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Review article

Bio-inspired coatings for natural fibre composites

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ABSTRACT

Natural fibre composites (NFC) are gaining popularity due to their versatility and environmental benefits, but they often need enhancements to withstand extreme conditions and maintain performance across various applications. Bio-inspired coatings offer a promising solution by mimicking natural systems to develop advanced properties such as self-cleaning, water repellency, thermal regulation, and corrosion resistance. This review examines recent advancements in bio-inspired coatings for NFC, highlighting a range of innovative coatings and their unique properties. We discuss the latest developments, applications, and the specific challenges these coatings address in NFC contexts. Additionally, the review explores future research opportunities, including the integration of emerging technologies like nanotechnology and additive manufacturing. By providing an overview of the current state of bio-inspired coatings for NFC, this review aims to encourage further research and innovation in this rapidly growing field.

1. Introduction

Natural fibre composites (NFC) are gaining traction across various industries due to their eco-friendly properties and lightweight structure. They are widely used in the automotive industry for lightweight, sustainable components such as interior panels and under-the-hood parts. In the construction sector, NFC are employed in roofing, insulation, and cladding materials due to their environmental benefits and thermal insulation properties. NFC are also making headway in the marine and drone industries, where their lightweight and eco-friendly characteristics are utilized in boat hulls, marine structures, and drone frames, while consumer goods and furniture industries benefit from their strength and flexibility. However, NFC face specific issues such as moisture absorption, mechanical wear, fouling, and UV degradation, compared to traditional synthetic materials. In response to these challenges, bio-inspired coatings have emerged as a specialized solution, offering unique advantages over conventional coatings [1]. Fig. 1 illustrates the need for bioinspired coatings in NFC applications across aerospace, marine, construction, and consumer products to address challenges like impact damage, marine organism growth, environmental degradation, and moisture absorption, enhancing durability and performance. By drawing inspiration from nature's ingenious designs and mechanisms, bio-inspired coatings offer tailored solutions that not only enhance moisture resistance and protect against environmental degradation but also leverage the remarkable properties found in biological systems.

In general, bio-inspired coatings can be categorized into bio-structuring, biomimicry, and bio-functionalization based on the specific mechanisms by which they draw inspiration from nature. Bio-structuring involves modifying the physical architecture of the coating to replicate features found in nature [2]. 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 anti-fouling properties in NFC. Wei et al. [3] suggested

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additive manufacturing to develop bio-structures in the scale of nanometer, micrometer, micro-macrometer, and macrometer 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 in NFC. Liu et al. [4] 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 matrix of the coating [5]. These additives could provide antimicrobial properties, promote cell adhesion for biomedical applications, or facilitate specific chemical interactions particularly in NFC applications. Coatings inspired by the adhesive proteins in mussels, for instance, utilize bio-functionalization to enhance adhesion to various surfaces. Soler et al. [6] studied the optimum chemical modification and bio-functionalization procedures to develop antifouling and biomimetic functional coatings for optical sensor applications.

In the evolving landscape of bio-inspired coatings, another noteworthy category is Engineered Living Materials (ELM), where living cells and coatings converge to create active and responsive biomaterials [7]. Within ELM, microorganisms serve as the bioactive component, offering intricate responses to environmental stimuli and allowing genetic engineering for controlled reactions. This convergence introduces a paradigm shift in the area of self-healing coatings, where ELM, armed with living cells, autonomously repair damage induced by environmental factors, thereby amplifying durability. The adaptability of ELM to external stimuli opens avenues for coatings that dynamically respond to ever-changing environmental conditions, delivering versatile and dynamic protective features. Furthermore, ELM contribute to sustainability objectives by facilitating the development of biodegradable coatings that naturally degrade over time. ELM also holds promising potential in biomedical contexts, ranging from biosensing and wound healing to stem-cell-based tissue engineering and drug delivery which is essential during crewed space missions [8]. This dynamic field not only addresses current challenges but also offers a glimpse into the future applications of ELM. ELM enhance the sustainability and durability of NFC by reducing the need for frequent maintenance and repairs, thus extending the lifespan of NFC products. Additionally, ELM contribute to sustainability by potentially reducing the environmental impact of coatings using renewable biological components and minimizing waste.

According to the data presented in Table 1, a multitude of studies has been conducted by researchers focused on the development of bio-inspired coatings utilizing diverse coating materials and methods. The investigations commonly centered around examining mechanical properties, thermal properties, tribological properties, corrosion resistance, and water contact angle, as outlined in Table 1. For instance, Xu et al. [9] successfully crafted seashell-inspired coatings with remarkable heat resistance, demonstrating the ability to withstand extremely high temperatures ranging from 1150 to 1650 °C. This notable attribute renders these coatings particularly appealing for applications in NFC, where the inherent low thermal properties of natural fibres often restrict their use in high-temperature environments.

In the context of surface wettability, Qi et al. [29] and Vardaki et al. [30] reported low contact angles in their respective mussel protein-inspired and chitosan coatings. A low contact angle, below 90°, signifies a wettable (hydrophilic) surface where liquids spread out. The super hydrophilic nature of zwitterionic polypeptide facilitates the rapid spread of water molecules into pseudo films on the surface. This characteristic not only prevents the accumulation of water molecules but also impedes the interference of light transmittance. Additionally, superhydrophilicity imparts protein coatings with exceptional self-cleaning properties and resistance to bacterial adsorption. On the other hand, a high-water contact angle, greater than 90° indicates that the surface is not wettable (hydrophobic), and the liquid will bead up. According to Li et al. [20], lotus inspired composite coating achieved a high contact angle at 121°. This superhydrophobic attribute enhances the corrosion resistance of the coating, with inhibition efficiency

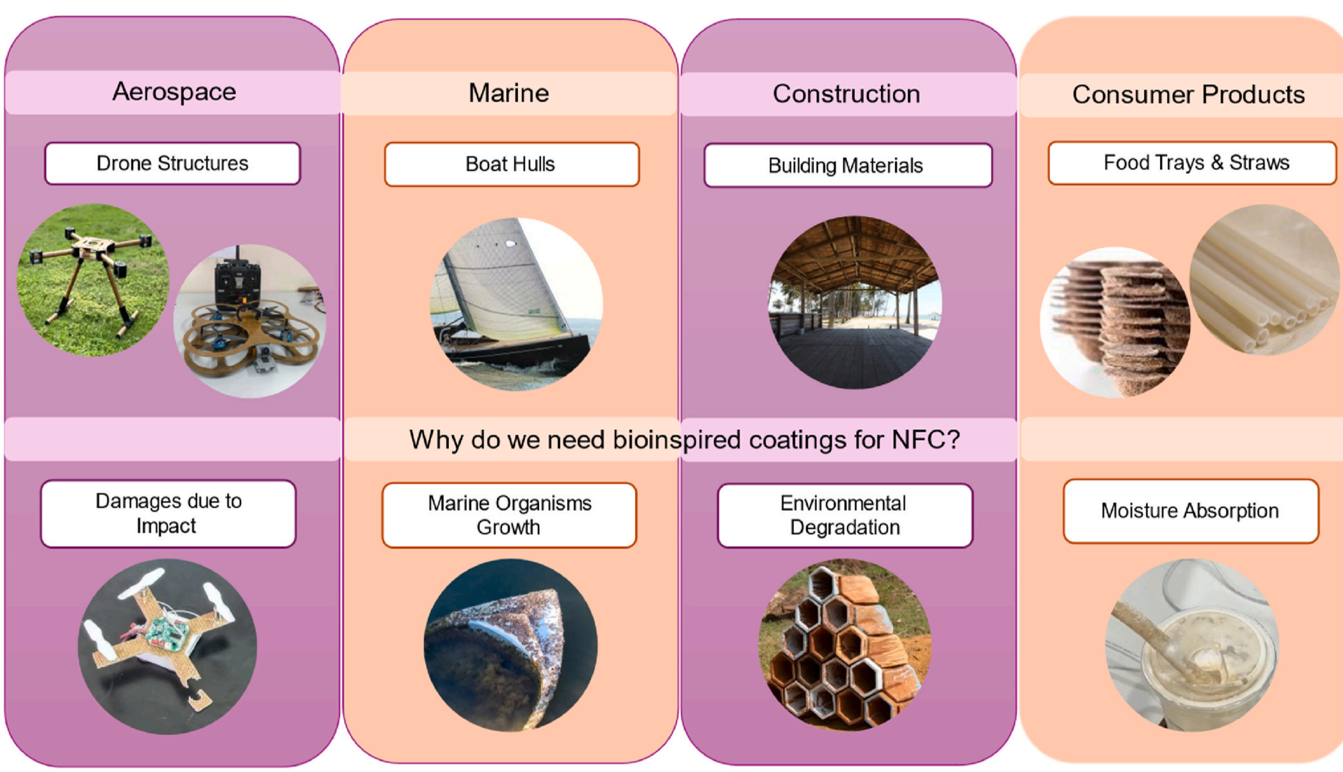

Fig. 1. Growing areas of NFC applications and challenges.

Table 1
Previous research on properties of bio-inspired coatings.

Year	Author	Bio-inspiration	Coating Material	Properties investigated	Results
2024	Lu et al. [10]	Interdigitated structures in phloeodes diabolicus elytra	Interlocking polydimethylsiloxane (PDMS) coating	Tensile adhesion Shear resistance	270% increment 520% increment
2024	Sandak et al. [11]	Bio-active living coating system	Microorganisms	Number of colonies (Dominance)	Aureobasidium sp. (Dominant genus)
2023	Lu et al. [12]	Skin, urchin like microstructure, natural chrysanthemum pollen grain microstructures	Polybutylene adipate-polyurethane (PBAPU) elastomer matrix with conducting MXene nanosheets	Elastic modulus Tensile strength Stretchability Sensor sensitivity Detection limit	1.7 MPa 18.87 MPa 1190 % 784.02 kPa−1 0.12 Pa
2023	Bu et al. [13]	Manta ray skin	Hyperbranched amine-rich polysiloxane (HPS), glycidyloxypropyl polyhedral silsesquioxane (GPOSS) and epoxy groups modified poly(3,3,3-trifluoropropylmethylsiloxane) (EPFS)	Hardness Coefficient of friction Ice adhesion strength	0.94 GPa 0.076 8.9 kPa
2023	Bhakare et al. [14]	Tapioca starch and Arjuna bark	Tapioca starch and arjuna bark composite	Tensile strength Limiting oxygen index (LOI) Vertical flammability test (VFT)	55.5 MPa 46.98% 2 cm char length
2023	Wang et al. [15]	Energy storage	Polydopamine/polyethyleneimine-functionalized (PDA/PEI)-coated MXene sheets	Tensile strength Energy storage capability Rate performance	366 MPa 454 F g−1 at 5 mV s−1 48% at 10 000 mV s−1
2023	Liu et al. [16]	Strength and toughness of muscles	Soybean protein-functionalized boron nitride nanosheets & epoxy hyperbranched polyester (EHP)	Wet shear strength	1.05 MPa
2023	Wang et al. [17]	Cyphochilus beetle scales	Bicontinuous interfacially jammed emulsion gels (bijels)	Solar reflectance Longwave-infrared (LWIR) emissivity Subambient temperature drop	≳0.97 ≳0.93 5.6 °C
2022	Xu et al. [9]	Seashell structure	Sugar-derived carbon	Elastic modulus Hardness Surviving temperature	120 GPa 11 GPa 1150–1650 °C
2022	Dong et al. [18]	Nacre	TiSiCN (hard phase) & Ag (soft phase)	Fracture strength Fracture toughness	12.42 GPa 12.12 MPa.m1/2
2022	Lin et al. [19]	Mussel protein	Silicone-based polybenzoxazine	Adhesion strength (dry condition) Adhesion strength (wet condition)	3.6 MPa 3 MPa
2021	Li et al. [20]	Lotus leaf	Graphene oxide (GO) + carbon nanotubes (CNTs) reinforced polyurethane (PU)	Tensile strength Yield strength Elongation at break Elastic modulus Hardness Contact angle Inhibition efficiency (corrosion resistance)	26.77 MPa 24.31 MPa 274.38 % 2.271 GPa 0.081 GPa 121° 98.35 %
2021	Wang et al. [21]	Structural colours of plants and animals	Straw fibre reinforced coloured starch-based films & monodispersed silicon dioxide nanoparticles	Tensile strength Elongation at break Melting temperature	42.8 MPa 3.5 % 87.6 °C
2020	Li et al. [22]	Articular cartilage	Polytetrafluoroethylene (PTFE) layer on top of a porous titanium dioxide (TiO2) coating	Elastic modulus Hardness Coefficient of friction Load bearing capability	231.3 GPa 12.4 GPa 0.1 3.2 GPa
2020	Dong et al. [23]	Superhydrophobic microstructures	Copper oxide surface modified with stearic acid	Contact angle (air) Contact angle (cyclopentane)	160° ± 3.1° 170.7° ± 2.5°
2020	Nan et al. [24]	Dopamine chemistry	Thin polydopamine (PDA) coatings on the surface of nanodiamond (ND) particles & polyvinyl alcohol (PVA)	Thermal conductivity (K) Tensile strength Volume resistivity	5.864 W/mK 35.38 MPa 6.088 × 1015 Ω cm
2019	Chen et al. [25]	Hydroxyapatite crystallites of enamel	Anodic alumina oxide (AAO)-assisted, double-layered gel system	Elastic modulus Hardness	52 GPa 0.73 GPa
2019	Malollari et al. [26]	Mussel protein	Polydopamine (pDA)	Penetration Depth Scratch Depth	21.4 ± 3.2 nm −4.7 ± 1.7 nm
2019	Wat et al. [27]	Nacre	Nickel-coated alumina ceramic	Resistance-curve toughness Flexural strength	16 MPa m½ 300 MPa
2019	Liu et al. [28]	DNA induced	Calcium phosphate (Ca–P)	Corrosion current (icorr)	6.2 × 10−6 A/cm2

(continued on next page)

Table 1 (*continued*)

Year	Author	Bio-inspiration	Coating Material	Properties investigated	Results
				Polarization resistance (rp)	1.3 × 107 ·cm2
2019	Qi et al. [29]	Mussel protein	Zwitterionic polypeptide chimeric protein (MP-KE)	Contact angle	5°
				Light transmittance	90 %
2017	Vardaki et al. [30]	Hydroxyapatite and chitosan	Hydroxyapatite (hap) & chitosan (CS)	Contact angle	42°
				Porosity	0.32 %

maintaining at an impressive 98.35% even after immersion in a 3.5% NaCl solution for 20 days. Consequently, this coating presents itself as a promising option for demanding corrosion prevention applications, such as marine engineering and the construction industry. An interesting approach was carried out by Wang et al. [15] by developing bio-inspired energy storage flexible 2D film that achieved a very high mechanical strength with superior energy storage capability. The study has proven the material's capability in the application of flexible energy storage device for wearable electronics.

