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REVIEW

A review of biomimetic research for erosion wear resistance

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Abstract
One of the reasons behind failed engineering surfaces and mechanical components is particle erosion wear; thus, to mitigate its happening, biomimetic engineering is the current state-of-the-art being applied. Hence, this paper reviews the literature and the development trends on erosive wear resistance that employ biomimetic methods as well as analyze the bio-inspired surface, the bio-inspired structure, the bio-based materials, the associated challenges, and the future trends. Furthermore, the feasibility of the multi-biological and perspective on the coupling biomimetic method for anti-erosion wear are studied. It is concluded that the design of anti-erosion materials or structures by the bio-inspired methods is of great significance in the development of engineering applications.

Keywords Erosion wear · Biology to engineering · Biomimetics · Erosion reduction

Introduction

Since the 1960s, erosion wear has drawn significant concern [1] by being responsible for many failures in engineering applications. Erosion wear is caused by the dynamic action of solid particles flowing along water or gas [2–4], impacting against the solid surfaces, in turn resulting in repeated deformations [5]. It is quite often observed in the mining operations, oil and gas transportation, to name a few, thus causing serious financial losses [6]. Erosion wear is a complex phenomenon [7–15], depending on erodent particles (size, shape, hardness, concentration), eroded substance (elastic properties, surface hardness, surface morphology), flow condition (impacting velocity, angle, location), and so on. The major factors of erosion wear are summarized in Fig. 1.

Erosion rate, penetration depth, load spreading, and stress distribution are the four factors [16–18] backing the investigation of erosive wear. The actual mechanism of erosion being not completely clear [19] restricts the establishment of a simple, reliable, and universally quantitative erosion model. The most common expression of erosion wear is based on experimental experience and the erosion rate is usually defined by the mass loss per unit time. It is considered that within a certain limit range of the hardness [20], the erosion wear resistance improves with the hardness of the eroded substance [20–22]. An increase in impact velocity results in a larger peak impact force, whereas the contact time and energy absorption decrease [23]. According to energy conservation, the particle kinetic energy is absorbed by the target surface and transformed into plastic deformation energy, wave stress-energy and residual energy [24]. The eroded substance identifies the role of controlling the motion and energy absorption during the particle impact.

In the harsh nature, evolved creatures have formed their unique structures and characteristics [25], carrying numerous secrets of success. Human beings continue to learn from natural concepts and features in science and production methods, which increase our ability to evaluate and transform the world. A large number of studies suggest that natural designs can be notably effective in resolving engineering problems [26–28]. There has been a gradual interest in the anti-erosion characteristics of living creatures inhabiting harsh environments. There exist types of anti-erosion wear materials and structures with broad applications. However, the current research is still scattered, although some have reviewed the research on erosion wear based on different classification methods. Yet, fewer studies focus on biomimetic classification of erosion wear. Hence, this review provides a thorough overview of recent advances in bio-inspired design for anti-

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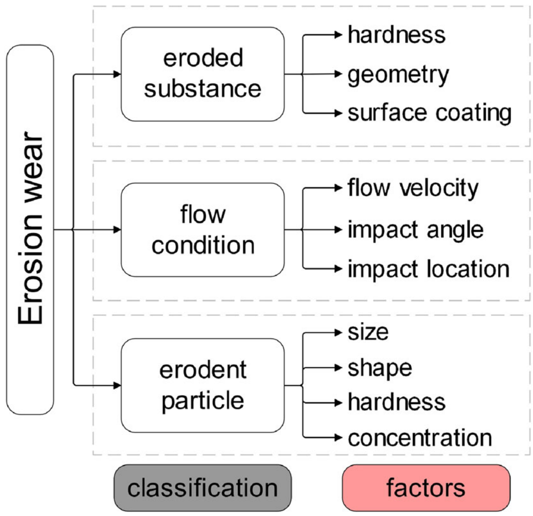

Fig. 1 Factors of erosion wear: erodent particle, eroded substance, and flow condition

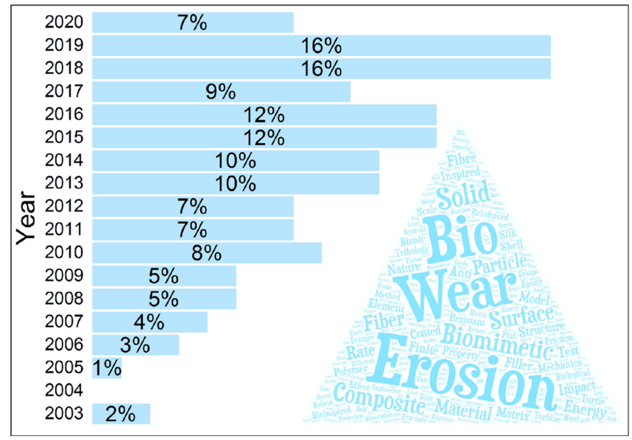

Fig. 2 Literature distribution and word cloud in this review

erosion wear. The eroded substance will be the main part of this review as changes of erodent particles and fluid conditions remain unpredictable in practice.

This article reviews the related literature, which focuses on biomimetic research for erosion wear reduction. Figure 2 illustrates the selected publications in this review and the cloud of keywords. Studying Fig. 2, it is apparent that the keywords erosion, wear, biomimetic, composite, solid, surface, particle, energy occupy the main position. Hence, they are the principal part of the review. The following sections present a review of the effect of bio-inspired approaches on anti-erosion wear. The second section provides a brief review of bio-inspired surfaces in reducing erosion wear. The energy absorption and anti-erosion wear of bio-inspired structures are discussed in the third part. The fourth section summarizes the application of bio-based materials in erosion. Finally, conclusions and future research suggestions are discussed. Figure 3 displays the main parts and the typical biology in this review. These biological archetypes inspire the design of novel bio-inspired surfaces, structures and bio-based materials with excellent erosion wear capacities.

