increase the overall power output of solar panels [107,108].	Plant leaves [109] Cyanobacteria [110] Moth eye [111]	- Solar Sail Propulsion - Satellite Solar Panels - Energy Harvesting Sensors
Structural Strengthening Coatings	Some bio-inspired coatings draw inspiration from the structure and composition of materials found in nature, such as bones or seashells [112,113]. These coatings can be applied to strengthen and reinforce structural components of aircraft, improving their durability and resistance to impact or fatigue.	Spidersilk [114] Bones Seashells	- Aerospace Structures and Framework - Engine Mounts and Attachments
Thermal Management Coatings	Managing heat distribution and dissipation is crucial in aerospace applications. Bio-inspired coatings that replicate the cooling mechanisms found in the skin of certain animals, such as polar bear fur or penguins, can be used to enhance thermal management [115,116]. These coatings can assist in heat dissipation and reduce thermal stress on critical components.	Penguins Polar bear fur Saharan silver ant hair [117]	- Satellite Surfaces and Components - Power Generators or Energy Storage Units

In summary, bio-inspired coatings hold immense promise for the aerospace industry, offering transformative solutions to enhance the performance, durability, and sustainability of aerospace components and systems. By drawing inspiration from nature's genius, these coatings can provide self-healing capabilities, anti-fouling properties, and thermal regulation, thereby paving the way for safer, more efficient, and reliable aerospace technologies.

3. Future research and development

The potential for future research and development in the field of bio-inspired coatings for aerospace applications is vast and promising. Modern technologies such as additive manufacturing and nanotechnology, can be closely related and interconnected when it comes to the development of bio-inspired coatings. Integration of advanced technologies such as nanotechnology can improve the mechanical and electrical properties of bio-inspired coatings, making them more durable and effective. Additionally, additive manufacturing of bio-inspired coatings can enable the creation of complex and highly precise coatings that are tailored to specific applications [118,119]. Bio-inspired coatings often derive their functionality from nanoscale structures found in nature. Nanotechnology, which deals with materials and structures at the nanoscale level (typically below 100 nanometres), provides the means to replicate and incorporate these features into bio-inspired coatings [120,121]. Additive manufacturing techniques, such as stereolithography or digital light processing (DLP), can achieve high-resolution printing, allowing for the precise replication of nanoscale structures in coatings. Hence, the synergy between additive manufacturing and nanotechnology in bio-inspired coatings offers several advantages. It enables the fabrication of coatings with precise nanoscale features, hierarchical structures, and tailored material compositions. This combination allows for enhanced functionalities, improved performance, and increased customization of coatings for specific aerospace requirements. The integration of additive manufacturing and nanotechnology in bio-inspired coatings represents a powerful approach to achieve biomimicry and unlock the potential of nature-inspired solutions in aerospace engineering (Table 2). Technologies such as microfabrication, lithography, and etching can be also employed to create intricate surface topographies, patterns, and textures like those observed in natural systems.

Table 2. Future research on bio-inspired coatings for aerospace industry.