NFC demands coatings that improve durability and withstand high temperatures, moist and corrosive environments, and mechanical stress. While few studies have focused on coatings for NFC, there is a pressing need to explore bioinspired coatings due to their potential to provide superior multifunctional properties, such as self-healing, enhanced hydrophobicity, and resistance to environmental degradation. Previous research on coatings for NFC is listed in Table 2.

The table summarizes research on enhancing NFC using fibre and surface coatings to improve their properties. Fibre coatings directly modify the individual fibres with materials like graphene oxide, polylactic acid, or nano-TiO_2, targeting properties such as conductivity, thermal stability, and mechanical performance. For instance, graphene oxide coatings on jute fibre resulted in a remarkable 183% increase in tensile strength and 450% improvement in Young's modulus, while nano-TiO_2 on flax fibre enhanced tensile strength by 23.1% and interfacial shear strength by 40.5%. Similarly, coatings like polylactic acid on sisal fibres reduced water absorption and mitigated strength degradation. These studies highlight the multifunctionality of fibre coatings in improving specific intrinsic properties.

In contrast, surface coatings focus on the composite's outer layer to enhance overall mechanical performance and durability. For example, epoxy resin on kenaf fibres increased tensile strength by 11.65% and degradation temperature by 10.22%, while acrylic resin on fique fibres improved interfacial shear strength by 110%. These coatings primarily optimize bonding at the fibre-matrix interface and structural integrity, as seen in bamboo fibres treated with Sikadur and sand particles, resulting in a 38% improvement in bond strength. Fibre coatings work at the micro or nano level to enhance specific fibre properties, while surface coatings address macro-level composite performance, emphasizing strength, durability, and adhesion. Together, they enable tailored advancements in natural fibre composites.

Writing a systematic review on bio-inspired coatings for NFC applications is crucial to advancing this field, particularly as current research predominantly explores synthetic or conventional coatings with limited emphasis on bio-inspired approaches. While previous studies, as summarized in the table, highlight enhancements in mechanical, thermal, and interfacial properties using conventional coatings like graphene oxide, polylactic acid, or epoxy, they lack focus on sustainable, bio-inspired strategies tailored to the unique requirements of NFC. This review specifically examines the latest research from the past five years, addressing a critical gap by exploring bio-inspired coatings that mimic natural processes or structures to enhance the performance and environmental compatibility of NFC. Such coatings hold immense potential for addressing challenges like durability, adhesion, and multi-functionality in a sustainable manner, making this review timely and essential. By presenting a focused analysis of recent advances, this paper provides fresh insights and consolidates knowledge on bio-inspired strategies, justifying the need for a new publication in this rapidly evolving area.

2. Bio-inspired coatings for NFC 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. By mimicking natural systems, researchers can

Table 2
Research on coatings in NFC.

Year	Author	Natural Fibre	Coating Material	Properties investigated	Results
Fibre coating					
2023	Rodriguez et al. [31]	Sisal fibre	Graphene nanoplatelets	Electrical conductivity	5.19 x 10-4 S/m
				Glass transition temperature	63.29 °C
2021	Karim et al. [32]	Jute fibre	Graphene oxide	Tensile strength	183 % increment
				Young's modulus	450 % increment
2020	Filho et al. [33]	Piassava fibre reinforced epoxy	Graphene oxide	TGA/DTG	200 °C
				DSC	125 °C
2019	Sahu et al. [34]	Sisal fibre	Polylactic acid	Water absorption	30 % degradation
				Tensile strength degradation	3.59 % decrement
				Flexural strength degradation	33.18 % decrement
				Hardness degradation	11.96 % decrement
2015	Wang et al. [35]	Flax fibre	Nano-TiO2	Tensile strength	23.1 % increment
				Interfacial shear strength	40.5 % increment
Surface coating					
2023	Owen et al. [36]	Kenaf fibre	Epoxy resin	Tensile	11.65% increment (42.4 MPa)
				Flexural	4.71% increment (61.09 MPa)
				Impact	5.2% (0.1135 KN/mm2)
				Degradation temperature	10.22% increment (331.6 °C)
2023	Cao et al. [37]	Flax fibre	Polylactic acid	Bending strength	36.6% increment
				Short beam shear strength	27.2 % increment
2023	Vargas et al. [38]	Fique fibre	Acrylic resin	Interfacial shear strength	110% increment
2017	Rahman et al. [39]	Bamboo fibre	Sikadur, sand particles, epoxy	Bond strength	38 % increment

develop coatings that enhance the performance of NFC, making them more durable, lightweight, and resistant to environmental factors such as corrosion and abrasion. 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 NFC in various industries.

2.1. Sharkskin inspired coatings

Sharkskin has a unique texture that reduces drag in water by minimizing flow separation and turbulence. These coatings offer advantages such as improved hydrodynamics, and aerodynamics, particularly beneficial for NFC used in aerodynamic surfaces or marine vehicles [40]. The unique texture of the coating also enhances the coating's anti-fouling and antimicrobial properties, preventing the accumulation of contaminants, such as dirt, or debris, on the surface [41]. This feature is beneficial in marine applications where NFC is used in boat hulls, pontoons, or offshore structures, as it helps reduce the growth of algae, barnacles, and other marine organisms [42].

Li et al. [43] used laser surface texturing to produce bioinspired shark skin texture on ceramic surfaces and coated with transition-metal-disulfide (WS2). The surface modification exhibited reduced surface friction and shear stress when compared to those of only polished surface. Pan et al. [44] 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 [45].

Sharklet Technologies is a company that has developed a bio-inspired surface technology based on the microstructure of shark skin [46]. Their technology mimics the roughness and pattern of shark skin to reduce bacterial contamination on high touch surfaces in the healthcare, public restrooms and point of sale counter tops where bacterial inhibition is desired. This groundbreaking technology presents promising research avenues and potential NFC applications in a wide range of fields, including high-touch NFC composites, furnitures, and food trays, where bacterial inhibition is essential.

Moreover, the sharkskin-inspired coating contributes to noise reduction [47]. The denticles on sharkskin create micro-vortices that effectively dampen the noise generated by turbulent airflow. Hence, the coatings have potential in the application of NFC in drone frame kits, drone propellers, and fan blades which contribute to the most noise. By incorporating this feature, the coating helps minimize noise emissions during operations, providing a quieter experience and reducing noise pollution.

2.2. Lotus leaf inspired coatings

The lotus-inspired superhydrophobic coating creates a rough and textured surface at the microscale, interspersed with nanoscale structures [48]. This intricate surface architecture traps air pockets, mimicking the lotus effect (Fig. 2), which enables droplets of water or other liquids to effortlessly roll off the surface [49]. As a result, the coating exhibits exceptional water-repellent properties, preventing liquid accumulation, and the adherence of contaminants, such as dirt, and pollutants [50].

Efforts have been taken by researchers in developing lotus leaf inspired hydrophobic coatings. Yang et al. [52] 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. [20] 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.

Lotus leaf-inspired coatings offer innovative solutions for improving the performance of NFC across various applications. Mimicking the unique microstructure of lotus leaves, these coatings provide NFC with exceptional water-repellent properties, known as the "lotus effect" [53]. By creating a micro- and nano-scale roughness on the surface, lotus leaf-inspired coatings enable NFC to repel water droplets, preventing moisture absorption and enhancing durability. This feature is particularly advantageous in outdoor applications where NFC is exposed to rain or humidity, as it helps prevent water-related damage and degradation. Furthermore, the self-cleaning properties of lotus leaves, facilitated by their ability to shed dirt and debris along with water droplets, can be replicated in coatings applied to NFC surfaces, reducing maintenance requirements and prolonging their lifespan. Overall, lotus leaf-inspired coatings offer NFC enhanced water resistance, durability, and self-cleaning capabilities, demonstrating the potential of biomimicry to drive advancements in materials science and engineering.

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 [54]. Inspired by the gecko's unique ability to cling to various surfaces (Fig. 3), gecko-inspired

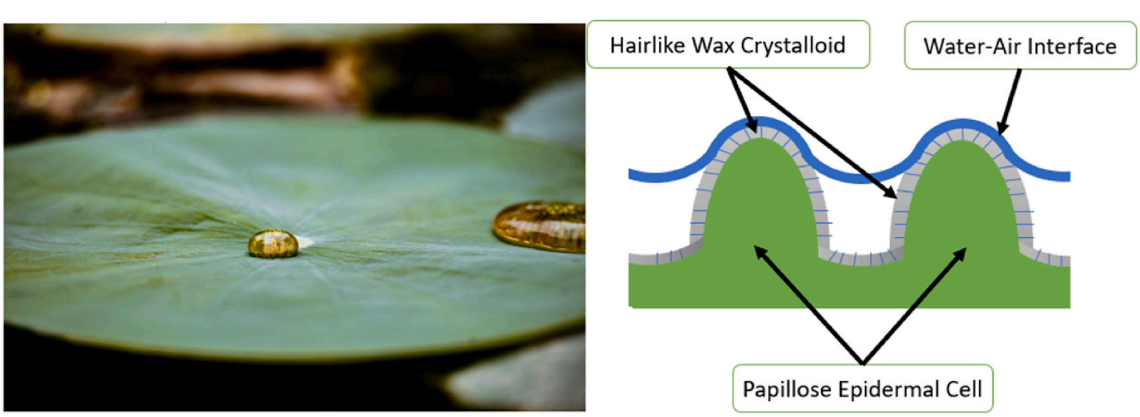

Fig. 2. Hierarchical structure of lotus leaf surface [51].

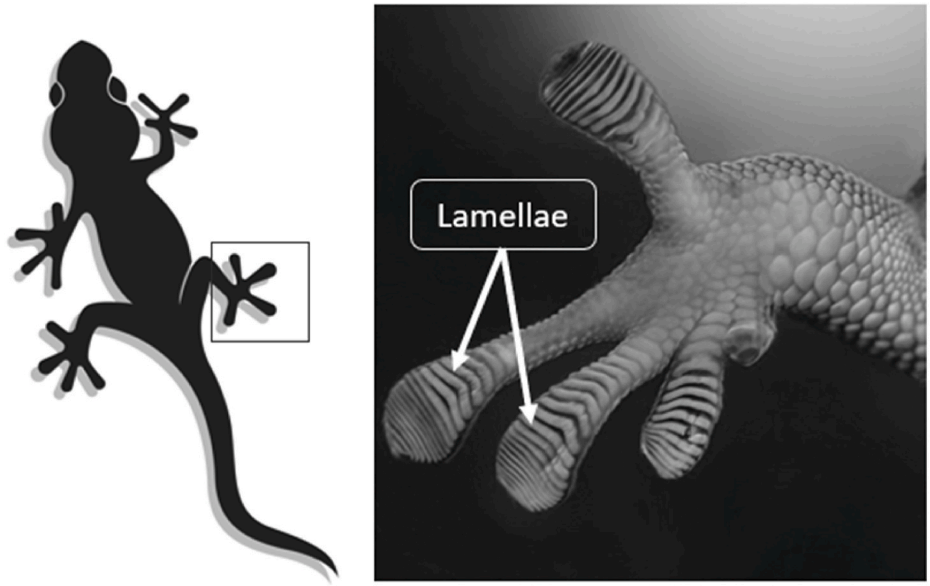

Fig. 3. Microstructure of Gecko foot [57].

coating has been developed, revolutionizing adhesion, and maneuverability in the various fields. Singh et al. [55] 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. [56] 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.

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

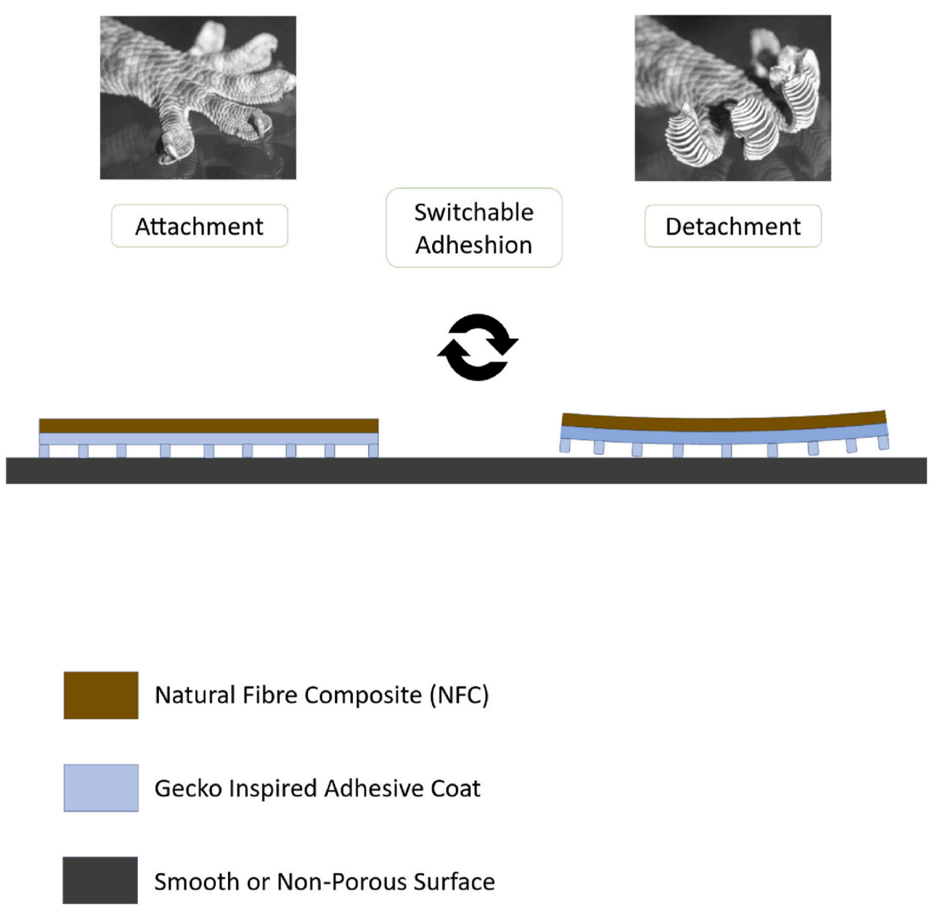

Fig. 4. Switchable adhesion of gecko inspired coatings in NFC application.

geckos to create strong adhesive forces and easy detachment through Van der Waals interactions [58,59]. 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 for NFC that can stick to smooth or non-porous surfaces without using fasteners such as bolts and rivets in building materials, drone frame kits, and automotive applications. This would result in significant weight reduction and lower mechanical vibrations caused by bolts and rivets.

By replicating the hierarchical structure and material composition of gecko foot pads, these coatings enable NFC to adhere firmly to various substrates without the need for traditional adhesives as depicted in Fig. 4. This adhesive ability is particularly advantageous in applications where NFC is used in structural components or as an alternative to traditional fastening methods, as it provides strong, reversible adhesion even in challenging environments. Additionally, gecko-inspired coatings offer the potential for NFC to be easily attached and detached multiple times without leaving residue or causing damage, enhancing versatility and ease of use.