Bio-inspired surface in erosion wear reduction

As mentioned earlier, the eroded substance is a major element of erosion wear. Biology has formed a biological surface that reduces erosion and wears in perennial evaluation [29–31], such as desert lizards, sandfish, tamarisk, desert scorpion, dung beetle, and so on [31–33]. The distinctive non-smooth skins surface obtain lower friction and better anti-wear performance, which enables them to survive in a severe environment. In general, the erosion wear depends on the surface morphology [34,35]. Reason for erosion wear protection of bio-inspired surface can be concluded as follows: (1) the fluid turbulence along the wall is enhanced, and the motion of particles are disturbed by bio-inspired surface; (2) the non-smooth surface decreases the number of particles impacting on the eroded substance; (3) bio-inspired surface can prevent particles from sliding and rolling along the surface.

The typical literature of bio-inspired surfaces for improving the anti-erosion wear characteristics and their erosion wear mechanisms will be reviewed in this section.

(1) Snake-inspired surfaces

Extensive research on the snake [36] has confirmed the unique characteristics of the ventral surface of the snake and optimized tribological response in terms of energy loss and wear resistance [37–39]. Mühlberger et al. [40] directly replicated the snakeskin texture features and the results showed that the snake-like skin samples had significantly less wear than the smooth samples. Although the snakeskin is applied to the bio-inspired surface, the interaction between the wear-resistant bionic properties of snakes and geometry, materials and mechanics is inseparable. Therefore, there is still a lot of scope for the engineering application of snake-like skin. Mitigation of the phenomenon depends on optimizing the interaction and the interference between every contributing factor (geometry, material, and mechanics).

(2) Dung beetle-inspired surfaces

Inspired by the head and pronotum surface of the dung beetle, Yang et al. [31] built and optimized the non-smooth surface of a drill bit. According to the results of comparable experiments, when the diameter of the dome and pit on

Fig. 3 Main parts and typical biology in this review

the drill bit surface was the range of 0.8–1.2 mm, the bio-inspired drill exhibited better performance in reducing wear and attaining higher levels of efficiency. Although the range of the domes was given according to the digging ability of the dung beetle, the exact size and location of the domes demanded to be optimized based on the soil environment and the species of the dung beetle. The schematic diagram of the smooth surface and the domes in erosion wear can be seen in Fig. 4(1). Tong et al. [41] studied the bionic wear-resistant mechanism inspired by dung beetles, demonstrating that the shape of the dome can reduce wear: the solid particles hit the domes and the trajectory changes, resulting in reduced wear of other domes. At the same time, the link between the location of the dome and wear is addressed in the literature [41], showing that the front domes at a larger distance of the specimens have a lower wear rate.

Although the obtained results show that the wear reduction effect of the convex dome is significant, the relationship between the position and volume of the domes is not discussed in detail. When the front domes wear are severely worn away, the behind ones are also at risk. Additionally, the shape and position of the semi-convex domes have to be further studied for better erosion wear property.

(3) Desert scorpion-inspired surfaces

A hexagonal pit structure inspired from the back of desert scorpion was reported in [26]. The 3D printed biomimetic samples with the microstructures (depth: 200–300 μm, length: 200–500 μm) showed excellent anti-erosion property. Zhang et al. [26] revealed the erosion resistance mechanism of bio-inspired microstructure. As shown in Fig. 4(2), the normal velocity of the solid particles was reduced due to the rotational low velocity, which plays a vital role in reducing erosive wear. Han et al. [42] inspired by the desert scorpion surface and explored the erosion resistance of the bump, groove shape, and curvature. An adult desert scorpion was chosen for obtaining the size of the bumps and groove shape. The bio-inspired surface was fabricated according to the observation. Compared with the smooth structure, the erosion resistance property of the bionic groove and bump shaped structure increased by approximately 10% and 25%, respectively. The higher the similarity between the bio-inspired structure and the desert scorpion skin, the better the anti-erosion performance they had. Moreover, the curvature of the bio-inspired structure played a vital role in anti-erosion wear.

(4) Tamarisk-inspired surfaces

Jung et al. [43] evaluated quantitatively the erosion rates of tamarisk-inspired V-shape grooved solid surfaces under the particle impact, and a framework for the design of bio-inspired anti-erosive surfaces was provided in [43]. The bio-inspired grooves effectively reduced the erosion wear at an impingement angle ranging from 20^{circ} to 60^{circ}, but the impingement angles range were not constant, generally related to the ductility of the eroded substance. Based on the grooves on the tamarisk surface, Yin et al. [44] designed three kinds of bio-inspired grooves (square, U-shaped, and

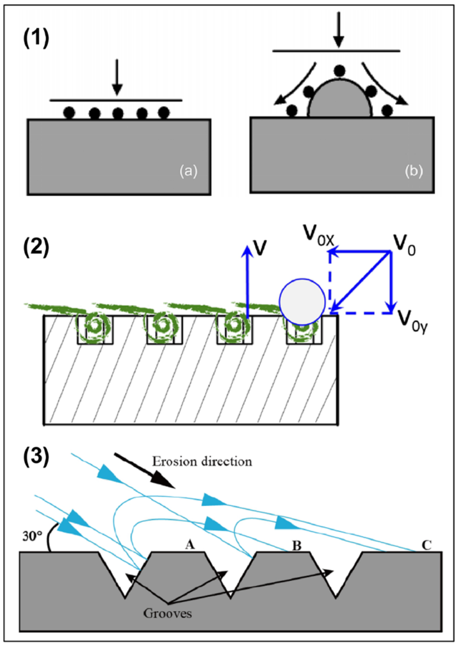

Fig. 4 Bio-inspired surface: (1) **dung beetle**-inspired surfaces. Schematic diagram of **a** smooth surface and **b** the domes in erosion wear [31]; (2) **desert scorpion**-inspired surfaces. Rotational flow for the impact velocity of particles [26]; (3) **tamarisk**-inspired surfaces. Schematic diagram of the interaction between V-grooves and erodent particles [44]

V-shaped) to analyze the erosive wear resistance behavior. According to the experiment design method, the biomimetic model with a morphology of a V-shaped groove, a space between two ribs of 4 mm and a rib size of 2 mm displayed the lowest erosion rate. The schematic diagram of the interaction between V-grooves and erodent particles is presented in Fig. 4(3).

