Biomimicry as a Pathway to Sustainable Development - An Overview

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ABSTRACT

Human activities have significantly transformed Earth's ecosystems and biodiversity, with over 75% of ice-free land altered due to habitation and land use. The 2023 planetary boundaries framework update indicates that six out of nine critical boundaries for Earth's health have been breached, highlighting the urgent need to reduce anthropogenic environmental impacts. The United Nations' 17 Sustainable Development Goals, adopted in 2015, aim to protect the environment and promote prosperity through innovations, infrastructure improvements, and sustainable urban development. Biomimicry, a multidisciplinary field drawing inspiration from nature, offers a promising pathway to minimize environmental impacts and advance these goals. This paper provides an overview of biomimicry, highlighting its impact on various sectors including architecture, healthcare, transportation, agriculture, engineering, and technology. By emulating nature's efficient designs and processes, biomimicry fosters sustainable innovations and practices, such as energy-efficient building design inspired by termite mounds, self-repairing concrete modeled after human bones, and healthcare innovations like microneedles and biodegradable surgical glues. To realize its full potential, it is necessary to incorporate biomimicry into educational curricula to bridge the gap between natural systems and classroom learning, foster environmental stewardship, and drive progress toward a more sustainable future.

Keywords: Biomimicry, sustainable development, environmental impact, natural processes, innovative solutions, nature inspired innovations, interdisciplinary approach, eco-friendly technologies, eco-inspired system, energy-efficient designs.

INTRODUCTION

Humans have profoundly transformed Earth's ecosystems and biodiversity to accommodate a rapidly growing population and improve living standards. Over 75% of Earth's ice-free land has been altered due to human habitation and land use during the last millennium (Arneth et al., 2019; Luyssaert et al., 2014), with at least 17% occurring in the past 60 years (Winkler et al., 2021). The 2023 planetary boundaries framework update revealed that all nine boundaries critical to Earth's health have been impacted by human activities, with six of these boundaries breached, indicating that Earth has exceeded its safe capacity limit for humanity (Richardson et al., 2023). Consequently, there is an urgent need to reduce anthropogenic environmental impacts. In 2015, the United Nations adopted the 17 Sustainable Development Goals, which represent a concerted global effort to protect the environment and promote prosperity, encompassing innovations, infrastructure improvements, and sustainable urban development. Biomimicry offers a promising pathway to minimize environmental impacts and advance the Sustainable Development Goals (Ajayi, 2023). A 2013 report by the Germanian Business & Economic Institute estimated that biomimicry could contribute approximately $425 billion to the U.S. GDP by 2030.

Biomimicry is an inherently multidisciplinary field with diverse applications, but its full potential has not yet been achieved (Himel et al., 2023; Mejia-Villa et al., 2023). By drawing inspiration from the natural world to address complex challenges, biomimicry has been applied in various fields of science and engineering (Himel et al., 2023). This paper aims to provide an overview of biomimicry and its applications in different sectors, highlighting its role in sustainable development.

BIOMIMICRY: A PROMISING PATHWAY TO SUSTAINABLE DEVELOPMENT

Drawing inspiration from nature, biomimicry is a transformative approach to innovation. It studies the intricate and energy-efficient designs, structures, forms, processes, and strategies found in the natural world, then seeks to emulate them in solving the complex challenges faced by humans, developing more sustainable products and policies, and creating a more sustainable world. Using an ecological standard to measure innovations, biomimicry replicates nature’s brilliance and creates solutions that are effective and environmentally harmonious (Benyus, 1997).

According to the international standard ISO 18458, the transferring of biological principles to technology development is the essence of biomimicry, which involves leveraging insights gained from the analysis of biological systems to solve problems and drive innovation. Biomimicry, highly interdisciplinary and multidisciplinary, brings close cooperation of experts across fields such as biology, chemistry, physics, engineering, and social science, and fosters a high innovation potential, enabling the creation of cutting-edge solutions and advancements (ISO 18458).