In the realm of robotics and wearable technology where NFC is gaining traction, these coatings can be utilized to create grippers and attachments that adhere securely to surfaces, enabling robots to climb walls or navigate challenging terrain [60]. In the automotive industry, gecko-inspired coatings can be applied to NFC-based interior panels or trim components, providing a lightweight and versatile alternative to traditional fastening methods. Additionally, in the field of consumer electronics, gecko-inspired coatings can be used to create NFC-based gadgets and accessories that adhere to surfaces for convenient storage or display purposes. Overall, the versatility and strong adhesion capabilities of gecko-inspired coatings offer promising opportunities for NFC innovation across a wide range of industries and applications.

2.4. Spider silk coatings

Spider silk (Fig. 5) is a strong, lightweight, and flexible material that has potential in NFC applications. Inspired by spider silk, coatings have been developed with lightweight and improved strength properties, offering substantial advantages where high strength to weight ratio is crucial for NFC's application in aerospace and automotive sectors [61,62]. The thin and lightweight nature of these coatings minimizes added mass while providing considerable strength and protection benefits. Spider silk is a protein fibre composed predominantly of alanine and glycine amino acids. The strength of spider silk is attributed to the formation of a crystalline structure through hydrogen bonds in alanine-rich regions, while the elasticity of the silk is derived from glycine-rich regions. Additionally, certain types of silk contain notable amounts of serine and proline. Researchers have leveraged spider silk's structure to create coatings for NFC component protection. These coatings can reinforce NFC structures or shield them from impacts and vibrations. The coating is designed to mimic the complex hierarchical structure of spider silk, which consists of aligned fibres 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 [63].

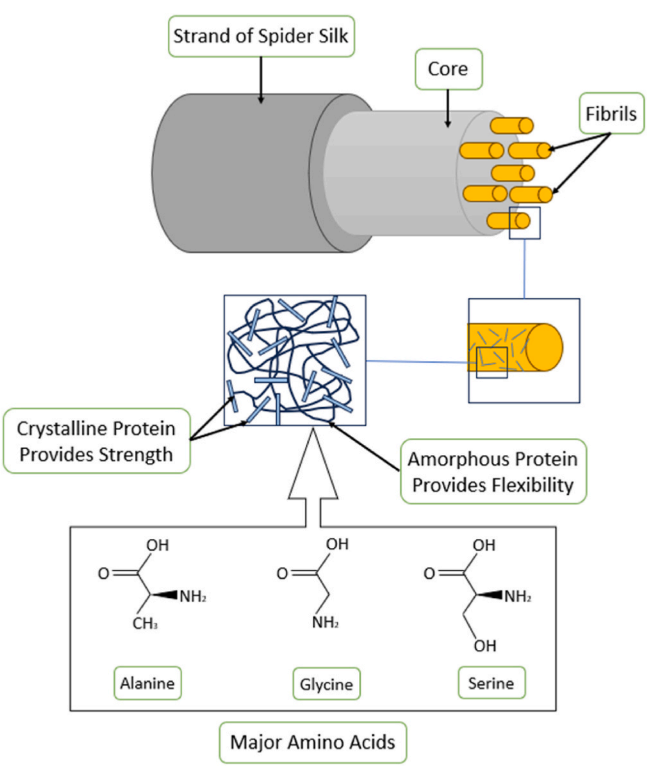

Fig. 5. Hierarchical structure of spider silk [64].

Koga et al. [65] 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 [66]. Wu et al. [67] 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 NFC components [68]. Spider silk-inspired materials can be used to develop strong, lightweight vehicle bumpers, drone structures and fan blade applications. For instance, these coatings could resist damage from sand and dust particles encountered during vehicle or drone operations. 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.

2.5. Mussel inspired coatings

Mussels can attach themselves to various surfaces, such as rocks or ship hulls, in wet and turbulent environments (Fig. 6). 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 [69]. Researchers have studied the molecular structure of this adhesive to develop new materials that can stick to wet or underwater surfaces [70]. The 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 [71]. The adhesive proteins found in mussels rely significantly on the amino acid component L-3,4-dihydroxyphenylalanine (L-DOPA), which contains a catechol unit, to play a crucial role in the adhesion process [72]. The mussel-inspired coating exhibits exceptional adhesion under both dry and wet conditions, making it particularly valuable for NFC 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

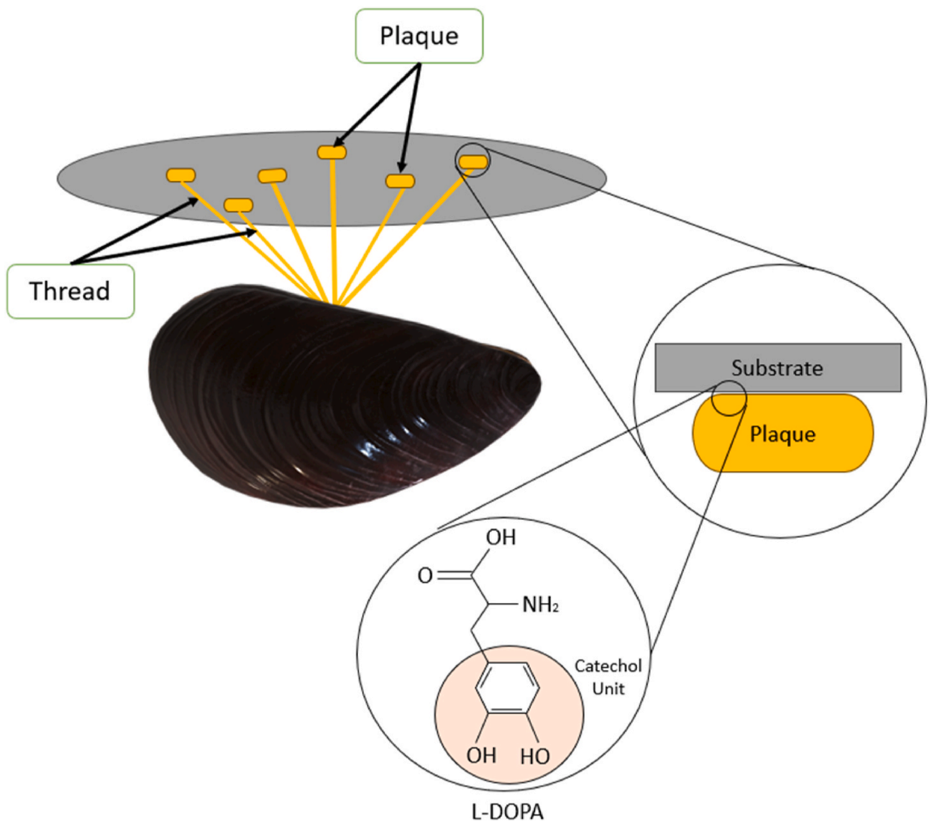

Fig. 6. Adhesive structure of mussels [74].

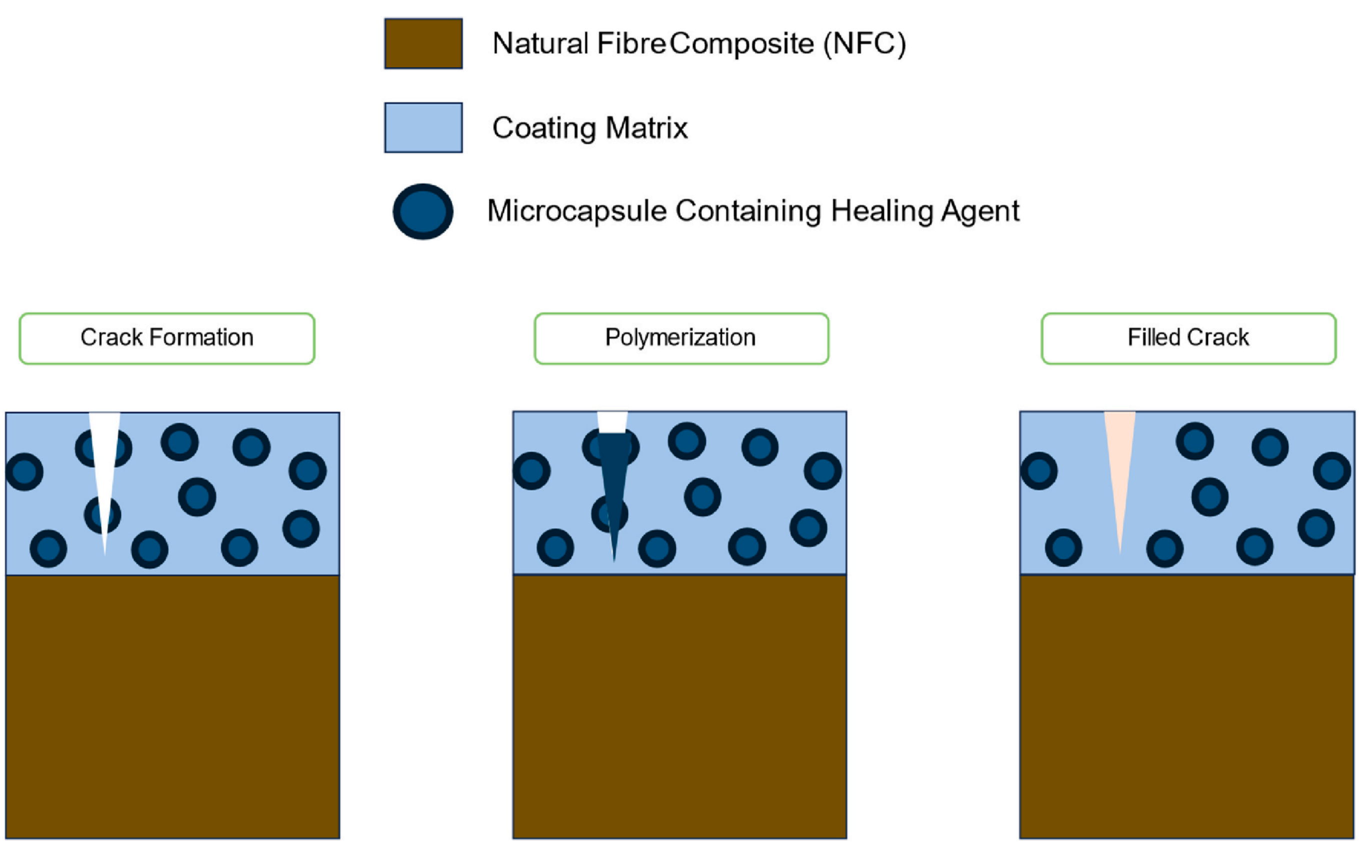

Fig. 7. Self healing properties of mussel inspired coating in NFC application.

challenging environments [73].

The versatility of the mussel-inspired coating extends beyond adhesion. It can also serve as a protective barrier, shielding NFC 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 NFC 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.

Fig. 7 demonstrates the self-healing mechanism of a mussel-inspired coating applied in NFC. The coating matrix, embedded with microcapsules containing a healing agent, covers the composite material. When a crack forms in the matrix due to stress or damage, it ruptures the microcapsules, releasing the healing agent into the damaged area. Inspired by mussel chemistry, the healing agent typically contains catechol-

Table 3
Potential applications of bio-inspired coatings in NFC.

Type of Bioinspired Coatings	Description	Bio-inspiration	Physical/Chemical Attributes	Possible NFC Applications
Anti-fouling coating	Prevents the attachment of organisms to NFC, reducing maintenance requirements and improving performance [77].	Sharkskin [78] Butterfly wings Lotus leaves	Microscale dermal denticles Micro- and nanoscale structures Microscale papillae and nanoscale wax crystals	- Outdoor recreational products - Marine and offshore structures
Anti-microbial coating	Mimics the properties of natural antimicrobial substances that help inhibit the growth of bacteria, viruses, and fungi, reducing the risk of contamination in NFC [79].	Spider Silk [80] Chitosan [81,82]	Natural antimicrobial peptides	- Aircraft interiors - Ventilation systems - Food storage and preparation surfaces
Anti-reflective coating	Mimics moths and butterfly wings to minimize reflection and enhance light absorption [83,84]. In solar energy applications, where NFC may be used in photovoltaic panels or solar collectors.	Moths'eye [85] Butterfly wings [86] Rose petals [87]	Densely packed, hexagonal arrays of microscale protrusions Multilayer structures with specific refractive index Microscale papillae	- Solar panels
Corrosion resistance coating	Mimics the structure of mollusk shells or coral skeletons to provide a barrier against corrosion [88] and extend the lifespan of NFC exposed to marine or humid environments [89].	Mollusk shells [90] Coral skeletons [91] Mussel	Calcium carbonate and organic biopolymer composition Adhesive proteins with catechol groups	- Fuel tanks - Pipelines
Drag reduction coating	Mimics the microscopic riblets found on shark skin, which decrease drag by reducing the size and intensity of turbulent air flow over the surface.	Sharkskin Pufferfish skin [92] European sea bass scales [92]	Microscale dermal denticles and streamlined body Ctenii, comb-like structures	- Drone frame kits
Heat shielding coating	Mimics the heat resistance and thermal insulation properties of silica shells of diatoms to protect NFC from heat or high temperature exposure.	Diatom frustules [93]	Highly porous nanoscale structure with intricate patterns	- Roofing - Insulation materials
Noise reduction coating	Surface microstructures that suppress noise generated by NFC drone propellers and fan blades, leading to quieter operations.	Riblet [94] Mushroom-like microstructure [94]	Streamwise grooves Microscale structures for aerodynamic and noise reduction	- Drone propellers - Fan blades
Self-cleaning coating	Inspired by the lotus effect, or the self-cleaning ability of butterfly wings, these coatings repel dirt particles and allow rain or airflows to remove contaminants, reducing maintenance needs and improving efficiency.	Lotus leaves Butterfly wings Fly eye [95]	Microscale papillae and epicuticular wax crystals Micro- and nanoscale structures Nanoscale structures with tiny protrusions	- Outdoor furniture - Decking - Solar panels - Building materials
Self-healing coating	Autonomously repairs cracks, scratches, or delamination, and ensures structural integrity and reduce the need for frequent inspections and maintenance.	Mussel [96,97] Tree frog toes [98,99]	Reversible bonding by catechol group in adhesive protein Tissue regeneration	- Automotive components - Sporting equipment
Solar energy harvesting coating	Mimics the light-trapping structures found in plant leaves or photosynthetic bacteria to enhance light absorption, optimize energy conversion, and increase the overall power output of NFc integrated solar panels [100].	Plant leaves [101] Cyanobacteria [102] Moth eye [103]	Chlorophyll pigment structure Densely packed, hexagonal arrays of microscale protrusions	- Solar sail propulsion - Solar panels - Energy harvesting sensors
Structural strengthening coating	Mimics the structure and composition of bones or seashells to strengthen and reinforce NFC, improving their durability and resistance to impact or fatigue.	Spidersilk [104] Bones [105,106] Seashells	Amino acids that form crystalline and amorphous molecular structure Calcium phosphate composition and collagen fibres Calcium carbonate composition	- Drone/UAV structures - Furniture - Automotive components
Thermal management coating	Replicate the cooling mechanisms found in the skin of polar bear Fur or penguins to assist heat dissipation and reduce thermal stresses in NFC.	Penguins [107,108] Polar bear Fur Saharan silver ant hair [109]	Dense layer of feathers Hollow and transparent guard hairs Reflective hair structure and colour	- Satellite surfaces and components - Power generators or energy storage units
Water-repellant coating	Mimics the microstructure of lotus leaves or insect wings, to provide water-repellent properties to NFC surfaces.	Lotus leaves [110] Cicada wings [111,112] Gecko feet [113]	Microscale papillae and nanoscale waxy structures Densely packed nanoscale pillars Microscale spatulae	- Construction materials - Boat hulls - Outdoor furniture - Decking

functionalized molecules that bond strongly with the surrounding matrix. This reaction initiates polymerization, effectively filling the crack and restoring the structural integrity of the material, thereby preventing further damage. The mussel-inspired chemistry, particularly the use of catechol groups, enhances the adhesion and cohesion of the healing agent, ensuring efficient self-repair. This self-healing capability enhances the coating's longevity and minimizes the need for frequent repairs or replacements [75]. 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 composites. Mussel-inspired coatings can be used as sealants to prevent air or gas leakage in NFC structures like pressure vessels, fuel tanks, and compartments. Their ability to adhere even in the presence of moisture makes them ideal for these applications [76]. Moreover, development of the coatings can provide strong and reliable adhesion for attaching solar panels to the NFC used in building materials such as roofing and exterior facades.

