Tribology and Materials
Vol. 2, No. 1, 2023, pp. 38-45

ISSN 2812-9717
https://doi.org/10.46793/tribomat.2023.004

Areas of green tribology: A review

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Keywords
tribology
renewable energy
biomimetics
biomimicry
bionics
environmental design

History
Received: 21-10-2022
Revised: 22-03-2023
Accepted: 25-03-2023

Abstract
This article presents an introduction to green tribology, a new direction in the field's evolution, an exciting new topic for scientific study, and a novel approach to making tribology a friend to the environment and a proponent of energy conservation. Green engineering and green chemistry are two more "green" fields that are thought to be closely related to green tribology. The article has discussions on a variety of green tribology topics, including the concept, views, role and goal, major principles, key areas, challenges, and future development directions. As an interdisciplinary topic combining energy, materials science, green lubrication, and environmental science, green tribology also attracted human interest due to its biomimetic approach. Hence, the use of biomimicry in environmental design is also discussed in this article.

1. Introduction

The term "green tribology" comes from the field of tribology, which is the science of interacting surfaces in motion. Tribology originally aimed to reduce friction, wear, and increase efficiency through strategies that encompass design, lubrication, and material technology [1]. However, as the environmental impact of current tribological approaches became increasingly apparent, researchers recognised that tribology could move beyond its original remit and contribute to reducing environmental harm. In the late 1990s, tribologists began to speak about "tribology for energy conservation" and "environmentally friendly tribology", which eventually evolved into the term "green tribology". The term "green" is used to emphasise the importance of sustainability and environmental protection in tribology, and it is an emerging field that focuses on reducing the environmental impact of tribological processes and systems [2].

The concept of green tribology was initially defined by H.P. Jost as the "science and technology of the tribological aspects of ecological balance and environmental and biological impacts", and Professor Si-wei Zhang from China was attributed to coining the term "green tribology" [3].

Green tribology aims to develop new materials, lubricants, and technologies that reduce the environmental impact of tribological systems. This includes reducing the consumption of non-renewable resources, minimising the production of waste and emissions, and improving the durability and efficiency of tribological systems. The principles of green tribology are being applied in a wide range of fields, including transportation, manufacturing, and energy production. By promoting sustainable and environmentally friendly tribological practices, green tribology is helping to create a more sustainable future [4].

The aim of this review paper is to provide a concise overview of the domains related to green tribology while highlighting the obstacles and prospective avenues for advancement.

2. Objectives of green tribology

Designing and managing the environment such that it cannot be harmed is a component of green tribology. In order to do this, tribology in a living plant, animal, and insect life is used in scientific inquiry and creation. Green tribology is closely related to the study of mimicking nature, often known as biomimicry or biomimetics. Its goal is to research nature's brilliant ideas and then replicate these structures and procedures to address human issues. An example would be researching a leaf to create a better solar cell. Simply said, it is "innovation inspired by nature." One could wonder, "why emulate nature?" The major goal of green tribology is accomplished by everything in nature being completely safe and environmentally friendly.

The specialized field of "green" or "environmentally friendly" tribology highlights the features of interacting surfaces in relative motion that are significant for the sustainability of the environment or the energy supply, or that affect the current environment. The control of friction and wear, which is crucial for energy conservation and conversion, environmental aspects of lubrication and surface modification techniques, and tribological aspects of green applications, such as wind turbines, tidal turbines, or solar panels, are all included in this. Biomimetic surfaces, a type of tribological technology that imitates living nature, is also included. It is obvious that a variety of tribological issues might fall under the purview of "green tribology" and are mutually beneficial [1].

Green chemistry and green engineering are two more "green" fields that may be seen in a larger perspective when discussing green tribology. Green engineering is the design, commercialisation, and use of processes and products that are technically and commercially viable while limiting (i) the creation of pollution at the source and (ii) danger to human health and the environment. The design of chemical products and processes that minimise or completely stop the use or creation of harmful compounds is known as green chemistry, often referred to as sustainable chemistry [5].

Green tribology can utilise the goals of green chemistry. The twelve goals of green tribology are as follows [6]:

- reducing heat and energy loss to a minimum;
- wear is kept to a minimum;
- reduction in lubrication and self-lubrication, or their disappearance entirely;
- making natural lubrication (e.g. vegetable oil-based);
- making a biodegradable lubricant;
- implementing green engineering and sustainable chemistry concepts;
- using biomimetic techniques;
- having more knowledge of surface texturing;
- effects of coatings and other surface modification techniques on the environment (texturing, depositions, etc.);
- designing for surface, coating, and tribological component deterioration;
- real-time observation, evaluation, and management of tribological systems while they are in use;
- assuring uses of sustainable energy.