The bio-inspired surface presents both its pros and cons when dealing with anti-erosive wear. Worn scars having the size of scales increase with growing impact cycles [45]. Although the bio-inspired structure reduces the erosion rate, after a certain time the bionic structure on the surface degrades. Eddy currents on non-smooth surfaces are reduced, and erosion resistance is decreased. The bio-inspired grooves can mitigate the erosion wear under certain impingement angles [43], but, following the addition of erosion wear, erosion resistance gradually decreases until it disappears. Hence, other approaches must be determined to limit erosive wear in bionic surfaces.

Bio-inspired structure in erosion wear reduction

It is observed that erosion behavior is largely due to the particle and wall properties [46,47]. The initial kinetic energy before particle impact the surface is the total of particle translation and rotation kinetic energy. During particle impact, energy is absorbed by the particles and the walls. According to energy conservation in erosion wear [46,48]:

$$E_{k,i} = E_{k,r} + E_p + E_w. \quad (1)$$

In Eq. (1), $E_{k,i}$ is the initial translational kinetic energy of the particles, $E_{k,r}$ is the translational kinetic energy of the particles after impact, E_p is the particle energy absorption, and E_w is the energy absorbed by wall surface. E_w is divided into two parts, the energy required to form the permanent indentation in-wall (E_c) and deformation (E_d):

$$E_w = E_c + E_d \quad (2)$$

Therefore, to reduce the loss of wall materials, it is necessary to increase the deformation energy of the structure to reduce erosion wear. Likewise, the elastic modulus of the material has a significant effect on the impact of the particles [49]. As the material's elastic modulus decreases, the deformation increases. The erodent particle loses its kinetic energy by being converted to the deformation of eroded substance.

In recent years, the biomimetic approach used in the field of energy absorption is rapidly increasing [50]. The structures inspired by animals and plants for energy absorption applications play a crucial role in replacing conventional structures in the future. The relationship between erosion, energy dissipation and particle size has been explored in [47], and the authors contributed to examine the erosion mechanism. This section reviewed the energy absorption of the bio-inspired structures based on elasticity (reversible) deformation behavior.

Human body-inspired energy-absorbing structure

(1) Human teeth

Human teeth are well-known wear resistance tissue in the human body [51] that utilize different structures to generate hard surface layers to resist wear. They also consist of a subsurface that accommodates grown deformation [52]. The hardness of teeth decreases from the surface to the interior [53]. Enamel is the hardest coating on dentin with high stiffness and it has strong tolerances to fracture and wear [54,55]. Zhang et al. [55] inspired by the nature of the enamel, provided a guideline for designing bio-inspired composites. It is also observed in its microstructure that enamel-inspired composites have a hierarchical structure. The soft and elastic dentin below the dentin enamel junction also holds the ability to resist impact forces [51] shown in Fig. 5(1).

(2) Cartilage and tissue

Similarly, the principle of energy absorption is also reflected in other tissues of the human body. Cartilage tissue is distributed widely in the human body and plays an essential role in joint lubrication and loads transmission [62]. It consists of chondrocytes, progenitor cells, extracellular matrices [63], and the following visible characteristics: strong but not brittle, hard, flexible, light enough to support tissues, high strength with a porous appearance, to name a few. Natural cartilage has a complex hierarchical structure [64] and soft tissue is known to perform significant negative work during the collision of the leg with the ground and dissipates more collision energy at a faster walking speed [56]. Muscles act as a buffer layer and can absorb energy quickly and effectively during stretching, in turn protecting human tissues and organs [57,65].

The effort of muscles actively dissipating energy was saved by soft tissue deformation [56]. Tsang et al. inspired by the internal structure of skeletal muscle and tendon tissues [57,58] designed a hierarchy tubular for impact protection and energy absorption, as shown in Fig. 5(2). According to simulation and experimental results, the tubular sections with multiple length scales showed noticeable improvement in energy absorption. The performance of energy absorption was enhanced by 172% for three-order to the muscle-inspired hierarchical structure [57]. Similarly, the sandwich structure was found in many bones, consisting of two sheets of cortical bone outside a filling of cancellous bone and fat [66,67]. The fat layer commonly absorbed energy and mitigated the impact received by the bones.

Flora- and fauna-inspired energy-absorbing structure

(1) Laudakia stoliczkana

Similarly, structures with energy-absorbing functions have also been found in other animals and plants. Some creatures live in windy and sandy environments, such as lizards and scorpions. Their survival in the severe environment may be a combination of distinctive surface topography, microstructure and biological flexibility [49]. Inspired from the body surface and layered structure of Laudakia stoliczkana, Liang et al. [59] produced the coupling bionic samples and evaluated their erosion wear performance. According to the morphology of Laudakia stoliczkana and previous researches [as shown in Fig. 5(3)], the erosion wear rate of three classical convex hulls (circle, square, prismatic) was carried out by using jet type solid particle erosion test. Interestingly, circle convex hulls showed the best anti-erosion wear performance. To reveal the impact of bionic layered structure on erosion wear, ABAQUS software was used to analyze the transmission and reflection of stress waves. According to energy conservation, stress waves indirectly reflect the kinetic energy of particles. The results show that the soft layer almost blocks the spread of stress waves in the interior of the bionic layer structure. The kinetic energy of the particles is partially transformed into elastic potential energy of the structure, so the plastic strain energy that causes the erosion wear of the surface material is reduced in turn reducing the erosion rate of the structure.