Table 3 highlights the diverse potential applications of bio-inspired coatings in NFC, showcasing how nature-derived strategies can overcome these challenges through unique physical and chemical attributes. This table not only summarizes coatings extensively discussed in the paper but also introduces additional bio-inspired coatings that mimic natural systems like flyeye, mollusk shells, rose petals, and cicada wings, among others. By illustrating a range of coating types and their inspirations, Table 3 provides a comprehensive overview to guide future research directions, emphasizing the versatility and multifunctional benefits of bio-inspired coatings for NFC applications.

The accompanying table offers a granular breakdown of these bio-inspired coatings, including their specific biological inspirations, key attributes, and its application in NFC. For example, anti-fouling coatings inspired by sharkskin and butterfly wings use micro- and nanoscale structures to prevent organism attachment, making them suitable for

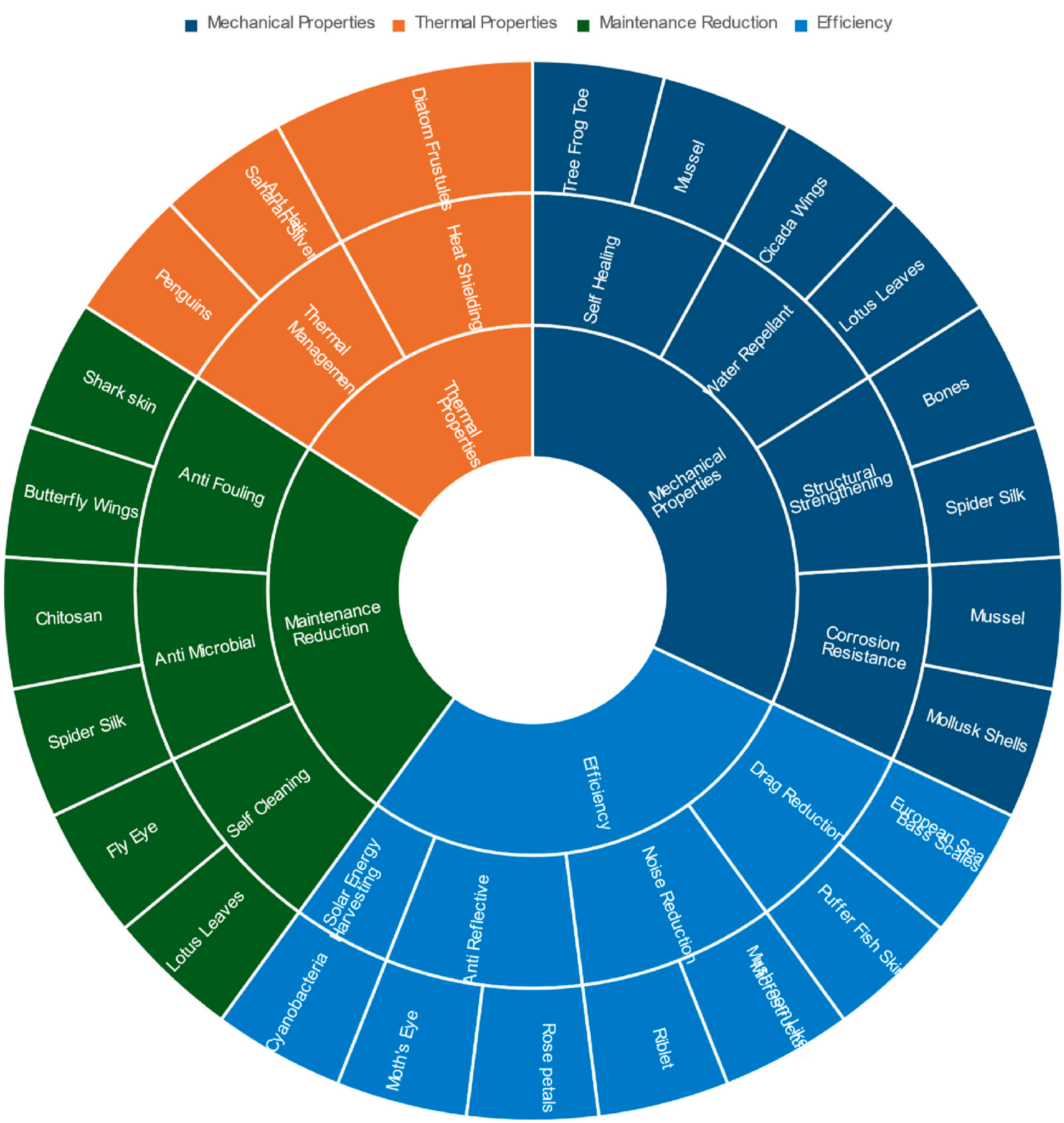

Fig. 8. Properties improved by bioinspired coatings in NFC.

marine and offshore NFC structures. Anti-microbial coatings, such as those inspired by chitosan or spider silk, inhibit bacterial growth, making them valuable in food storage and aircraft interiors. Self-healing coatings, modeled after tree frog toes and mussel proteins, provide autonomous crack repair for NFC integrated automotive components and sporting equipment. Further, heat-shielding coatings replicate the intricate patterns of diatom frustules for roofing and insulation materials, while drag reduction coatings, inspired by sharkskin and pufferfish scales, enhance energy efficiency in drone frame kits. Noise reduction coatings use riblet microstructures to minimize aerodynamic noise in drone propellers and fan blades. The table demonstrates a wide array of possibilities, from structural applications like automotive and drone parts to sustainability-focused solutions in solar panels and marine structures.

Fig. 8 delivers a detailed exploration of bio-inspired coatings for NFC by categorizing their functional properties and highlighting the biological inspirations behind them. The diagram organizes these coatings into four primary categories: Mechanical Properties, Thermal Properties, Maintenance Reduction, and Efficiency, providing a visual roadmap of their respective capabilities. For instance, under Mechanical Properties, examples include spider silk, mussel adhesion, and mollusk shells, showcasing their potential for structural strengthening and corrosion resistance. The Thermal Properties category emphasizes heat shielding and thermal management, drawing inspiration from diatom frustules and Saharan silver ant hairs, respectively. Similarly, Maintenance Reduction focuses on anti-fouling (sharkskin), anti-microbial (chitosan), and self-cleaning (lotus leaves) capabilities, while the Efficiency segment highlights innovations like drag reduction (sharkskin) and anti-reflective coatings (moth's eye).

In summary, bio-inspired coatings hold immense promise for NFC, offering transformative solutions to enhance the performance, durability, and sustainability of ecofriendly and sustainable composites. By drawing inspiration from nature, these coatings can provide self-healing capabilities, anti-fouling properties, and thermal regulation, thereby paving the way for safer, more efficient, and reliable materials.

3. Challenges or limitations of implementing these bio-inspired coatings in NFC

Integrating bio-inspired coatings can be complex, requiring careful consideration of compatibility issues with other materials, components, and environments. Organisms are adapted to ambient temperatures, water-based chemistry, locally available materials, and specific growth parameters. The translation of bio-inspired principles from organisms living in more forgiving conditions to the harsh realities of NFC introduces complexities related to adaptation, efficacy, and the overall feasibility of implementing these coatings successfully. Addressing these challenges necessitates an understanding of both biological systems and the unique demands of NFC to bridge the gap between inspiration from nature and practical application in materials engineering. Table 4 depicts the limitations of bio-inspired coatings in NFC applications and some common examples.

One of the primary challenges posed by NFC is the challenging operation environment that the composites must endure. Harsh conditions such as extreme temperatures, UV radiation, chemical and moisture exposure can degrade bioinspired coatings over time, reducing their effectiveness and protective properties. The careful selection of coating materials is paramount to ensure their effective application across a wide spectrum of temperatures and environments. For instance, ceramic coatings are an excellent choice to withstand high temperatures in aerospace applications, offering thermal insulation, corrosion resistance, and protection against oxidation [114]. On the other hand, aerospace-grade epoxies are preferred for low-temperature applications, providing flexibility, strong adhesion, and resistance to moisture [115].

Superhydrophobic coatings, characterized by their extreme water-repellent properties, can significantly enhance the performance of NFC, particularly in applications where moisture resistance and durability are critical [116]. The coatings also prevent water from freezing on the surface, which can help avoid freeze-thaw cycles that could otherwise damage the composite. Khedir et al. [117] mentioned that bioinspiration from lotus leaf, strider's leg, Steno Cara beetle's back, and the shark's skin could pave the way for development of anti-icing coatings. However, superhydrophobic coatings can be vulnerable to mechanical abrasion, UV radiation, and chemical exposure. Over time, these factors can degrade the coating, reducing its effectiveness. Maintaining the superhydrophobic properties in real-world conditions, especially in high-traffic or outdoor environments, remains a significant challenge. Researchers reported that superhydrophobic coatings show limitations in real-time applications. A work by Kulinich et al. [118], reported that superhydrophobic surfaces show gradual decrease in anti-icing performance, hence limiting its applications in anti-icing applications. This is due to the low abrasive resistance of the coating surface and a gradual damage on its microstructure during icing and deicing cycles [119].

Table 4
Challenges for application of bio-inspired coatings in NFC.

Challenges and Limitations	Type of Challenges	Examples	Effected NFC Applications
Challenging operation environments	Chemical exposure	Exhaust emissions Acidic rain	Outdoor furniture
	Thermal degradation	External heat Internal heat	Roofing
	UV exposure	Solar	Solar panel
	Water exposure	Rain Marine	Decking
Mechanical stresses	Abrasive forces	Impact of airborne particles, dust, sand	Drone frame kits
	Impact forces	Stone strikes Drop impact	Automotive exterior components
Coating-substrate compatibility	Adhesion strength	Elastic mismatch Thermal mismatch	Structural, non-structural and outdoor applications
Manufacturing processes	High complexity	Layer-by-layer deposition Nano structuring Chemical treatments	–
Sustainability	Material type	Petroleum based coatings Fluorinated compounds Added weight of coatings	–
	Maintenance and repair	Coating lifespan and maintenance cycle	UV exposure/ Degradation Chemical exposure/ Degradation

Moreover, NFC in structures operate in environments that subject them to intense vibrations, mechanical stresses, and abrasive forces, which can take a toll on the protective coatings applied to their surfaces. Coatings must not only adhere securely to these surfaces but also remain intact to provide reliable protection, especially in situations where structural integrity is critical. According to Sousa et al. [120], application of nanolayered and nanocomposite coatings significantly improves the mechanical, hardness, wear performance, and crack resistant properties compared to other types of coatings.

Furthermore, the compatibility and adhesion strength of a coating to its substrate can be affected by the thermal and elastic differences between the coating material and the substrate material. When the thermal expansion coefficients of the coating material and the substrate material differ significantly, it can lead to thermal stresses during temperature changes. These stresses can result in delamination, cracking, or reduced adhesion between the coating and the substrate. Differences in the elastic modulus between the coating and the substrate can lead to stress concentrations and reduce the ability of the coating to absorb mechanical loads. Therefore, it is crucial for materials engineers and scientists to carefully consider the selection of coating materials and their compatibility with NFC to ensure long-lasting and effective protection.

Additionally, in an era of heightened environmental awareness, the composites industry is increasingly committed to sustainability. Therefore, the production and disposal of bio-inspired coatings should align with these goals, with a focus on minimizing environmental impact. Nartita et al. [121] stated that fluorinated compounds used to make bio-inspired coatings cause toxic effects to the environment. Hence, researcher focus on development of bio-inspired coatings using sustainable materials (renewable, bio-based, non-fluorinated compounds) and sustainable coating processes (dip coating, spray coating, spin coating, grafting method, and vapor deposition method) [122,123]. Another challenge of bio-inspired coatings is the lifespan and maintenance cycles [124]. While self-healing and self-cleaning coatings offer significant advantages, it's essential to develop maintenance and repair procedures, especially for long-duration missions. Clear guidelines and procedures shall be established for inspecting, maintaining, and repairing these coatings during and after missions. Ensuring that these coatings can effectively self-repair is crucial to their sustained functionality. Besides that, any additional material, including coatings, adds mass to NFC [125]. This added mass can have a profound impact on strength to weight ratio, efficiency, performance, and payload capacity. Hence, engineers are challenged to carefully balance the benefits of a coating with the weight it introduces to NFC.

Despite the limitations of bioinspired coatings in NFC, innovative solutions can mitigate these challenges. For instance, selecting coating materials tailored for specific conditions, such as ceramics for high temperatures or superhydrophobic coatings for moisture resistance, can improve performance. Adopting sustainable materials and methods like bio-based, non-fluorinated compounds and efficient processes like spray coating or vapor deposition can reduce environmental impacts. Furthermore, self-healing and self-cleaning coatings, alongside guidelines for maintenance and repair, can extend lifespan and functionality. By addressing these factors holistically, researchers and engineers can bridge the gap between bio-inspired designs and practical NFC applications, paving the way for more robust and sustainable material solutions.