3. Areas of green tribology

The following three tribology areas are crucial for green tribology since they have a significant influence on environmental issues: tribology of biomimetic materials and surfaces, biodegradable and environmentally friendly lubricants, and renewable and/or sustainable sources of energy [6-9]. The current situation of these places and their importance for the emerging science of green tribology are briefly discussed below.

3.1 Biomimetic and self-lubricating materials/surfaces

Biomimetics, also known as bionics or biomimicry, is the study and creation of engineering systems and contemporary technology using biological techniques and systems found in nature [7]. Many biological materials offer extraordinary qualities that are difficult to create using traditional engineering techniques. For instance, a spider can manufacture enormous quantities of silk fibre, which is stronger than steel, compared to the linear dimension of his body, without having access to the high temperatures and pressures needed to produce materials like steel using normal human technology. Due to their composite structure and hierarchical multi-scale organisation, biomimetic materials can acquire these characteristics [8]. The following concepts have been put forth in the context of biomimetics.

Non-adhesive surfaces based on the lotus effect. Surface roughness-induced superhydrophobicity and self-cleaning are referred to as the "lotus effect". The capacity to have a large water contact angle (greater than 150°) and, at the same time, a low contact angle hysteresis is known as superhydrophobicity. The lotus flower is well-known for its capacity to emerge spotless from the murky water and for its leaves' ability to fend off water. This is caused by the leaf surface's unique structure (multi-scale roughness) in conjunction with hydrophobic coatings. Similar performance has been achieved in the fabrication of these surfaces in the lab (Fig. 1) [10].

Figure 1. Lotus leaf (left), and lab-made surface inspired by a lotus leaf (right)

Gecko effect. The gecko effect stands for the ability of specially structured hierarchical surfaces to exhibit controlled adhesion. Due to a tight bond between their toes and a variety of surfaces, geckos are well-recognised for their capacity to scale vertical walls. When necessary, they may also quickly separate from a surface (Fig. 2). This is caused by the gecko foot surface's intricate hierarchical structure [11].

Figure 2. Gecko foot (left) and artificial gecko foot (right)

Microstructured surfaces for non-reflective (the moth-eye effect) optical applications. The biomimetic approach involves designing and engineering surfaces that mimic the natural structures found in the moth's eyes, such as the fine, nanostructured protrusions on the surface (Fig. 3). These structures can be replicated on a range of materials, including plastics, metals, and glass, to achieve the desired optical properties. By using biomimicry, scientists created highly effective and efficient non-reflective surfaces with minimal use of materials and energy, as the designs are based on nature's solutions [12].

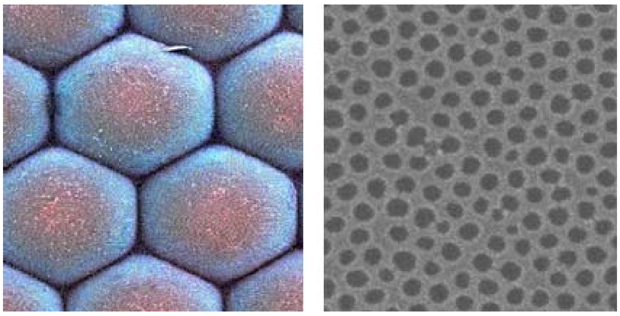

Figure 3. Moth eye (left) and non-reflective microstructured film inspired by moth eye (right)

Water strider effect. The water strider is an aquatic insect that has inspired biomimetic designs due to its ability to walk on water. This effect is known as the water strider effect or water-repellent legs (Fig. 4). The insect's legs are coated with microscopic hairs that allow it to float on the surface of the water without breaking the surface tension. Scientists and engineers have studied this effect to develop water-repellent materials that can be used in various applications, such as self-cleaning surfaces, anti-fouling coatings for ships, and waterproof clothing. The water strider effect has also inspired the development of small robots that can walk on water, which can be used for monitoring water quality or performing environmental surveys [13].

Figure 4. Water strider (left) and robot inspired by water strider (right)

Sandfish lizard effect. The sandfish lizard is known for its unique ability to swim through sand as if it is water. Scientists have studied this lizard to understand the mechanisms that enable it to move through sand so effectively, and this has led to the development of new technologies inspired by the sandfish lizard. One example of biomimicry of the sandfish lizard effect is in the design of robots that can move through sand more efficiently (Fig. 5). By copying the lizard's technique of using its limbs to create wave-like motion in the sand, researchers have created robots that can move through loose sand more quickly and with less energy than traditional designs [14].

Figure 5. Sandfish (left) and lab-made sandfish (right)

Burdock burr and Velcro tape. In 1941, Swiss engineer George de Mestral's dog was coated in burdock burrs during a hunting expedition in the Alps. Mestral examined one under his microscope and found that it had a straightforward pattern of hooks that nimbly connect to socks and fur. He developed Velcro after years of testing (Fig. 6), obtaining a U.S. patent in September 1952. It is likely the most well-known and financially successful use of biomimicry [15].