Advanced Bio-inspired Coating Technology	Description
Additive Manufactured Coatings [122–125]	Additive manufacturing, specifically 3D printing, offers unique opportunities for the development of bio-inspired polymer coatings in the aerospace industry. Future research should focus on utilizing 3D printing techniques to fabricate polymer based coatings with intricate designs, complex geometries, and precise control over material composition. By integrating bio-inspired features directly into the coating's structure, such as hierarchical patterns or biomimetic textures, it is possible to achieve enhanced functionalities and performance tailored to specific aerospace applications.
Biomimetic Nanomaterials [126–128]	Advancements in nanotechnology provide exciting opportunities for the development of bio-inspired polymer coatings at the nanoscale. Researchers can explore the synthesis and characterization of biomimetic nanomaterials that replicate the unique properties found in natural systems. By incorporating nanomaterials with specific functionalities, such as super hydrophobicity, anti-reflectivity, or enhanced heat resistance, novel coatings can be created to improve the durability, performance, and safety of aerospace components.
Biomimetic Sensing and Actuation [129–131]	Exploring the incorporation of biomimetic sensing and actuation mechanisms within coatings opens exciting possibilities for aerospace functionality. By mimicking biological systems such as *Mimosa pudica*, coatings could react to environmental changes, such as airflow, temperature fluctuations, or chemical exposures, to adjust surface properties and optimize aerodynamic performance. This bio-inspired approach could lead to aircraft with enhanced fuel efficiency, reduced drag, and improved maneuverability. Future research should focus on understanding and harnessing these adaptive characteristics to create polymer coatings that adapt to different temperatures, pressures, or exposure to chemicals and radiation.
Multifunctional Coatings [132–134]	One promising avenue for future research is the development of multifunctional coatings inspired by nature. While current bio-inspired coatings focus primarily on mimicking specific properties, such as anti-icing or self-cleaning, there is a need to integrate multiple functionalities into a single coating. For instance, exploring the incorporation of structural coloration with anti-corrosion or drag-reducing capabilities could lead to coatings that provide enhanced performance and efficiency in aerospace applications.
Sustainable and Eco-friendly Coatings [135–137]	As the aerospace industry strives for more sustainable practices, future research should focus on developing bio-inspired coatings that are environmentally friendly. This includes exploring alternative bio-based polymers, eco-friendly fabrication processes, and biodegradable polymer coatings that minimize the environmental impact without

compromising performance. By integrating sustainable principles into bio-inspired coatings, the aerospace industry can contribute to a greener and more sustainable future.

Another growing technology is artificial intelligence (AI), Machine Learning (ML), and Quantum Computing (QC), which is about to transform our world where biomimicry or simulation of nature can be done to develop new materials [138]. AI and ML are revolutionizing the development of new materials and structures by enabling rapid material discovery and optimization through proper design, predicting material properties, and accelerating the synthesis and characterization processes [139-152]. These technologies are playing a crucial role in the development of bio-inspired polymer coatings by analyzing biological data, simulating complex natural processes, and generating optimized coating designs, allowing for the creation of coatings that mimic nature's ingenious strategies and offer enhanced functionalities such as self-healing, anti-fouling, and thermal regulation. A powerful practical QC will open the possibility to simulate fluids accurately, molecule behaviours, protein folding and in fact, do many things we've never been able to before [141,142]. This will result in a torrent of technological breakthroughs from new materials to the invention of new coatings, and a host of other materials we've yet to even imagine [143]. Further, integration of bio-inspired coatings with other advanced materials and composites can enhance their properties and functionalities [144–146]. Lastly, there is an opportunity to explore the use of bio-inspired coatings for space applications, such as protecting spacecraft from radiation and micrometeoroids. Future research in this field has the potential to lead to the development of highly advanced and efficient aerospace materials, enabling safer, more sustainable, and more efficient aircraft and spacecraft. Exploring multifunctionality, adaptability, nanomaterials, self-assembly techniques, and sustainability will pave the way for novel polymer coatings that push the boundaries of aerospace advancements.

4. Conclusion

In conclusion, bio-inspired polymer coatings offer a promising avenue for enhancing the performance of aerospace materials, enabling safer, more efficient, and more sustainable aircraft and spacecraft. The development of these coatings has been driven by the need for materials that can withstand extreme conditions and maintain their efficiency in the aerospace industry. By drawing inspiration from nature, researchers have been able to develop coatings with enhanced properties such as self-cleaning, anti-icing, and corrosion resistance. The review of recent developments in bio-inspired coatings presented in this paper provides valuable insights into the state-of-the-art in this field and highlights the potential for future research and development. With the integration of advanced technologies such as nanotechnology and 3D printing [147], bio-inspired polymer coatings are poised to play a significant role in the future of aerospace materials design and manufacturing, especially using CAx systems [148–150] and CNC techniques [151–152].

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