(2) Turtle carapace

Turtles are generally found inside the water and their carapaces often undergo blunt impact loads in lotic streaming environments [68,69], which is similar to the condition of erosion wear. The turtle carapace has a sandwich structure of epidermal scutes, dorsal cortex, trabecular bone, and ventral cortex [60,69,70]. The hard external layers and foam-like structure of carapace lead to absorb and mitigate the impact force [70]. The carapace with a functionally graded material structure usually distributes the energy input to the soft tissues [71,72]. Achrai and Wagner [68] recommended that the bumper-buffer toughening mechanism of the carapace that is involved in the outermost keratin layer (adsorbing part) and the intermediate collagenous layer (energy absorbed part). Inspired by the carapace structure, Achrai et al. [60] explored the impact resistance of a thin compliant coating on a stiff and brittle substrate, as shown in Fig. 5(4). Compared with the pristine substrate, the impact energy absorption is increased with the presence of additional toughening mechanisms in the form of delamination between the various interfaces.

(3) Pomelo peel

New natural materials with hierarchical or gradient structures help customize the excellent mechanical properties of engineering applications [52,73]. Pomelo peel is a natural protecting barrier for pulp and the seed [61] that has a unique spongy mesocarp layer, as shown in Fig. 5(5). The mesocarp layer can dissipate energy from free fall without leading to visible outer damage of the peel [61,74]. Experimental studies have summarized that pomelo peel can absorb kinetic energy.

Moreover, parallels can be drawn between erosion wear-protective structures and natural defensive structures because natural defensive structures have a balance between energy absorption and dissipation. Natural creatures usually have excellent properties, and the armor of some animals can effectively resist external attacks [75–77]. After millennia of evolutionary developments, biological armor systems (such as White rhinoceroses skin [78]) have been developed to defeat penetrating injuries and crushing blows from preda-