Figure 6. Burdock bur (left) and Velcro tape (right)

Shinkansen bullet train. The design of the Shinkansen train was inspired by the aerodynamic shape of the Kingfisher beak (Fig. 7). The Kingfisher bird has a long, slender beak that helps it to dive into water without creating a splash, which allows it to catch fish more easily. When the Shinkansen train was first introduced in the 1960s, it faced a major design challenge, i.e. how to travel at high speeds without creating a loud sonic boom. To solve this problem, engineers turned to nature for inspiration and studied the Kingfisher beak in detail. They found that the beak's unique shape allowed the bird to move through water with minimal resistance and noise. By using advanced computer modelling techniques, the engineers were able to replicate the Kingfisher beak shape in the design of the train's nose cone, which greatly reduced the amount of noise and energy required to travel at high speeds [16].

Figure 7. Kingfisher beak (left), adapted from Wikimedia Commons, licensed under CC BY 3.0 and nose of a bullet train (right), adapted from Wikimedia Commons, licensed under CC BY-SA 4.0

Boats inspired by shark skin. The skin of a shark has a unique texture that helps to reduce drag and turbulence in the water, allowing the shark to swim faster and with greater efficiency. This texture has been replicated in the design of boat surfaces, which has led to significant improvements in the performance and fuel efficiency of boats. The texture of shark skin is made up of tiny, diamond-shaped scales called dermal denticles. These scales are covered with ridges and grooves that create a microscopically rough surface. When water flows over the shark skin, the ridges and grooves disrupt the flow of water, reducing turbulence and drag. This allows the shark to move more easily through water, conserving energy and enabling it to swim faster. To replicate this effect, engineers and designers have developed surfaces for boats that mimic the texture of shark skin (Fig. 8). These surfaces have been shown to reduce drag and increase the speed and efficiency of boats. In addition to improving performance, these biomimetic surfaces can also reduce fuel consumption and emissions, making boats more environmentally friendly [17].

Figure 8. Shark skin (left), adapted from Wikimedia Commons, licensed under CC BY-SA 3.0 and boat (right)

Harvesting desert fog. The Namibian desert beetle is another example of how biomimicry can inspire innovative solutions to real-world problems. The beetle can survive in one of the driest environments on Earth by collecting water droplets from the air through its unique shell structure. This mechanism has been replicated in the design of a fog-harvesting device known as the dew bank bottle. The Namibian desert beetle shell has a series of bumps and channels that help to capture water droplets from the air. The bumps create a hydrophilic (water-attracting) surface, while the channels allow water to flow towards the beetle mouth. By collecting water in this way, the beetle can survive in an environment where water is scarce. The dew bank bottle works in a similar way (Fig. 9). It is a simple device that uses the same principles as the Namibian desert beetle to collect water from the air. The device consists of a large plastic bottle with a mesh screen at the top. As air passes through the screen, water droplets are captured on the hydrophilic surface of the mesh and flow down into the bottle. This technology has proven to be effective in areas with low humidity and limited access to clean water [18].

Figure 9. Namibian beetle (left), adapted from Wikimedia Commons, licensed under CC BY-SA 3.0 and dew bank bottle (right)

Fin to the wind. To meet the growing demand for electricity, wind energy, as the most promising renewable energy resource, will play a vital role in the future [19]. The humpback whale fin has inspired the design of a more efficient wind turbine blade. Humpback whales are known for their unique flippers or fins, which have a series of bumps and ridges on the leading edge. These bumps and ridges, called tubercles, are believed to help the whale to manoeuvre more effectively and efficiently in the water. Engineers have replicated the humpback whale's fin design in the design of wind turbine blades (Fig. 10), which has led to significant improvements in the efficiency of wind turbines. The tubercles on the leading edge of the blade help to prevent turbulence and stalling, allowing the blade to generate more power even in low wind conditions. This technology has been shown to improve the efficiency of wind turbines by up to 20 % [20].

Figure 10. Humpback whale fin (left) and developed turbine (right)

3.2 Biodegradable lubrication

Environmentally friendly lubricants are lubricants that are designed to be biodegradable and less harmful to the environment. They are also known as eco-lubricants. Research has been conducted to explore various ways of producing these lubricants using natural resources. One approach involves the creation of a new lubricant using amino acids derived from natural resources. This lubricant does not contain phosphorus and sulphur, which makes it an environmentally friendly option [21]. Another research direction involves investigating the potential of chitin, chitosan, and acylated derivatives as thickening agents for vegetable oils. These natural substances may offer a more sustainable and eco-friendly alternative to synthetic thickening agents [22].