4. Conclusion

In conclusion, bio-inspired coatings offer a promising avenue for enhancing the performance of NFC, enabling safer, more efficient, and more sustainable materials. The development of these coatings has been driven by the need for materials that can withstand extreme conditions and maintain their efficiency in the composites industry. By drawing inspiration from nature, researchers have been able to develop coatings with enhanced properties such as self-cleaning, self-healing, drag-reduction, 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 its potential for future research and development. With the integration of advanced technologies such as nanotechnology and 3D printing, bio-inspired coatings are poised to play a significant role in the future of NFC design and manufacturing.

5. Future research and development

The potential for future research and development in the field of bio-inspired coatings for NFC is vast and promising. Integration of advanced technologies such as nanotechnology can improve the mechanical, thermal, and electrical properties of bio-inspired coatings in NFC, making them more durable and effective. 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 nm), provides the means to replicate and incorporate these features into bio-inspired coatings. For instance, nanoparticles can be tailored to promote self-healing attributes in bio-inspired coatings, either by introducing nanocapsules carrying curative agents or by utilizing nanomaterials with inherent self-repair capabilities. Hossain et al. [126] introduces nanotechnology-inspired microfluidic systems that emulates nature's self-cleaning and fluid transport mechanisms, advancing nanoscale precision and efficiency in fluid handling applications. Additionally, the precision afforded by nanotechnology in manipulating the surface properties of bio-inspired coatings is noteworthy. Through meticulous nanoscale engineering, surfaces can be crafted with distinct functionalities such as superhydrophobicity, oleophobicity, or augmented adhesion. The inclusion of nanomaterials, including carbon nanotubes, graphene, and nano-sized fibres, plays a pivotal role in increasing its resistance to wear, impacts, and mechanical stresses commonly encountered in challenging environments [127]. Furthermore, nanomaterials are renowned for their lightweight nature, enabling their seamless integration into coatings without imposing significant mass on NFC components. This aspect is critical for the composites industry, where the imperative to minimize weight takes precedence, ultimately enhancing fuel efficiency, overall performance, and payload capacity.

Graphene, which is currently a trending nanomaterial serves as an exceptional reinforcement material in bio-inspired coatings, enhancing structural integrity and providing resilience against wear, impact, and mechanical stresses particularly advantageous in structural applications facing harsh environmental conditions. According to Ding et al. [128, 129], nacre inspired graphene composite coatings significantly improved the mechanical performance of graphene-based coatings. This is due to the organic-inorganic 'brick-and-mortar' structure of nacre that inspired the alignment and orientation of graphene sheets embedded in the coating. Leveraging graphene's excellent electrical conductivity, bio-inspired coatings can achieve enhanced functionality, creating conductive surfaces for sensing or electrical communication [130]. Hu et al. [131], developed bioinspired multi-functional wearable sensor based on an asymmetric graphene composite film. The wearable sensor, not only rapidly detects diverse human body motions and tactile signals with high sensitivity but also serves as a versatile multi-functional device, integrating light-induced actuation, large deformation, and color change to mimic human skin in next-generation smart wearable systems. Furthermore, graphene's lightweight nature contributes to fuel efficiency and overall performance of NFC in automotive, aerospace and marine by enabling lightweight constructions. Its exceptional thermal conductivity facilitates efficient heat dissipation, crucial for NFC components exposed to high temperatures. Additionally, graphene's remarkable barrier properties against gases can be utilized to create protective barriers in bio-inspired NFC coatings, safeguarding against environmental factors like moisture or corrosive agents [132].

Additionally, additive manufacturing of bio-inspired coatings in NFC can enable the creation of complex and highly precise coatings and surface microstructures that are tailored to specific applications. 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 [133]. This precision allows for the development of coatings with tailored surface properties, such as enhanced adhesion, wear resistance, or hydrophobicity, which are crucial for improving the performance and durability of NFC. Hence, the synergy between additive manufacturing and nanotechnology enables the fabrication of coatings with precise nanoscale features, hierarchical structures, and tailored material compositions. 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. Ongoing research on bio-inspired coatings and their application in NFC applications is in its infancy, warranting increased focus to overcome existing limitations and fully harness their potential. The integration of cutting-edge technologies and exploration of research areas such as additive manufacturing, nanotechnology, biosensors, multifunctional tailoring, and sustainable methods hold significant promise for the future of NFC coatings. The potential research directions for the advancement of bio-inspired coatings are summarized in Table 5.

One promising avenue for future research is the development of multifunctional coatings inspired by nature. Notably, coatings that combine features like self-healing and corrosion resistance, self-cleaning paired with antifouling, and the integration of antifouling properties along with anticorrosion measures offer an impressive array of benefits for enhanced performance in NFC. Mozumder et al. [144] have reported advancements in enhancing the surface morphology and properties of solar panels through the application of multifunctional thin films or coatings. The fabrication of these coatings for solar panels involves the utilization of diverse materials and methods, including super-hydrophobic, super hydrophilic, and photoactive surfaces which can be inspired from moths' eyes and lotus leaves. Yang et al. [145], investigated a bio-inspired magnetic shielding coating with multifunctionality, incorporating interactions among cellulose nanofibre (CNF), carbon nanotubes (CNTs), and crosslinking of polydopamine (PDA) inspired by mussel adhesion. The resulting coating demonstrates resilience against

Table 5
Future research on bio-inspired coatings for NFC.

Advanced Bio-inspired Coating Technology	Description	Examples
Additive Manufactured Coatings [134,135]	3D printed polymer, ceramic, metal and composite coatings with intricate designs, complex geometries, and precise control over material composition tailored to specific NFC applications.	Microfabrication, lithography
Biomimetic Nanomaterials [136,137]	Synthesis and characterization of biomimetic nanomaterials that replicate the unique properties found in natural systems.	Nacre-inspired nanocoating, photosynthetic nanocoating
Biomimetic Sensing and actuation [138,139]	Mimicking biological systems such as mimosa pudica to develop sensor coatings that react to environmental changes, such as temperature fluctuations, chemical or radiation exposures, to adjust surface properties and optimize NFC performance.	Wearable biosensors
Multifunctional Coatings [140,141]	Exploring the incorporation of structural coloration with anti-corrosion capabilities could lead to coatings that provide enhanced performance and efficiency in NFC applications.	Superhydrophobic/ Antimicrobial coatings
Sustainable and eco-friendly coatings [142,143]	Exploring alternative bio-based polymers, eco-friendly fabrication processes, and biodegradable polymer coatings that minimize the environmental impact without compromising performance.	Polylactic acid (PLA), polyhydroxyalkanoates (PHAs)

harsh space conditions such as thermal shock, atomic oxygen exposure, UV radiation, and electromagnetic waves. This provides research opportunities for NFC application in space probes, artificial satellites, and diverse high-precision electronic instruments used for space exploration.

Bio-based polymers and biodegradable materials can be integrated into bio-inspired coatings for NFC by carefully selecting and engineering these materials to mimic the functional properties of traditional coatings while ensuring environmental sustainability. For instance, bio-based polymers such as polylactic acid (PLA) or polyhydroxyalkanoates (PHAs) can be chemically modified or combined with natural additives to enhance their mechanical strength, adhesion, and durability, making them suitable for demanding NFC applications [146]. Additionally, incorporating natural reinforcing agents, like cellulose nanocrystals or lignin, can improve the barrier properties and stability of these coatings, ensuring they provide adequate protection against moisture, UV radiation, and wear [147]. This approach allows for the development of sustainable coatings that do not compromise the performance of NFCs while promoting biodegradability and reducing the environmental impact.

Fig. 9 illustrates a conceptual example of bioinspired multifunctional coating applied to a natural fiber composite (NFC) substrate using additive manufacturing and nanotechnology. The bio-based coating matrix contains embedded microcapsules filled with healing agents that enable self-healing by releasing the agent upon damage, while nanoparticles dispersed in the matrix enhance mechanical strength, thermal stability, and durability. The lotus-inspired nanostructured surface on the top layer mimics the superhydrophobic properties of lotus leaves, providing water repellency and anti-fouling capabilities. Additive manufacturing allows precise layer-by-layer deposition of the coating, ensuring optimal integration of nanostructures and healing components. The comceptual image aims to provide readers with future research directions for developing multifunctional bioinspired coatings tailored for sustainable and high-performance NFC applications.

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 [148]. 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 [149]. These technologies are playing a crucial role in the development of bio-inspired 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 [150]. This will result in a torrent of technological breakthroughs from the invention of new coatings for NFC we've yet to even imagine. Future research in this field has the potential to lead to the development of highly advanced and efficient NFC, enabling safer, more sustainable, and more efficient structures. Exploring multifunctionality, adaptability, nanomaterials, self-assembly techniques, and sustainability will pave the way for novel coatings that push the boundaries of natural fibre reinforced composites advancements.

CRediT authorship contribution statement

Thinesh Sharma Balakrishnan: Writing – original draft, Visualization, Conceptualization. **Mohamed Thariq Hameed Sultan:** Writing – review & editing, Supervision, Funding acquisition. **Farah Syazwani Shahar:** Writing – review & editing, Project administration. **Kamarul Arifin Ahmad:** Writing – review & editing, Supervision, Funding acquisition. **Sharul Sham Dol:** Writing – review & editing, Supervision, Funding acquisition. **Fatin Hana Naning:** Writing – review & editing,

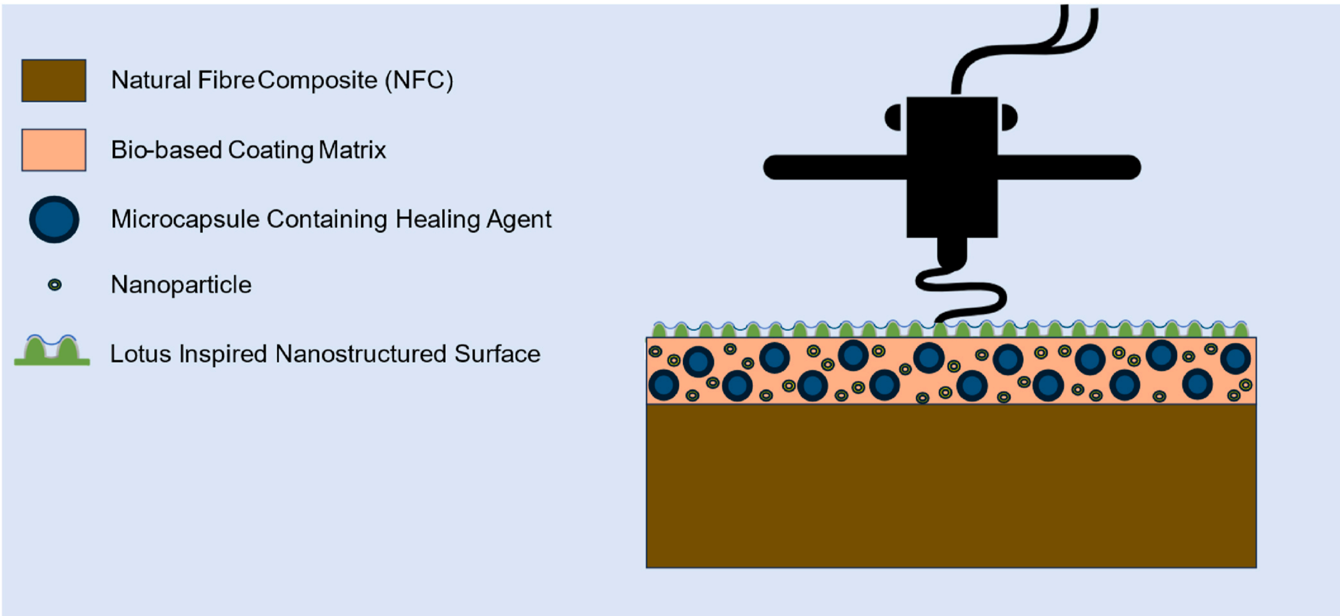

Fig. 9. Bioinpired multifunctional coatings integrated by additive manufacturing and nanotechnology.

Project administration, Funding acquisition.

Data availability statement

Data sharing does not apply to this article as no new data were created or analyzed in this study.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] M. Lian, Y. Huang, Y. Liu, D. Jiang, Z. Wu, B. Li, Q. Xu, V. Murugadoss, Q. Jiang, M. Huang, Z. Guo, An overview of regenerable wood-based composites: preparation and applications for flame retardancy, enhanced mechanical properties, biomimicry, and transparency energy saving, Adv. Compos. Hybrid Mater. 5 (3) (2022) 1612–1657, https://doi.org/10.1007/S42114-022-00475-6, 5 (2022).
[2] W. Wang, S. Yang, K. Ding, L. Jiao, J. Yan, W. Zhao, Y. Ma, T. Wang, B. Cheng, Y. Ni, Biomaterials- and biostructures Inspired high-performance flexible stretchable strain sensors: a review, Chem. Eng. J. 425 (2021) 129949, https://doi.org/10.1016/J.CEJ.2021.129949.
[3] J. Wei, F. Pan, H. Ping, K. Yang, Y. Wang, Q. Wang, Z. Fu, Bioinspired additive manufacturing of hierarchical materials: from biostructures to functions, Research 6 (2023), https://doi.org/10.34133/RESEARCH.0164.
[4] S. Liu, J. Bao, Y. Lu, J. Li, S. Lu, X. Sun, Digital twin modeling method based on biomimicry for machining aerospace components, J. Manuf. Syst. 58 (2021) 180–195, https://doi.org/10.1016/J.JMSY.2020.04.014.
[5] L.S. Puumala, S.M. Grist, J.M. Morales, J.R. Bickford, L. Chrostowski, S. Shekhar, K.C. Cheung, Biofunctionalization of multiplexed silicon photonic biosensors, Biosensors 13 (2023) 53, https://doi.org/10.3390/BIOS13010053, 53 13 (2022).
[6] M. Soler, L.M. Lechuga, Biochemistry strategies for label-free optical sensor biofunctionalization: advances towards real applicability, Anal. Bioanal. Chem. 414 (2022) 5071–5085, https://doi.org/10.1007/S00216-021-03751-4/TABLES/1.
[7] T.C. Tang, B. An, Y. Huang, S. Vasikaran, Y. Wang, X. Jiang, T.K. Lu, C. Zhong, Materials design by synthetic biology, Nat. Rev. Mater. 6 (4) (2020) 332–350, https://doi.org/10.1038/s41578-020-00265-w, 6 (2020.
[8] A. Rodrigo-Navarro, S. Sankaran, M.J. Dalby, A. del Campo, M. Salmeron-Sanchez, Engineered living biomaterials, Nat. Rev. Mater. 6 (12) (2021) 1175–1190, https://doi.org/10.1038/s41578-021-00350-8, 6 (2021).
[9] G. Xu, H. Fan, C.A. McCoy, M.M. Mills, J. Schwarz, Bioinspired synthesis of thermally stable and mechanically strong nanocomposite coatings, MRS Adv 7 (2022) 337–341, https://doi.org/10.1557/S43580-022-00245-Y/TABLES/1.
[10] P. Lu, X. Li, J. Xu, Y. Fan, J. Sun, Y. Liang, L. Tian, W. Ming, L. Ren, J. Zhao, Bio-inspired interlocking structures for enhancing flexible coatings adhesion, Small 20 (2024), https://doi.org/10.1002/SMLL.202312037.
[11] A. Sandak, K.B. Ogorelec, A. Gubenšek, F. Poohphajai, Bioinspired living coating system for regenerative and circular architecture, J. Sustain. Architect. Civ. Eng. 34 (2024) 53–61, https://doi.org/10.5755/J01.SACE.34.1.35570.
[12] M. Lu, C. Huang, Z. Xu, Y. Yuan, M. Wang, M. Xiao, L. Zhang, P. Wan, A skin-bioinspired urchin-like microstructure-contained photothermal-therapy flexible electronics for ultrasensitive human-interactive sensing, Adv. Funct. Mater. 33 (2023), https://doi.org/10.1002/ADFM.202306591.
[13] X. Bu, C. Sun, C. Qiao, X. Gao, Y. Zhang, X. Ji, F. Tao, L. Gai, L. Liu, A bio-inspired slippery coating with mechanochemical robustness for anti-ice and anti-corrosion, Appl. Surf. Sci. 639 (2023) 158143, https://doi.org/10.1016/J.APSUSC.2023.158143.
[14] M.A. Bhakare, K.D. Lokhande, M.P. Bondarde, P.S. Dhumal, S. Some, Dual functions of bioinspired, water-based, reusable composite as a highly efficient flame retardant and strong adhesive, Chem. Eng. J. 454 (2023) 140421, https://doi.org/10.1016/J.CEJ.2022.140421.
[15] J. Wang, D. Jiang, Y. Du, M. Zhang, Y. Sun, M. Jiang, J. Xu, J. Liu, Strong Ti3C2Tx MXene-based composite films fabricated through bioinspired bridging for flexible energy storage devices, Small 19 (2023) 2303043, https://doi.org/10.1002/SMLL.202303043.
[16] Z. Liu, X. Zhang, W. Zhou, G. Wang, T. Liu, J. Luo, Q. Gao, J. Luo, J. Li, Bioinspired water-retaining and strong soybean flour-based adhesive for efficient