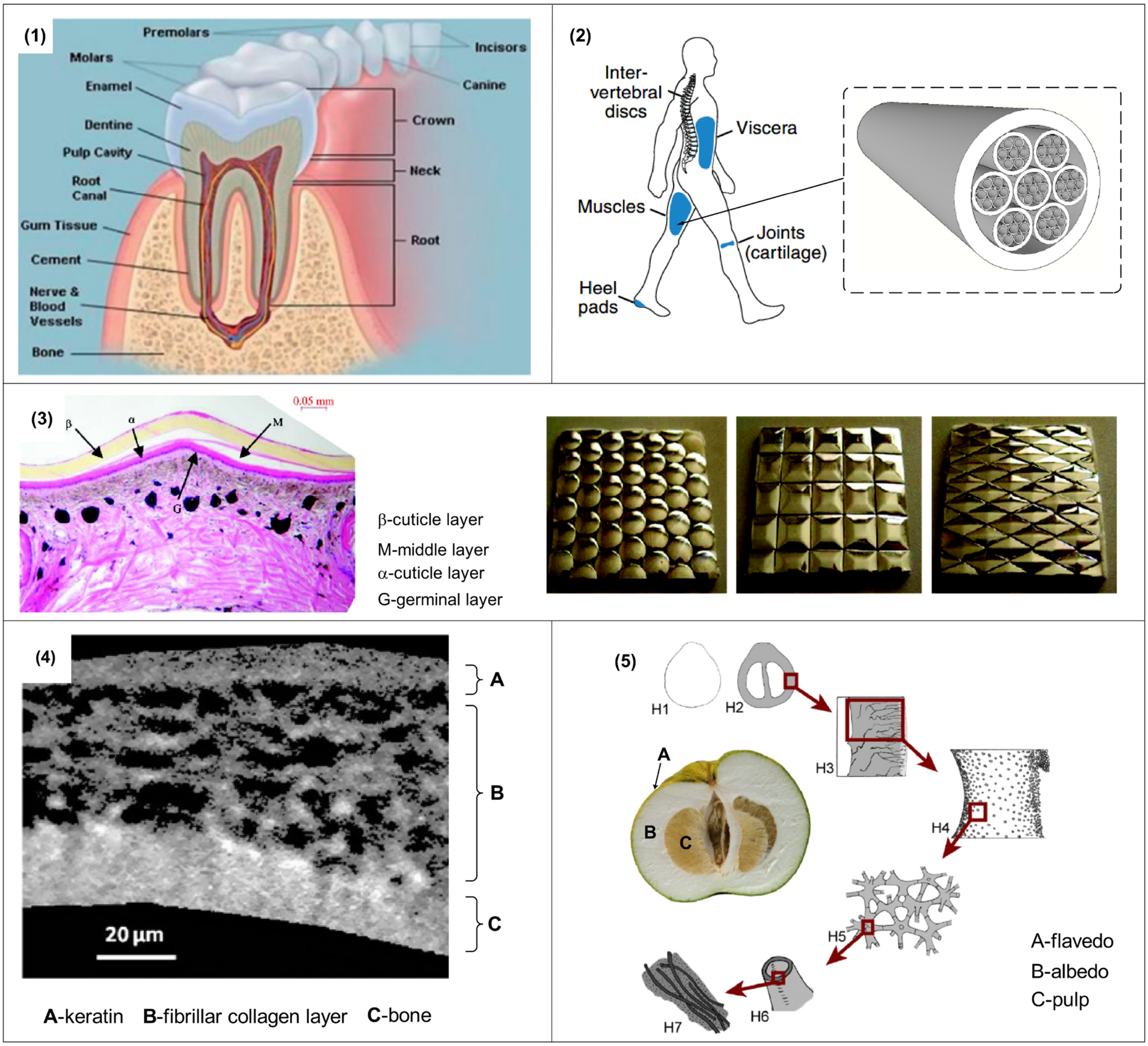

Fig. 5 Bio-inspired structure for energy absorption. **(1)** anatomy of the human tooth (layered structure) [51]; **(2)** deformation tissues of the body may affect walking [56] and the muscle-inspired energy absorption structure [57,58]. **(3)** the hierarchical structure of the skin of Laudakia stoliczkana, and three kinds of bio-inspired structure [59]; **(4)** the sandwich structure of the turtle shell: keratin, fibrillar collagen layer and bone [60]; **(5)** schematic representation (not to scale) of the hierarchical levels of the pomelo peel H1∼H7, showing A-flavedo, B-albedo, and C-pulp [61]

tors [69]. The aciniform spider silk is used as a soft inner egg case layer, that provides additional protection or to wrap captured prey [79]. Fishes utilize the manner of overlapping hard plates to protect themselves. Fish scales are composed of calcium-deficient hydroxyapatite [80], which is also present in the bone and teeth. The scales of the fish have a hierarchical structure and the collagen under the scales are connected to the scales, which increases flexibility while ensuring strength [75,77]. When a fish is under an impact, the scales redistribute the load to a larger area and reduce the stress concentration [77]. The impact force is mitigated because the scale structure can cause scales sinking into much softer ones under impact [81,82].

Deformation energy absorption is an essential factor affecting erosion wear. The bionic multilayer rigid–flexible structure cushions the impact of particles to increase the deformation energy absorption and to reduce erosion wear rate. However, optimization of the bio-inspired rigid-flexible structure is needed for further investigation. In the process of erosion wear, the erosion rate of ductile materials is severe at low impingement angles (15°–45°), while the erosion wear rate of brittle materials has maximum erosion under normal impacts [35]. Therefore, the rational distribution of rigid and flexible layers according to the erosion environment has to be further studied. According to the requirements of stiffness, the rigid-flexible composition ratio of the bio-inspired structure also needs to be considered more broadly.

Biomimetic composite in erosion wear reduction

Bio-based composite

Recently, an extensive and significant interest in the field of development of recyclable and biodegradable polymeric composites has been developed. Natural materials represent ideal models for bio-inspired materials design with highly optimized characteristics and multiple functionalities [83]. Bio-inspired materials incorporated in biomimetic design using synthetic materials provided a new type of high-performance material with promising applications in the fields of aerospace, biomedicine, and so on [84]. Bio-inspired materials generally have the following characteristics: the constituents are simple but the structure is complex as the interface between the materials undergoes a gradual transition requiring self-organization, composite characteristics, functional adaptability, and self-healing properties. Compared with monolithic metal, bio-inspired composite materials have good strength, low density and higher impact properties [85]. Table 1 illustrates the bio-based materials for erosion wear reduction from the representative literature.

Plant fiber filler

Owning to the environmental concerns and sustainable development, natural filler-reinforced composites are being increasingly explored and developed [118]. In the last few decades, several attempts have been made to polymer composite used natural fibers as reinforcement to improve the anti-erosion wear performance [1,119,120]. Biological filler-reinforced plastic composites have been the center of many investigations in structural application helping in abrasive wear reduction [121]. Filling polymer composites with biological particles can change their erosion wear behavior and reduce the cost of composites [122,123]. Solid particle erosion experiments of natural fiber polymer composites are reviewed in section.

(1) Rice husk

The erosion wear of rice husk-filled epoxy composites presented in [86], changed due to the kinetic energy absorption. Rout and Satapathy [86] investigated the effects of impact velocity, rice husk content, impingement angle, and particle size on the erosion properties of polymer composites. The experimental results displayed that the erosion rate was lowest when the rice husk content was 15 wt%.

(2) Bagasse fiber

Mishra and Acharya [87] investigated the solid particle erosion behavior of bagasse fiber-reinforced polymer composites. The erosion wear experiments showed that the steady-state erosion rate decreased with increasing fiber content in the composite at the velocity of 109 m/s.

(3) Bamboo Fiber

Bamboo fiber is a traditional building material and a good choice for natural fibers in composite materials. Bamboo fiber is environment friendly, easily available, and has received extensive attention [88–90]. Gupta et al. [88] studied the erosion wear behavior of bamboo fiber-reinforced epoxy composites. According to the erosion test results, the 10 wt%, 20 wt%, 30 wt%, and 40 wt% bamboo fiber-filled epoxy composite had a lower erosion rate. When the impingement angle was less than 70°, the higher was the bamboo fiber content, the lower was the erosion rate of the epoxy composite. Similar results were found in [89] and [90].

(4) Other plant Fiber

According to the mechanical properties and tribological behavior of wood apple shell particle polymer composites, it is reported in [91] that the wood apple particulate composite shows excellent erosion and mechanical properties. Similarly, some composite with plant fibers filled also exhibit good abrasive wear resistance, such as coir fibers [92], sisal fiber [93,94], banana fiber [95], date palm leaf fiber [96], Luffa cylindrica fiber [97], jute fiber [98], maize husk [99], and so on.