Microbial biofilms have also been studied as potential lubricants. In one study, titanium coated with mixed biofilms of *Candida albicans* and *Streptococcus mutans* was found to have very little friction when sliding across alumina immersed in artificial saliva. This finding is particularly relevant for prosthetic joints and dental implants [23]. Hydration lubrication is a contemporary research topic. According to Gaisinskaya et al. [24], combining the supramolecular advantages of polymer brushes with the highly hydrated state of zwitterionic phosphorylcholine monomers should offer significant benefits in the construction of incredibly effective border lubricants.

Recently, there has been a lot of effort done on developing novel bio-based metalworking fluids based on different vegetable oils. The benefits and drawbacks of using vegetable oils as lubricants are discussed below [25].

Benefits:

- Renewable resource: Vegetable oils are derived from plants, which are renewable resources. This makes vegetable oils a sustainable alternative to petroleum-based lubricants.

- Biodegradable: Vegetable oils are biodegradable, which means they break down naturally over time and do not harm the environment. This makes them a more environmentally friendly option compared to petroleum-based lubricants.
- Cost-effective: Vegetable oils are often less expensive than synthetic lubricants.
- Good lubricity: Vegetable oils have good lubricity, which means they reduce friction between moving parts and can help prolong the life of machinery.

Drawbacks:

- Oxidation: Vegetable oils can oxidise over time, which can lead to the formation of deposits that can clog machinery and reduce efficiency.
- Viscosity: The viscosity of vegetable oils can change with temperature, which can affect their performance as lubricants.
- Corrosion: Some vegetable oils can be corrosive to certain metals, which can lead to damage to machinery and equipment.
- Stability: Vegetable oils have lower stability compared to synthetic lubricants, which means they may break down more quickly and require more frequent replacement.

The elastomeric bearings for maritime propeller shaft systems were the subject of tribological research and case investigations [26].

3.3 Renewable energy

Renewable energy refers to the energy that is generated from renewable resources that can be replenished naturally over a relatively short time [28,37]. The tribology of renewable energy sources is a relatively recent area of tribology [1]. The following problems can be mentioned.

A well-established field of tribological study, wind-power turbines have a variety of unique tribological challenges. These problems include tainted water, electric arcing on generator bearings, problems with the main shaft and gearbox bearings and gears wear, and blade erosion (due to solid particles, cavitation, rain, and hailstones, among other things) [29].

Another significant method of generating renewable energy that has some tribological issues is the use of tidal-power turbines. Although various possible locations in North America have been mentioned, Europe (and notably the UK) continues to be the leader in the development of tidal-power turbines. The tidal-power turbines have several unique tribological problems, including their lubrication (seawater, lubricants, and greases), erosion, corrosion, and biofouling as well as the interactions between these sources of damage.

In addition to tidal energy, river flow energy (without dams) and ocean water flow energy may also be harnessed with the use of specialized turbines, such as the Gorlov helical turbine (Fig. 11), which gives the same rotational direction regardless of the direction of the current flow. Specific tribological problems are also present in these applications [30].

Figure 11. Gorlov helical turbine; reprinted from Wikimedia Commons, licensed under CC BY-SA 3.0

4. Challenges

One of the main challenges of biomimicry is that nature is complex and diverse, and it can be difficult to identify and understand the underlying principles that make certain biological systems work. It requires interdisciplinary collaboration between biologists, engineers, and designers to understand the biological mechanisms and apply them to human-made systems.

Another challenge is that not all biological systems are suitable for replication in human-made systems. Some biological systems are too complex or require environmental conditions that are difficult to replicate in artificial settings. In some cases, the benefits of mimicking a biological system may not justify the costs and resources required to develop and implement it.

Furthermore, intellectual property rights and patent laws can pose a challenge to biomimicry. Some biological systems may be patented by companies or individuals, limiting the ability of others to use them for innovation and development.

Additionally, although the concept of biodegradable lubricants is appealing, their production requires a significant amount of bio-source. Unfortunately, with the current state of technology, it is challenging for humanity to provide for itself. This issue raises concerns about the practice of using human food to feed machines, which is a controversial topic. Furthermore, the demand for lubricants on a daily basis is enormous, which is beyond our current capacity to meet. Despite the appealing notion of renewable energy, it remains in the research and development stage, and its capacity to provide continuous power is not limitless. Fossil fuels still dominate the energy production landscape globally [1,31].

5. Conclusion

The incorporation of green tribology in environmental design is crucial for creating a habitable planet for all living beings. The term "green" refers to the application of nature-based solutions, making green tribology particularly relevant in modern society. Tribology, encompassing wear, adhesion, and lubrication, must continue to evolve while simultaneously embracing sustainability. The success of green tribology would result in a sustainable world, and therefore, researchers are dedicating significant effort to this field. As green tribology gains more prominence, it is expected that the world will see immense progress towards a prosperous and sustainable future.

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