preparation of plywood, J. Clean. Prod. 414 (2023) 137739, https://doi.org/10.1016/J.JCLEPRO.2023.137739.

[17] T. Wang, Y. Xiao, J.L. King, M.A. Kats, K.J. Stebe, D. Lee, Bioinspired switchable passive daytime radiative cooling coatings, ACS Appl. Mater. Interfaces (2023), https://doi.org/10.1021/ACSAMI.3C11338/SUPPL_FILE/AM3C11338_SI_002.AVI.

[18] M. Dong, Y. Zhu, K. Chang, J. Li, L. Wang, Bioinspired nanoheterogeneous alternating multiarched architecture: toward a superior strength-toughness integration, ACS Appl. Mater. Interfaces 14 (2022) 32395–32403, https://doi.org/10.1021/ACSAMI.2C07899/SUPPL_FILE/AM2C07899_SI_001.PDF.

[19] Y. Lin, Y. Xie, F. Chen, S. Gong, W. Yang, X. Liang, Y. Lian, J. Chen, F. Wei, W. Bai, Y. Xu, R. Jian, Bioinspired self-stratification fouling release silicone coating with strong adhesion to substrate, Chem. Eng. J. 446 (2022) 137043, https://doi.org/10.1016/J.CEJ.2022.137043.

[20] S. Li, R. Xu, G. Song, B. Li, P. Fang, Q. Fu, C. Pan, Bio-inspired (GO + CNTs)-PU hydrophobic coating via replication of Lotus leaf and its enhanced mechanical and anti-corrosion properties, Prog. Org. Coating 159 (2021) 106414, https://doi.org/10.1016/J.PORGCOAT.2021.106414.

[21] Y. Wang, Y. Meng, Z. Ji, X. Meng, X. Song, P. Lu, F. Chen, Bioinspired colored degradable starch-based films with excellent tensile strength, Ind. Crops Prod. 167 (2021) 113525, https://doi.org/10.1016/J.INDCROP.2021.113525.

[22] A. Li, F. Su, P.K. Chu, J. Sun, Articular cartilage inspired bilayer coating on Ti6Al4V alloy with low friction and high load-bearing properties, Appl. Surf. Sci. 515 (2020) 146065, https://doi.org/10.1016/J.APSUSC.2020.146065.

[23] S. Dong, M. Li, C. Liu, J. Zhang, G. Chen, Bio-inspired superhydrophobic coating with low hydrate adhesion for hydrate mitigation, J. Bionic Eng. 17 (2020) 1019–1028, https://doi.org/10.1007/S42235-020-0085-5/METRICS.

[24] B. Nan, K. Wu, W. Chen, Y. Liu, Q. Zhang, M. Lu, Bioinspired modification strategy to improve thermal conductivity of flexible poly(vinyl alcohol)/nanodiamond nanocomposite films for thermal management applications, Appl. Surf. Sci. 508 (2020) 144797, https://doi.org/10.1016/J.APSUSC.2019.144797.

[25] Z. Chen, Z. Miao, P. Zhang, H. Xiao, H. Liu, C. Ding, H. Tan, J. Li, Bioinspired enamel-like oriented minerals on general surfaces: towards improved mechanical properties, J. Mater. Chem. B 7 (2019) 5237–5244, https://doi.org/10.1039/C9TB00676A.

[26] K.G. Malollari, P. Delparastan, C. Sobek, S.J. Vachhani, T.D. Fink, R.H. Zha, P. B. Messersmith, Mechanical enhancement of bioinspired polydopamine nanocoatings, ACS Appl. Mater. Interfaces 11 (2019) 43599–43607, https://doi.org/10.1021/ACSAMI.9B15740.

[27] A. Wat, C. Ferraro, X. Deng, A. Sweet, A.P. Tomsia, E. Saiz, R.O. Ritchie, Bioinspired nacre-like alumina with a metallic nickel compliant phase fabricated by spark-plasma sintering, Small 15 (2019), https://doi.org/10.1002/SMLL.201900573.

[28] P. Liu, J.M. Wang, X.T. Yu, X.B. Chen, S.Q. Li, D.C. Chen, S.K. Guan, R.C. Zeng, L. Y. Cui, Corrosion resistance of bioinspired DNA-induced Ca–P coating on biodegradable magnesium alloy, J. Magnesium Alloys 7 (2019) 144–154, https://doi.org/10.1016/J.JMA.2019.01.004.

[29] H. Qi, C. Zhang, H. Guo, W. Zheng, J. Yang, X. Zhou, L. Zhang, Bioinspired multifunctional protein coating for antifogging, self-cleaning, and antimicrobial properties, ACS Appl. Mater. Interfaces 11 (2019) 24504–24511, https://doi.org/10.1021/ACSAMI.9B03522/SUPPL_FILE/AM9B03522_SI_004.AVI.

[30] M. Vardaki, D. Ionita, A.B. Stoian, I. Demetrescu, Increasing corrosion resistance of a ZrTi alloy with a bioinspired coating with low porosity, Mater. Corros. 68 (2017) 988–994, https://doi.org/10.1002/MACO.201609408.

[31] J.A. Rodríguez-González, V. Renteria-Rodríguez, C. Rubio-González, E.A. Franco-Urquiza, Spray-coating of graphene nanoplatelets on sisal fibers and its influence on electromechanical behavior of biocomposite laminates, Https://Doi.Org/10.1177/07316844231152911, https://doi.org/10.1177/07316844231152911, 2023.

[32] N. Karim, F. Sarker, S. Afroj, M. Zhang, P. Potluri, K.S. Novoselov, N. Karim, S. Afroj, K.S. Novoselov, F. Sarker, P. Potluri, M. Zhang, Sustainable and multifunctional composites of graphene-based natural jute fibers, Adv. Sustain. Syst. 5 (2021) 2000228, https://doi.org/10.1002/ADSU.202000228.

[33] F. da Costa Garcia Filho, F.S. da Luz, M.S. Oliveira, A.C. Pereira, U.O. Costa, S. N. Monteiro, Thermal behavior of graphene oxide-coated piassava fiber and their epoxy composites, J. Mater. Res. Technol. 9 (2020) 5343–5351, https://doi.org/10.1016/J.JMRT.2020.03.060.

[34] P. Sahu, M.K. Gupta, Lowering in water absorption capacity and mechanical degradation of sisal/epoxy composite by sodium bicarbonate treatment and PLA coating, Polym. Compos. 41 (2020) 668–681, https://doi.org/10.1002/PC.25397.

[35] H. Wang, G. Xian, H. Li, Grafting of nano-TiO2 onto flax fibers and the enhancement of the mechanical properties of the flax fiber and flax fiber/epoxy composite, Compos Part A Appl Sci Manuf 76 (2015) 172–180, https://doi.org/10.1016/J.COMPOSITESA.2015.05.027.

[36] M.M. Owen, E.O. Achukwu, A.Z. Romli, M.H. Ramlee, A.H. Abdullah, S. Shuib, H. M. Akil, Improved thermal and mechanical properties of kenaf fiber/ABS polymer composites via resin coating treatment, Pertanika J. Sci. Technol. 31 (2023) 39–57, https://doi.org/10.47836/PJST.31.S1.03.

[37] D. Cao, Investigation into surface-coated continuous flax fiber-reinforced natural sandwich composites via vacuum-assisted material extrusion, Progress in Additive Manufacturing (2023) 1–15, https://doi.org/10.1007/S40964-023-00508-6/METRICS.

[38] J. Vargas, M. Jalalvand, J.M. Meza, Improving interfacial shear strength of fique fibres using an acrylic coating, Sci. Prog. 106 (2023), https://doi.org/10.1177/00368504231207199/ASSET/IMAGES/LARGE/10.1177_00368504231207199-FIG12.JPEG.

[39] N. Rahman, L.W. Shing, L. Simon, M. Philipp, J. Alireza, E. Hebel Dirk, C.S. Ling, L.H. Wuan, S. Valavan, S.S. Nee, Enhanced bamboo composite with protective coating for structural concrete application, Energy Proc. 143 (2017) 167–172, https://doi.org/10.1016/J.EGYPRO.2017.12.666.

[40] M.K. Gabler-Smith, G.V. Lauder, Ridges and riblets: shark skin surfaces versus biomimetic models, Front. Mar. Sci. 9 (2022) 975062, https://doi.org/10.3389/FMARS.2022.975062/BIBTEX.

[41] N. Sun, Z. Hou, Z. Jiang, J. Geng, L. Xia, Facile modification of sepiolite and its application in wear-resistant and superhydrophobic epoxy coatings by mimicking the structure of shark skin, Appl. Clay Sci. 264 (2024) 107642, https://doi.org/10.1016/J.CLAY.2024.107642.

[42] A. Ghimire, R.B. Dahl, S.F. Shen, P.Y. Chen, Shark skin denticles: from morphological diversity to multi-functional adaptations and applications, Adv. Funct. Mater. 34 (2024) 2307121, https://doi.org/10.1002/ADFM.202307121.

[43] X. Li, J. Deng, H. Yue, D. Ge, X. Zou, Wear performance of electrohydrodynamically atomized WS2 coatings deposited on biomimetic shark-skin textured surfaces, Tribol. Int. 134 (2019) 240–251, https://doi.org/10.1016/J.TRIBOINT.2019.02.015.

[44] L.C. Pan, S.Y. Hsieh, W.C. Chen, F.T. Lin, C.H. Lu, Y.L. Cheng, H.W. Chien, H. Yang, Self-assembly of shark scale-patterned tunable superhydrophobic/antifouling structures with visual color response, ACS Appl. Mater. Interfaces (2023), https://doi.org/10.1021/ACSAMI.3C03086/SUPPL_FILE/AM3C03086_SI_001.PDF.

[45] X. Biomimetic, H. Liu, Z. Zhang, C. Wu, K. Su, X. Kan, Biomimetic superhydrophobic materials through 3D printing: progress and challenges, Micromachines 14 (2023) 1216, https://doi.org/10.3390/MI14061216, 1216 14 (2023).

[46] Home - Sharklet Technologies, Inc., (n.d.). https://www.sharklet.com/(accessed March 29, 2023).

[47] Z. Dang, Z. Mao, W. Tian, Reduction of hydrodynamic noise of 3D hydrofoil with spanwise microgrooved surfaces inspired by sharkskin, J. Mar. Sci. Eng. 7 (2019) 136, https://doi.org/10.3390/JMSE7050136, 136 7 (2019).

[48] J. Zhang, Y. Zheng, Constructing multi-protective functional polyurethane composite coating via internal-external dual modification: achieving superhydrophobicity, enhanced barrier, corrosion inhibition, and UV aging resistance properties, Prog. Org. Coating 194 (2024) 108540, https://doi.org/10.1016/J.PORGCOAT.2024.108540.

[49] M. Klicova, Z. Oulehlova, A. Klapstova, M. Hejda, M. Krejcik, O. Novak, J. Mullerova, J. Erben, J. Rosendorf, R. Palek, V. Liska, A. Fucikova, J. Chvojka, I. Zvercova, J. Horakova, Biomimetic hierarchical nanofibrous surfaces inspired by superhydrophobic lotus leaf structure for preventing tissue adhesions, Mater. Des. 217 (2022) 110661, https://doi.org/10.1016/J.MATDES.2022.110661.

[50] C.M. Collins, M. Safiuddin, Lotus-leaf-inspired biomimetic coatings: different types, key properties, and applications in infrastructures, Infrastructure 7 (2022), https://doi.org/10.3390/INFRASTRUCTURES7040046.

[51] O.A. Abdulrazzaq, S.M. Saeed, Z.H. Ali, S.A. Tuma, O.A. Ahmed, A.A. Faridoon, S. K. Abdulridha, Enhancement of low carbon steel corrosion resistance in acidic and saline media using superhydrophobic nanocomposite, Experi. Theoret. Nanotech. (2021) 77–87, https://doi.org/10.56053/5.1.77.

[52] J. Yang, F. Long, R. Wang, X. Zhang, Y. Yang, W. Hu, L. Liu, Design of mechanical robust superhydrophobic Cu coatings with excellent corrosion resistance and self-cleaning performance inspired by lotus leaf, Colloids Surf. A Physicochem. Eng. Asp. 627 (2021) 127154, https://doi.org/10.1016/J.COLSURFA.2021.127154.

[53] K.R.C. Soma Raju, A. Gautam, R. Patra, K. Srinivasa Rao, K.V. Gobi, R. Subasri, Bioinspired strategies for corrosion protection and antifouling coatings, Novel Anti-Corrosion and Anti-Fouling Coatings and Thin Films (2024) 251–285, https://doi.org/10.1002/9781394234318.CH9.