Animal tissues filler

(1) Fish scales

Similar to the composite with fiber filler, animal tissue filling composites have also been extensively studied. For the reason of the excellent mechanical properties of fish scale composites, the composites derived from fish scale have been used in protection and wear resistance [100–103]. Satapathy et al. [103] developed a composite by using short flakes of fish scales and embedded them into epoxy matrix composites. A commonly found freshwater fish (*Labeo rohita*) was considered for making the composite. The processing, characterization, and erosion wear characteristics of the

Table 1 The bio-based materials for erosion wear reduction from the representative literature

Classification	Reinforcement	References
Plant fiber	Rice husk	Rout and Satapathy [86]
	Bagasse fiber	Mishra and Acharya [87]
	Bamboo fiber	Gupta et al. [88], Biswas and Satapathy [89], Jena et al. [90]
	Wood apple shell	Ojha et al. [91]
	Coir fiber	Zainudin et al. [92]
	Sisal fiber	Lv et al. [93], Sahu and Gupta [94]
	Banana fiber	Bhatnagar et al. [95]
	Date palm leaf fiber	Mohanty [96]
	Luffa cylindrica fiber	Mohanta and Acharya [97]
	Jute fiber	Alok Kumar et al. [98]
	Maize husk	Verma et al. [99]
Animal tissue	Fish scales	Yang et al. [100], Browning et al. [101], Aradhyula et al. [102], Satapathy et al. [103]
	Eggshell powder	Toro et al. [104], Khan et al. [105], Panchal et al. [106]
	Feather fiber	Verma et al. [107], Jagadeeshgouda et al. [108], Ananda Rao et al. [109]
Mineral	Dolomite	Verma et al. [110]
	Granite powder	Rout and Satapathy [111], Pawar et al. [112], Rout et al. [113]
	Slag	Kalusuraman et al. [114], Purohit and Satapathy [115], Padhi and Satapathy [116], Pani et al. [117]

fish scales-filled composites were described. Turning to the experimental results on erosion wear test and morphology of samples, the adhesion between the short flakes and the epoxy matrix resists the erosion wear. Following the addition of the reinforcement fish scales, a significant decrease in the material loss was recorded. These composites using fish scale exhibit improved erosion wear property and indicated the application potential in erosive environments.

(2) Eggshell powder

Chicken eggshells powder are added as fillers in epoxy composites due to their extensive reinforcement property [104]. For comparative experiments, Khan et al. [105] prepared two composite material plates without and 5 wt% filler and conducted erosion tests and electron microscope observations. The experiment results showed that the filler weight of eggshell powder percentage contributed more to the erosive wear rate of the sample. It was from the surface morphology of the eroded sample that the eggshell powder was packed tightly in the polymer matrix, which reveals the erosion resistance mechanism of the polymer composite. Panchal et al. [106] added the boiled eggshell powder to epoxy composites and showed better anti-erosion property compared to the pure composite.

(3) Feather Fiber

Chicken feather fiber has excellent impact resistance and application value as a modified material in light bodywork, bicycle helmets, and so on [107,108]. Jagadeeshgouda et al. [108] developed the processing and testing of chicken feather fiber and promoted the successful application of chicken feather fiber in composite materials. Verma et al. [107] fused epoxy resin and chicken feather fiber with carbon residuum and fabricated the composite by hand layup technique. According to the mechanical and microstructural testing, the impact strength of the composite (5 wt% chicken feather fiber and 1 wt% carbon residuum) showed a substantial enhancement. Likewise, Ananda Rao et al. [109] studied the behavior of polymer reinforced with short feather fibers obtained from poultry and observed that the erosive wear properties of short fiber-reinforced polymer materials improved significantly.

Mineral

The composites prepared by using mineral and industrial slag as fillers being environmental friendly are less costly and demonstrate good mechanical properties. Several attempts have been made to utilize the mineral and industrial mineral wastes to prepare particle-reinforced polymer composites [110,111,116,124,125]. Table 2 summarizes a part of mineral fiber-reinforced composites in optimal erosion wear reduction. The remaining part of this subsection reviews mineral-filled reinforced composites in detail.

(1) Dolomite

Dolomite is a common sedimentary rock formed mineral [120,126,127] that consists of calcium magnesium carbonate found under several hundred feet thick sedimentary beds [127]. The filled dolomite composites exhibit excellent mechanical properties that are utilized in engineering applications [126]. Grewia optiva-glass fiber-reinforced epoxy composites with dolomite proposed in [110] was evaluated in different proportions to understand the physical properties and effect on erosion wear. The dolomite particles size was held from 80 to 200 mesh sieves. Based on the experimental analysis, with impact velocity, erodent size and impingement angle of 10 m/s, 150 μm, and 30°, the sample with a 10 wt% dolomite content displayed the best erosion wear performance.

(2) Granite

Granite powder is used as a filler in polymer composites to improve their mechanical properties [111–113] in the stone processing industry. Pawar et al. [112] and Rout and Satapathy [111] found that the granite filler content in jute epoxy composites plays a positive role in reducing erosive wear. Moreover, Rout et al. [113] developed a mathematical model based on the principle of energy conservation for the erosion process and verified the superior anti-erosion wear property of granite powder-filled composites.

(3) Slag

In the field of polymer composite research, waste slag has gained considerable interest [114,115]. Kalusuraman et al. [114] reported the erosion wear of waste copper slag-filled jute fiber-reinforced polyester composites. Purohit and Satapathy [115] made erosion-resistant polymer composites using steel industrial wastes slag and sludge particles as the filler. Padhi and Satapathy [116] used micro-scale blast furnace slag as a particulate filler to prepare a composite material that minimizes the erosion wear of solid particles. A model for predicting the erosion performance of composite materials based on artificial neural network was proposed. Pani et al. [117] explored the inclusion of iron-mud as a filler that improves the erosion resistance behavior of epoxy hybrid composites. They found an improvement in erosive wear occurrence due to the enhanced resistance to the formation of crack growth.