[54] L. Wang, Y. Hui, C. Fu, Z. Wang, M. Zhang, T. Zhang, Recent Adv. Gecko-Inspired Adhesive Mater. Appl. 34 (2020) 2275–2291, https://doi.org/10.1080/01694243.2020.1760478. Https://Doi.Org/10.1080/01694243.2020.1760478.

[55] N. Singh, A. Ghatak, Gecko-inspired hierarchically rough surface used as a reprintable paper, Chem. Eng. J. Adv. 12 (2022) 100420, https://doi.org/10.1016/J.CEJA.2022.100420.

[56] C. Kerst, S.A. Suresh, M. Ferro, M. Cutkosky, PEDOT: PSS coating improves gecko-inspired adhesive performance, J Micro Nanomanuf 8 (2020), https://doi.org/10.1115/1.4048927/1089155.

[57] W.R. Hansen, K. Autumn, Evidence for self-cleaning in gecko setae, Proc. Natl. Acad. Sci. U. S. A. 102 (2005) 385–389, https://doi.org/10.1073/PNAS.0408304102.

[58] M.T. Northen, C. Greiner, E. Arzt, K.L. Turner, A gecko-inspired reversible adhesive, Adv. Mater. 20 (2008) 3905–3909, https://doi.org/10.1002/ADMA.200801340.

[59] B. Bhushan, Adhesion of multi-level hierarchical attachment systems in gecko feet, J. Adhes. Sci. Technol. 21 (2007) 1213–1258, https://doi.org/10.1163/156856107782328353.

[60] B. Wang, Z. Weng, H. Wang, S. Wang, Z. Wang, Z. Dai, A. Jusufi, Wall-climbing performance of gecko-inspired robot with soft feet and digits enhanced by gravity compensation, Bioinspiration Biomimetics 19 (2024) 056001, https://doi.org/10.1088/1748-3190/AD5899.

[61] Z. He, S. Chen, Y. Liu, L. Long, Y. He, X. Wang, Z. Zeng, J. He, F. Shen, Y. Zhang, Bioinspired spiderweb-liked protective hydrophobic layer for improving the durability of superhydrophilic/air superoleophobic coatings, Compos. Struct. 321 (2023) 117309, https://doi.org/10.1016/J.COMPSTRUCT.2023.117309.

[62] A. Bardenhagen Mayank, V. Sethi, H. Gudwani, Spider-silk composite material for aerospace application, Acta Astronaut. 193 (2022) 704–709, https://doi.org/10.1016/J.ACTAASTRO.2021.08.013.
[63] A. Seisto, Spider Silk-Inspired Protein Coatings on Silica Substrates : impact of heat treatment and concentration on mechanical properties and wettability. http://www.theseus.fi/handle/10024/864966, 2024. (Accessed 17 December 2024).
[64] W.L. Lai, K.L. Goh, Consequences of ultra-violet irradiation on the mechanical properties of spider silk, J. Funct. Biomater. 6 (2015) 901–916, https://doi.org/10.3390/JFB6030901, 901-916 6 (2015).
[65] T. Koga, T. Morishita, Y. Harumoto, S.N. Nishimura, N. Higashi, Spider silk-inspired peptide multiblock hybrid copolymers for self-healable thin film materials, Mater. Adv. 2 (2021) 7851–7860, https://doi.org/10.1039/D1MA00823D.
[66] Airbus might make planes out of AMSilk's biofabricated silk, (n.d.). https://www.fastcompany.com/90235263/the-airplane-of-the-future-might-have-synthetic-spider-silk-inside-it (accessed April 3, 2023).
[67] S. Da Wu, W.T. Chuang, J.C. Ho, H.C. Wu, S.H. Hsu, Self-healing of recombinant spider silk gel and coating, Polymers 15 (2023) 1855, https://doi.org/10.3390/POLYM15081855, 1855 15 (2023).
[68] A. Seisto, A.S. Borisova, R. Pylkkänen, P. Mohammadi, Tailoring hydrophobicity and strength in spider silk-inspired coatings via thermal treatments, Comput. Struct. Biotechnol. J. 25 (2024) 177–185, https://doi.org/10.1016/J.CSBJ.2024.09.009.
[69] Z. Wang, P. Li, Y. Jiang, Z. Jia, P. Tang, X. Lu, F. Ren, K. Wang, H. Yuan, Mussel-inspired nanostructured coatings assembled using polydopamine nanoparticles and hydroxyapatite nanorods for biomedical applications, Biosurf Biotribol 3 (2017) 1–10, https://doi.org/10.1016/J.BSBT.2017.01.001.
[70] Z. Huang, J. Chen, R. Li, S. Shi, Y.K. Gong, Mussel adhesion and cell membrane antifouling mimetic strategies for durable fouling-resistant coating, Prog. Org. Coating 182 (2023), https://doi.org/10.1016/j.porgcoat.2023.107636.
[71] P. Tang, G. Ma, P. Nickl, C. Nie, L. Yu, R. Haag, Mussel-inspired polyglycerol coatings for surface modification with tunable architecture, Adv. Mater. Interfac. (2023) 2300165, https://doi.org/10.1002/ADMI.202300165.
[72] J.M. Krüger, H.G. Bçrner, J.M. Krüger, H.G. Bçrner, Accessing the next generation of synthetic mussel-glue polymers via mussel-inspired polymerization, Angew. Chem. Int. Ed. 60 (2021) 6408–6413, https://doi.org/10.1002/ANIE.202015833.
[73] A.S. Imbia, A. Ounkaew, X. Mao, H. Zeng, Y. Liu, R. Narain, Mussel-inspired polymer-based coating technology for antifouling and antibacterial properties, Langmuir 40 (2024) 10957–10965, https://doi.org/10.1021/ACS.LANGMUIR.4C00326/SUPPL_FILE/LA4C00326_SI_001.PDF.
[74] B.P. Lee, P.B. Messersmith, J.N. Israelachvili, J.H. Waite, Mussel-Inspired Adhesives and Coatings 41 (2011) 99–132, https://doi.org/10.1146/ANNUREV-MATSCI-062910-100429. Https://Doi.Org/10.1146/Annurev-Matsci-062910-100429.
[75] J. Gao, Q. Zhang, B. Wu, X. Gao, Z. Liu, H. Yang, J. Yuan, J. Huang, Mussel-inspired, underwater self-healing ionoelastomers based on α-lipoic acid for iontronics, Small 19 (2023) 2207334, https://doi.org/10.1002/SMLL.202207334.
[76] A. Taghizadeh, M. Taghizadeh, M.K. Yazdi, P. Zarrintaj, J.D. Ramsey, F. Seidi, F. J. Stadler, H. Lee, M.R. Saeb, M. Mozafari, Mussel-inspired biomaterials: from chemistry to clinic, Bioeng Transl Med 7 (2022) e10385, https://doi.org/10.1002/BTM2.10385.
[77] P. Hu, R. Xie, Q. Xie, C. Ma, G. Zhang, Simultaneous realization of antifouling, self-healing, and strong substrate adhesion via a bioinspired self-stratification strategy, Chem. Eng. J. 449 (2022) 137875, https://doi.org/10.1016/J.CEJ.2022.137875.
[78] M.D. Ibrahim, S. Philip, S.S. Lam, Y. Sunami, Evaluation of an antifouling surface inspired by Malaysian sharks Negaprion brevirostris and Carcharhinus leucas riblets, Tribol. Online 16 (2021) 70–80, https://doi.org/10.2474/TROL.16.70.
[79] M. Zabara, Q. Ren, H. Amenitsch, S. Salentinig, Bioinspired antimicrobial coatings from peptide-functionalized liquid crystalline nanostructures, ACS Appl. Bio Mater. 4 (2021) 5295–5303, https://doi.org/10.1021/ACSABM.1C00415.
[80] S. Kumari, G. Lang, E. DeSimone, C. Spengler, V.T. Trossmann, S. Lücker, M. Hudel, K. Jacobs, N. Krämer, T. Scheibel, Engineered spider silk-based 2D and 3D materials prevent microbial infestation, Mater. Today 41 (2020) 21–33, https://doi.org/10.1016/J.MATTOD.2020.06.009.
[81] L. Gond, P. Pradhan, A. Bajpai, Preparation and application of biomimetic and bioinspired membranes based on chitosan, Handbook of Chitin and Chitosan. Volume 3: Chitin- and Chitosan-Based Polymer Materials for Various Applications, 2020, pp. 307–339, https://doi.org/10.1016/B978-0-12-817966-6.00010-8.
[82] J. Xv, H. Li, W. Zhang, G. Lai, H. Xue, J. Zhao, M. Tu, R. Zeng, Anti-biofouling and functionalizable bioinspired chitosan-based hydrogel coating via surface photo-immobilization 30 (2019) 398–414, https://doi.org/10.1080/09205063.2019.1570435. Https://Doi.Org/10.1080/09205063.2019.1570435.
[83] A.E. Wetzel, N. Del Castillo Iniesta, E. Engay, N.K. Mandsberg, C. Schou Dinesen, B.R. Hanif, K. Berg-Sørensen, A.I. Bunea, R. Taboryski, Bioinspired microstructured polymer surfaces with antireflective properties, Nanomaterials 11 (2021) 2298, https://doi.org/10.3390/NANO11092298/S1.
[84] L. Feng, F. Wang, H. Luo, B. Qiu, Review of recent advancements in the biomimicry of structural colors, Dyes Pigments 210 (2023) 111019, https://doi.org/10.1016/J.DYEPIG.2022.111019.
[85] Z. Han, Z. Jiao, S. Niu, L. Ren, Ascendant bioinspired antireflective materials: opportunities and challenges coexist, Prog. Mater. Sci. 103 (2019) 1–68, https://doi.org/10.1016/J.PMATSCI.2019.01.004.
[86] K. Shanks, R. Ffrench-Constant, Understanding the anti-reflective glasswing butterfly for enhanced solar concentrator optics (2022) 54–59, https://doi.org/10.1117/12.2633041. Https://Doi.Org/10.1117/12.2633041 12214.
[87] S. Mattaparthi, C.S. Sharma, Bio-inspired Micro and Nano-Textured Self-Cleaning and Antireflective Polymer Surfaces, 2019.
[88] S. Pourhashem, F. Saba, J. Duan, A. Rashidi, F. Guan, E.G. Nezhad, B. Hou, Polymer/Inorganic nanocomposite coatings with superior corrosion protection performance: a review, J. Ind. Eng. Chem. 88 (2020) 29–57, https://doi.org/10.1016/J.JIEC.2020.04.029.
[89] J. Ding, H. Zhao, H. Yu, Bio-inspired multifunctional graphene-epoxy anticorrosion coatings by low-defect engineered graphene, ACS Nano 16 (2022) 710–720, https://doi.org/10.1021/ACSNANO.1C08228/SUPPL_FILE/NN1C08228_SI_001.PDF.
[90] H. Ehrlich, R. Martinović, D. Joksimović, I. Petrenko, S. Schiaparelli, M. Wysokowski, D. Tsurkan, A.L. Stelling, A. Springer, M. Gelinsky, A. Joksimović, Conchixes: organic scaffolds which resemble the size and shapes of mollusks shells, their isolation and potential multifunctional applications, Appl. Phys. Mater. Sci. Process 126 (2020) 1–13, https://doi.org/10.1007/S00339-020-03728-7/FIGURES/12.
[91] H.E.S. Nour, E.S. Nouh, Using coral skeletons for monitoring of heavy metals pollution in the Red Sea Coast, Egypt, Arabian J. Geosci. 13 (2020) 1–12, https://doi.org/10.1007/S12517-020-05308-8/METRICS.
[92] C. Yu, M. Liu, C. Zhang, H. Yan, M. Zhang, Q. Wu, M. Liu, L. Jiang, Bio-inspired drag reduction: from nature organisms to artificial functional surfaces, Giant 2 (2020) 100017, https://doi.org/10.1016/J.GIANT.2020.100017.
[93] V. Panwar, T. Dutta, Diatom biogenic silica as a felicitous platform for biochemical engineering: expanding frontiers, ACS Appl. Bio Mater. 2 (2019) 2295–2316, https://doi.org/10.1021/ACSABM.9B00050/ASSET/IMAGES/MEDIUM/MT-2019-00050Q_0001.GIF.
[94] G. Tian, Y. Zhang, X. Feng, Y. Hu, Focus on bioinspired textured surfaces toward fluid drag reduction: recent progresses and challenges, Adv. Eng. Mater. 24 (2022), https://doi.org/10.1002/ADEM.202100696.
[95] Z. Li, X. Wang, H. Bai, M. Cao, Advances in bioinspired superhydrophobic surfaces made from silicones: fabrication and application, Polymers 15 (2023) 543, https://doi.org/10.3390/POLYM15030543. , Page 543 15 (2023).
[96] Z. Huang, J. Chen, R. Li, S. Shi, Y.K. Gong, Mussel adhesion and cell membrane antifouling mimetic strategies for durable fouling-resistant coating, Prog. Org. Coating 182 (2023), https://doi.org/10.1016/j.porgcoat.2023.107636.
[97] Z. Ma, J. Feng, S. Huo, Z. Sun, S. Bourbigot, H. Wang, J. Gao, L.C. Tang, W. Zheng, P. Song, Mussel-inspired, self-healing, highly effective fully polymeric fire-retardant coatings enabled by group synergy, Adv. Mater. 36 (2024) 2410453, https://doi.org/10.1002/ADMA.202410453.
[98] H. Tian, Y. Zhan, L. Tian, J. Sun, Corrosion resistance self-healing coating with bioinspired interfacial structure, Prog. Org. Coating 174 (2023) 107303, https://doi.org/10.1016/J.PORGCOAT.2022.107303.
[99] Z. Ma, X. Liu, X. Xu, L. Liu, B. Yu, C. Maluk, G. Huang, H. Wang, P. Song, Bioinspired, highly adhesive, nanostructured polymeric coatings for superhydrophobic fire-extinguishing thermal insulation foam, ACS Nano 15 (2021) 11667–11680, https://doi.org/10.1021/ACSNANO.1C02254/SUPPL_FILE/NN1C02254_SI_003.MP4.
[100] Y. Wang, D. Shou, S. Shang, K.L. Chiu, S. Jiang, Cooling performance of a bioinspired micro-crystal-bars coated composite fabric with solar reflectance, Compos. Commun. 27 (2021) 100814, https://doi.org/10.1016/J.COCO.2021.100814.
[101] A. Malshe, K. Rajurkar, A. Samant, H.N. Hansen, S. Bapat, W. Jiang, Bio-inspired functional surfaces for advanced applications, CIRP Annals 62 (2013) 607–628, https://doi.org/10.1016/J.CIRP.2013.05.008.
[102] B. Gopal Krishna, S. Tiwari, Bioinspired solar cells: contribution of biology to light harvesting systems, Sustain. Mater. Solut. Solar Energy Technol.: Processing Tech. Appl. (2021) 593–632, https://doi.org/10.1016/B978-0-12-821592-0.00006-6.
[103] Y. Wang, P. Liu, F. Vogelbacher, M. Li, Bioinspired multiscale optical structures towards efficient light management in optoelectronic devices, Mater Today Nano 19 (2022) 100225, https://doi.org/10.1016/J.MTNANO.2022.100225.
[104] H. Wu, J. Li, Z. Zhu, L. Ma, N. Gao, F. Liu, Bioinspired ultra-tough, exceptionally stretchable, and self-recoverable bio-based coating for visual damage detection and self-healing, Prog. Org. Coating 182 (2023) 107663, https://doi.org/10.1016/J.PORGCOAT.2023.107663.
[105] J. Ding, H. Zhao, H. Yu, Superior and durable graphene-based composite coatings by bioinspired interfaces and alignment, Compos. Sci. Technol. 214 (2021) 108967, https://doi.org/10.1016/J.COMPSCITECH.2021.108967.
[106] B. Zhang, Q. Han, J. Zhang, Z. Han, S. Niu, L. Ren, Advanced bio-inspired structural materials: local properties determine overall performance, Mater. Today 41 (2020) 177–199, https://doi.org/10.1016/J.MATTOD.2020.04.009.
[107] S. An, B. Shi, M. Jiang, B. Fu, C. Song, P. Tao, W. Shang, T. Deng, Biological and bioinspired thermal energy regulation and utilization, Chem. Rev. (2023), https://doi.org/10.1021/ACS.CHEMREV.3C00136/ASSET/IMAGES/MEDIUM/CR3C00136_0026.GIF.
[108] M. Yang, M. Yang, W. Zou, W. Zou, J. Guo, J. Guo, Z. Qian, Z. Qian, H. Luo, H. Luo, S. Yang, S. Yang, N. Zhao, N. Zhao, L. Pattelli, L. Pattelli, J. Xu, D. S. Wiersma, D.S. Wiersma, Bioinspired "skin" with cooperative thermo-optical effect for daytime radiative cooling, ACS Appl. Mater. Interfaces 12 (2020) 25286–25293, https://doi.org/10.1021/ACSAMI.0C03897/SUPPL_FILE/AM0C03897_SI_001.PDF.
[109] Y. Wang, S. Shang, K. lok Chiu, S. Jiang, Mimicking Saharan silver ant's hair: a bionic solar heat shielding architextile with hexagonal ZnO microrods coating,

Mater. Lett. 261 (2020) 127013, https://doi.org/10.1016/J.MATLET.2019.127013.
[110] S. Jiang, Y. Diao, H. Yang, Recent advances of bio-inspired anti-icing surfaces, Adv. Colloid Interface Sci. 308 (2022) 102756, https://doi.org/10.1016/J.CIS.2022.102756.
[111] W. Cai, Z. Li, T. Cui, X. Feng, L. Song, Y. Hu, X. Wang, Self-assembly of hierarchical MXene@SnO2 nanostructure for enhancing the flame retardancy, solar de-icing, and mechanical property of polyurethane resin, Compos. B Eng. 244 (2022) 110204, https://doi.org/10.1016/J.COMPOSITESB.2022.110204.
[112] Z. Wang, B. Li, X. Feng, Z. Jiao, J. Zhang, S. Niu, Z. Han, L. Ren, Rapid fabrication of bio-inspired antireflection film replicating from cicada wings, J. Bionic Eng. 17 (2020) 34–44, https://doi.org/10.1007/S42235-020-0001-Z/METRICS.
[113] K. Zhang, Dissipative particle dynamics for anti-icing on solid surfaces, Chem. Phys. 568 (2023) 111824, https://doi.org/10.1016/J.CHEMPHYS.2023.111824.
[114] E.P. Venkatesan, P. Murugesan, S. Ellappan, S. Rajendran, A. Aabid, M. Abbas, C. A. Saleel, P.A. Remigious, S.R. Medapati, Effect of kariba weed biodiesel blended with n-pentane on the chosen parameters of a ceramic-coated thermal barrier direct injection diesel engine, ACS Omega 7 (2022) 46337–46346, https://doi.org/10.1021/ACSOMEGA.2C04937/ASSET/IMAGES/LARGE/AO2C04937_0015.JPEG.
[115] K. Ziętkowska, B. Przybyszewski, D. Grzęda, R. Kozera, A. Boczkowska, M. Liszewska, D. Pakuła, R.E. Przekop, B. Sztorch, Transparent silicone–epoxy coatings with enhanced icephobic properties for photovoltaic applications, Appl. Sci. 13 (2023) 7730, https://doi.org/10.3390/APP13137730, 7730 13 (2023).
[116] S. Brown, J. Lengaigne, N. Sharifi, M. Pugh, C. Moreau, A. Dolatabadi, L. Martinu, J.E. Klemberg-Sapieha, Durability of superhydrophobic duplex coating systems for aerospace applications, Surf. Coat. Technol. 401 (2020) 126249, https://doi.org/10.1016/J.SURFCOAT.2020.126249.
[117] K.R. Khedir, G.K. Kannarpady, C. Ryerson, A.S. Biris, An outlook on tunable superhydrophobic nanostructural surfaces and their possible impact on ice mitigation, Prog. Org. Coating 112 (2017) 304–318, https://doi.org/10.1016/J.PORGCOAT.2017.05.019.
[118] S.A. Kulinich, S. Farhadi, K. Nose, X.W. Du, Superhydrophobic surfaces: are they really ice-repellent? Langmuir 27 (2011) 25–29, https://doi.org/10.1021/LA104277Q/SUPPL_FILE/LA104277Q_SI_001.PDF.
[119] N. Rehfeld, B. Speckmann, C. Schreiner, V. Stenzel, Assessment of icephobic coatings—how can we monitor performance durability? Coatings 11 (2021) 614, https://doi.org/10.3390/COATINGS11060614, 614 11 (2021).
[120] V.F.C. Sousa, F.J.G. Da Silva, G.F. Pinto, A. Baptista, R. Alexandre, Characteristics and wear mechanisms of TiAlN-based coatings for machining applications: a comprehensive review, Metals 11 (2021) 260, https://doi.org/10.3390/MET11020260, 260 11 (2021).
[121] R. Nartita, D. Ionita, I. Demetrescu, Sustainable coatings on metallic alloys as a nowadays challenge, Sustainability 13 (2021) 10217, https://doi.org/10.3390/SU131810217, 10217 13 (2021).
[122] F. Zareanshahraki, H.R. Asemani, J. Skuza, V. Mannari, Synthesis of non-isocyanate polyurethanes and their application in radiation-curable aerospace coatings, Prog. Org. Coating 138 (2020) 105394, https://doi.org/10.1016/J.PORGCOAT.2019.105394.
[123] J. Page, S. Amziane, M. Gomina, C. Djelal, F. Audonnet, Using linseed oil as flax fibre coating for fibre-reinforced cementitious composite, Ind. Crops Prod. 161 (2021) 113168, https://doi.org/10.1016/J.INDCROP.2020.113168.
[124] Á.M. Costa, J.A. Orosa, D. Vergara, P. Fernández-Arias, New tendencies in wind energy operation and maintenance, Appl. Sci. 11 (2021) 1386, https://doi.org/10.3390/APP11041386, 1386 11 (2021).
[125] L. Chen, Y. Wang, X. Hao, X. Zhang, H. Liu, Lightweight refractory high entropy alloy coating by laser cladding on Ti–6Al–4V surface, Vacuum 183 (2021) 109823, https://doi.org/10.1016/J.VACUUM.2020.109823.
[126] A. Hossain, P. Rajput, Z. Li, A.V. Soldatov, E.A. Mukhanova, C. Yazbleydy Cárdenas Rodriguez, Engineering bioinspired microfluidics; biomimetic self-healing/cleaning coating designs and unique advanced materials, Chem. Eng. J. 489 (2024), https://doi.org/10.1016/J.CEJ.2024.151336.
[127] J. Mathew, J. Joy, S.C. George, Potential applications of nanotechnology in transportation: a review, J. King Saud Univ. Sci. 31 (2019) 586–594, https://doi.org/10.1016/J.JKSUS.2018.03.015.
[128] J. Ding, H. Zhao, H. Yu, Bioinspired strategies for making superior graphene composite coatings, Chem. Eng. J. 435 (2022) 134808, https://doi.org/10.1016/J.CEJ.2022.134808.
[129] J. Ding, H. Zhao, H. Yu, Superior and durable graphene-based composite coatings by bioinspired interfaces and alignment, Compos. Sci. Technol. 214 (2021) 108967, https://doi.org/10.1016/J.COMPSCITECH.2021.108967.
[130] M. Christian, R. Mazzaro, V. Morandi, Bioinspired design of graphene-based materials, Adv. Funct. Mater. 30 (2020) 2007458, https://doi.org/10.1002/ADFM.202007458.
[131] Y. Hu, K. Qi, L. Chang, J. Liu, L. Yang, M. Huang, G. Wu, P. Lu, W. Chen, Y. Wu, A bioinspired multi-functional wearable sensor with an integrated light-induced actuator based on an asymmetric graphene composite film, J. Mater. Chem. C Mater. 7 (2019) 6879–6888, https://doi.org/10.1039/C9TC02026H.
[132] X. Zhu, H. Zhao, L. Wang, Q. Xue, Bioinspired ultrathin graphene nanosheets sandwiched between epoxy layers for high performance of anticorrosion coatings, Chem. Eng. J. 410 (2021) 128301, https://doi.org/10.1016/J.CEJ.2020.128301.
[133] T. Šančić, M. Brčić, D. Kotarski, A. Łukaszewicz, Experimental characterization of composite-printed materials for the production of multirotor UAV airframe parts, Materials 16 (2023) 5060, https://doi.org/10.3390/MA16145060, 5060 16 (2023).
[134] X. Yan, B. Bethers, H. Chen, S. Xiao, S. Lin, B. Tran, L. Jiang, Y. Yang, Recent advancements in biomimetic 3D printing materials with enhanced mechanical properties, Front Mater 8 (2021), https://doi.org/10.3389/FMATS.2021.518886/FULL.
[135] D. Wang, D. Chen, Z. Chen, Recent progress in 3D printing of bioinspired structures, Front Mater 7 (2020) 530065, https://doi.org/10.3389/FMATS.2020.00286/BIBTEX.
[136] M.H. Himel, B. Sikder, T. Ahmed, S.M. Choudhury, Biomimicry in nanotechnology: a comprehensive review, Nanoscale Adv. 5 (2023) 596–614, https://doi.org/10.1039/D2NA00571A.
[137] A. Kumar, A. Al-Jumaili, O. Bazaka, E.P. Ivanova, I. Levchenko, K. Bazaka, M. V. Jacob, Functional nanomaterials, synergisms, and biomimicry for environmentally benign marine antifouling technology, Mater. Horiz. 8 (2021) 3201–3238, https://doi.org/10.1039/D1MH01103K.
[138] S. Damiati, R. Mhanna, S.A. Awan, R. Kodzius, B. Schuster, Editorial: the dual-use dilemma for biomimicry, Front. Mol. Biosci. 9 (2022) 915663, https://doi.org/10.3389/FMOLB.2022.915663/BIBTEX.
[139] M.D.L.Á. Ortega Del Rosario, K. Beermann, M. Chen Austin, Environmentally responsive materials for building envelopes: a review on manufacturing and biomimicry-based approaches, Biomimetics 8 (2023) 52, https://doi.org/10.3390/BIOMIMETICS8010052.
[140] S. Abedanzadeh, M. Nourisefat, Z. Moosavi-Movahedi, Bioinspiration and Biomimicry in Lifestyle (2021) 9–29, https://doi.org/10.1007/978-3-030-74326-0_2.
[141] A. Sandak, Engineered living materials for sustainable and resilient architecture, Nat. Rev. Mater. 8 (6) (2023) 357–359, https://doi.org/10.1038/s41578-023-00554-0, 8 (2023).
[142] Z. Li, P. Liu, S. Chen, X. Liu, Y. Yu, T. Li, Y. Wan, N. Tang, Y. Liu, Y. Gu, Bioinspired marine antifouling coatings: antifouling mechanisms, design strategies and application feasibility studies, Eur. Polym. J. 190 (2023) 111997, https://doi.org/10.1016/J.EURPOLYMJ.2023.111997.
[143] C. Zhang, X. Zhang, Y. Ling, M. Liang, H. Zou, Chitosan-doped carbon nanotubes encapsulating spread carbon fiber composites with superior mechanical, thermal, and electrical properties, Compos. Sci. Technol. 230 (2022), https://doi.org/10.1016/j.compscitech.2022.109755.
[144] M.S. Mozumder, A.H.I. Mourad, H. Pervez, R. Surkatti, Recent developments in multifunctional coatings for solar panel applications: a review, Sol. Energy Mater. Sol. Cell. 189 (2019) 75–102, https://doi.org/10.1016/J.SOLMAT.2018.09.015.
[145] K.-P. Yang, H. Chen, Z.-M. Han, C.-H. Yin, H.-C. Liu, D.-H. Li, H.-B. Yang, W.-B. Sun, Q.-F. Guan, S.-H. Yu, Bioinspired multifunctional high-performance electromagnetic shielding coatings resistant to extreme space environments PUBLIC SUMMARY Bioinspired multifunctional high-performance electromagnetic shielding coatings resistant to extreme space environments, Article Innovat. Mater. 1 (2023) 100010, https://doi.org/10.59717/j.xinn-mater.2023.100010.
[146] H. Park, H. He, X. Yan, X. Liu, N.S. Scrutton, G.Q. Chen, PHA is not just a bioplastic, Biotechnol. Adv. 71 (2024) 108320, https://doi.org/10.1016/J.BIOTECHADV.2024.108320.
[147] M.T. Hossain, M.A. Shahid, S. Akter, J. Ferdous, K. Afroz, K.R.I. Refat, O. Faruk, M.S.I. Jamal, M.N. Uddin, M.A. Bin Samad, Cellulose and starch-based bioplastics: a review of advances and challenges for sustainability, Polymer-Plastics Technol. Mater. 63 (2024) 1329–1349, https://doi.org/10.1080/25740881.2024.2329980.
[148] C. Zhai, T. Li, H. Shi, J. Yeo, Discovery and design of soft polymeric bio-inspired materials with multiscale simulations and artificial intelligence, J. Mater. Chem. B 8 (2020) 6562–6587, https://doi.org/10.1039/D0TB00896F.
[149] R. Batra, L. Song, R. Ramprasad, Emerging materials intelligence ecosystems propelled by machine learning, Nat. Rev. Mater. 6 (2021) 655–678, https://doi.org/10.1038/S41578-020-00255-Y.
[150] L. Bassman, M. Urbanek, M. Metcalf, J. Carter, A.F. Kemper, W.A. De Jong, Simulating quantum materials with digital quantum computers, Quantum Sci. Technol. 6 (2021) 043002, https://doi.org/10.1088/2058-9565/AC1CA6.