Table 2 Mineral fiber-reinforced composites in optimal erosion wear reduction

Matrix	Filler	Erodent size (μm)	Velocity	Impingement angle (°)	Mass fraction (wt%)	References
Epoxy	Dolomite	150	10 m/s	30	10	Verma et al. [110]
Epoxy	Granite	100	57 m/s	60	20	Rout and Satapathy [111]
Polyester	Copper slag	50	86.36 m/s	90	10	Kalusuraman et al. [114]
Epoxy	Steel slag	250	32 m/s	90	20	Purohit and Satapathy [115]
Epoxy	Furnace slag	200	32 m/s	60	20	Padhi and Satapathy [116]
Epoxy	Iron-mud	50	70.43 m/s	80.24	20	Pani et al. [117]

There is no doubt that natural filler-reinforced composites or bio-based composites are currently the focus to replace traditional synthetic fiber products. Although the natural filler-reinforced composites have a significant erosion resistance effect on solid particles, the composite material has certain limitations in the fields of metal and hydraulic systems. Firstly, the combination of matrix and filler reinforcement determines the reduction of erosion wear. Secondly, the erodent particle size plays a significant role in the erosion properties of natural filler-reinforced composites or bio-based composites. When erosion particle size changes in an extensive range, the erosion wear performance will be reduced, which limits the application of bio-based composites. Besides, it is rare to see statistical techniques in analyzing the erosion wear characteristics. Natural filler-reinforced composites are needed to research in view of the scientific understanding. Finally, choosing one from a variety of bio-fillers to meet actual needs is also a challenge in future applications.

Biomimetic materials-inspired function

Nature is the mentor of humanity, and biomimetic materials are usually formed by natural selection and evolution. The excellent characteristics of natural biomimetic materials are mainly determined by the multi-scale, multilayer, and multi-function organizational material and structure, which can provide inspiration for improving erosive wear performance.

(1) Stiffness with toughness

Biological systems are primarily constructed through bottom-up self-assembly processes [128]. Many biological materials achieve excellent properties such as ultra-high toughness through simple carbohydrates, proteins, and minerals.

Spider silks are the most extensively studied biological fibers [129]. It is renowned for its unique combination of high tensile strength and large strain at breaking [130]. Multi-mechanical and functional spider silk enable spiders to complete different tasks depicted in Fig. 6. The dragline silk of the spider with a very high tensile strength and toughness [131] is used as the orb-web frame and radii of the spider. The function of an orb-web is to prevent a rapidly flying insect from flying away. A crucial aspect of this process is the absorption of the kinetic energy of the insect's forward movement. So, the orb-web must absorb the energy of the insects without rebounding, similar to solid particle impact cases. The reasonable balance of stiffness, strength, and extensibility makes spider silk ideal for web construction. Consequently, the spider silks-inspired structure and

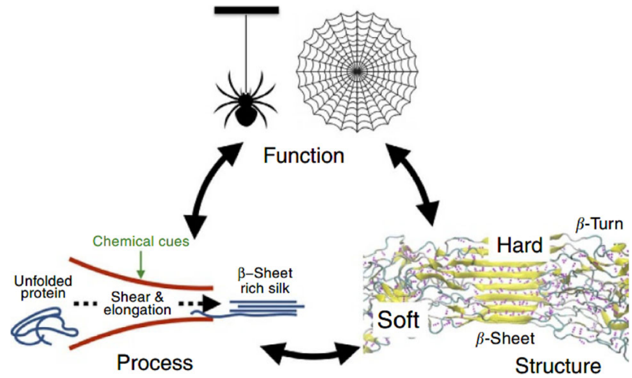

Fig. 6 Multi-mechanical and functional property of spider silks [128]

material can provide a novel approach for anti-erosion wear net structure.

(2) Reproducible

Dentin is similar to bone but has a more uniform structure than the former. Due to the complex environment of the oral cavity, the enamel directly exposed to the oral cavity has abrasion resistance, acid resistance, and mineralization. Only in this way can the teeth maintain their normal physiological functions. Teeth are susceptible to both corrosion and abrasion during chewing. This working environment is similar to the working conditions of pipelines, valves, and other equipment in the energy industry. Therefore, the mechanism of the tooth's corrosion resistance and erosion resistance can become a new direction to study abrasion resistance. The most common wear [51] of dental composite consists of distinct phenomena such as abrasion, adhesion, attrition, and fatigue wear. Dental wear is mainly caused due to the interaction of frictional surfaces. The anti-wear performance of the dental composite is related to the characteristics of the material. An agarose hydrogel biomimetic mineralization system was proposed to regenerating dental hard tissue in vitro [132,133]. The result demonstrated that a potential clinical application could repair the dentin exposed to gum diseases leading to erosion and wear.

Although the erosion wear of natural biomaterials has not been widely discussed, the excellent functions of natural biomaterials (such as energy absorption, wear resistance, material regeneration) might help reducing erosion wear. Following the development of biomimetic materials, it is expected to promote the research on anti-erosion wear.

Challenges and outlook

In preceding sections, we have outlined the biomimetic research in erosion wear resistance. With the continuous deepening of the study on erosion resistance, the importance of biomimetic methods has gradually become prominent, and extensive research results have been obtained. Scientific results verified the application of the biomimetic method to erosion wear. Nevertheless, the research on biomimetic anti-erosion wear is still in the preliminary findings and faces many challenges.

1. Nature-imitation or mimicking refers to more straightforward copying of physical and morphological features of organisms or natural systems in product or process design. However, it does not take or insufficiently takes into account mechanistic features. Imitating nature tends to target a single feature of its natural counterpart by mimicking its characteristics. Although the bio-inspired surface can reduce erosion wear under certain conditions when the solid particle impact conditions are changed (for example, the particle flow direction is either nearly parallel), the erosion resistance is not apparent, and even the surface erosion rate is increased [43]. When the particle impact height angle is not uniform, part of the surface is severely affected by the particle impact, and even an overlapping impact occurs [134]. So far, the influence of texture on erosion reduction based on the bio-inspired surface in solid particle erosion has not yet been discussed. The engraved micro-grooved texture onto the surface can prevent the propagation of cracks to the neighboring areas and promote enhanced coating anti-erosion property [135]. Up to now, the limited publication is available for the erosion wear of bio-inspired non-smooth surface combined with texture.
2. Energy absorption plays a vital role in erosion wear. Researchers have explored the erosion-resistant mechanism of biomimetic energy absorption structures. However, it still faces many challenges. The rebound behavior of particle after impact on the surface of the target material is stochastic, rather than the specula reflection [35]. The deformation direction of the erodent substance is variational, which makes it challenging to optimize energy absorption. Although some literature has analyzed the effect of energy absorption on erosion wear through the Taguchi experiment, the coupling optimization of biomimetic surfaces and flexible structures has not been attracted considerable attention. The rigid and flexible distribution and hardness changes of bionic structures have not been widely studied. The interaction of particles was critical because of the possibility for the particles to hit multiple sides and bottom surfaces in the channel. Spiders produce different types of silk through mechanical reeling processes that are adapted for the numerous conditions [128]. This environment adaptive property inspired the design of intelligent structures. Further studies of the intelligent anti-erosion bio-inspired structure, which dynamically changes the stiffness according to the environment, and adjusts the impingement angle with the erosion direction, are yet to be undertaken.
3. As mentioned above, natural fiber-reinforced composites and their friction properties have been extensively studied [88], but there is a lack of research on their erosion wear properties. Studies carried out worldwide on erosion behavior of composites have been mainly experimental, few published studies have focused on statistical techniques in analyzing wear characteristics [1]. Also, the increase in the reinforcement weight fraction in natural fiber-reinforced composites leads to void formation, which alters the behavior of the composite. This improvement in the erosion wear resistance depends on the type and content of filler. Therefore, the standardized design of natural fiber-reinforced composite materials, the modeling and simulation of their erosion and wear processes, and the optimization of the mass fraction of reinforced fibers require further assessment. It is striking that many of the discussed examples are based on a combination of natural fiber filler with composite, while the biocompatibility may not be included in composite design [136]. Novel nature-inspired composites with excellent properties have not yet fully to be realized.

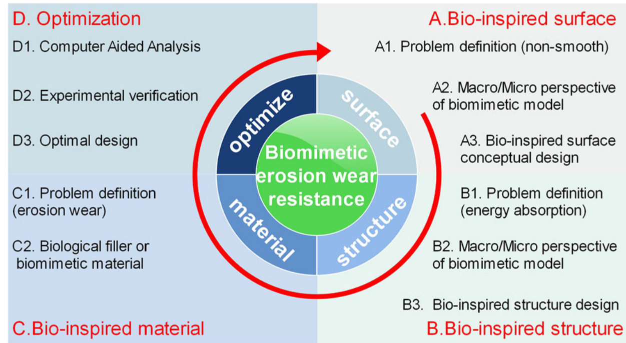

Fig. 7 Multi-biological and perspective coupling biomimetic design flowchart of the erosion wear resistance

Though it is unlikely to borrow solutions directly from living nature and apply them in engineering, it is possible to take biological systems as a source of inspiration for engineering design [137]. The characteristics of creatures in their living environment are formed by combining multiple factors [138]. To improve the erosion wear resistance property and durability of a structure, the biomimetic erosion resistance method should involve bio-inspired surface, structure, and material. Coupling designs further improved the anti-erosion wear performance of the structure and coupled biomimetic design methods are termed tandem processes. For successfully implementing biological principles to engineering, a multi-biological and multi-directional design process divided into four stages, as shown in Fig. 7, is proposed. Firstly, as per engineering requirements, the biological prototype of the bio-inspired surface is selected and the conceptual structure is designed. Secondly, to enhance energy absorption, the biological prototype with energy absorption function is determined and the structure is modified based on the bio-inspired surface. Then, a biomimetic filler composite material or a biological material is proposed to improve the abrasion resistance characteristics. Finally, the optimal design is determined through computer-aided analysis and experimental verification.

In summary, the proposed multi-biological and multi-directional coupled biomimetic design is complicated. The coupling design is a cross-disciplinary problem for researchers. In our previous research [139], we explored real-time communication design methods and managed design tasks, and the authors successfully used collaborative design methods to solve the design problems of water hydraulic valves. Therefore, we believe that the coupling biomimetic design has a foundation for implementation.

Conclusion

Erosive wear can be subdued by adopting biomimetic designs. This extensive review has validated the shortage of numerical and experimental studies outlining erosion mitigation through summarizing the bio-inspired anti-erosion effort giving clear analysis and introducing the multi-biological perspective as well as coupling biomimetic design process to overcome the challenges in correlational research. Future engineering erosion wear reduction is based on intelligent systems and smart erosion management should have roles such as feel, control, and feedback. In other words, the eroded substance optimizes energy absorption and changes surface hardness while maximally exchanging information with the surrounding environment, remaining both meaningful and challenging for active erosion resistance along with the environmental effect of erosion wear. The compiled bio-inspired strategies for erosion reduction will have more significance in future engineering applications.

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Compliance with ethical standards

Conflict of interest The authors declare that there is no conflict of interest.

Ethical approval This study does not contain any studies with human or animal subjects performed by any of the authors.

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