Biomimicry inspires innovative solutions at three levels: organism/form, behavior/process, and ecosystem/system. While the organism/form level models after the physical form or structures of organisms, the behavior/process level emulates how organisms interact with their environment or carry out specific processes, and the ecosystem/system level mimics the entire ecosystems and their complex interactions. Drawing from 3.8 billion years of evolutionary refinement, biomimicry has inspired a wide range of innovations, from Velcro to high-speed bullet trains, driving progress toward more efficient and sustainable technologies across various sectors (Lunawat, 2019). The following sections delve into architecture, healthcare, transportation, agriculture, and engineering & technology, highlighting biomimicry’s contributions to sustainable development.

ARCHITECTURE

The 2023 Global Status Report for Buildings and Construction by the UN Environment Programme found that the buildings and construction sector contributes significantly to global climate change, accounting for about 21% of global greenhouse gas emissions, with buildings responsible for 34% of global energy demand and 37% of energy and process-related CO_2 emissions in 2022. To address these challenges, architectural design has increasingly embraced biomimicry in recent decades, drawing inspiration from natural forms, processes, and ecosystems for more sustainable and energy-efficient designs (Yedekci Arslan, 2014).

One of the notable examples is the Eastgate Centre in Harare, Zimbabwe, designed by architect Mick Pearce who was inspired by the way termite mounds maintain constant temperature and humidity. Using a facade and passive cooling system that mimics natural ventilation, the building self-regulates to maintain a constant temperature year-round, reducing energy consumption by 35% compared to conventional buildings, and cutting construction costs by 10%. Additionally, the Eastgate Center incorporates a wastewater treatment system that mimics the natural ecosystem processes to recycle and treat wastewater, thereby reducing water consumption, cutting operational costs, and benefiting the environment (Pearce, 2016).

The Council House 2 (CH2) in Melbourne, Australia, also designed by Pearce, is another biomimicry marvel in architecture. Powered by wind and solar energy, CH2 incorporates natural ventilation and a dynamic facade that adjusts based on the sunlight condition, mimicking the natural temperature regulation process found in ecosystems. Additionally, its advanced water recycling and treatment system emulates natural water purification processes. This innovative design has achieved significant sustainability results, reducing water usage by 72%, gas consumption by 87%, electricity usage by 83%, and CO_2 emissions by 87%. Furthermore, the building has boosted staff effectiveness by 4.9%, and improved worker productivity by 10.9% (Pearce, 2016).

Another notable example is the Lavasa Hill Station in India. This area faced issues like deforestation, soil erosion, and huge fluctuation of water levels in the lake basin caused by heavy seasonal rains and long droughts. To address these environmental challenges, engineers designed solutions inspired by nature: (1) Buildings were designed to mimic a tree's taproot and circulation system to improve water availability during drought season; (2) Drainage systems were modeled after harvester ant nests, which redirect water using their complex dam structures, to resolve the water overflow issue during monsoon season; and (3) Roof tiles were designed to mimic the "drip-tip" shape of banyan fig tree to solve the water run-off issues, which enhances water flow and self-cleans the surface (AlAli et al., 2023).

Biomimicry has also influenced the development of construction materials. Brent Constantz, who was inspired by how coral builds reefs, developed an innovative and sustainable approach to making concrete. Constantz's method involves capturing CO_2 emissions and dissolving them in seawater to produce concrete, reducing CO_2 emissions from traditional concrete production, and promoting a circular economy by using CO_2 emissions as raw material (Salazar, 2011). In 2009, Henk Jonkers drew inspiration from how human bones heal themselves through mineralization and successfully developed self-healing concrete that can repair its own cracks, thereby significantly enhancing the durability and lifespan of structures. It also reduces the need for additional repair materials, decreases maintenance costs, and lowers environmental impact (Matchar, 2015; Halverson, 2019).

HEALTHCARE

In healthcare, biomimicry has inspired the development of innovative technologies, especially in medical devices and targeted drug delivery systems. For example, inspired by how mosquitoes effortlessly extract blood while causing minimal injury, researchers have developed microneedles (Dixon et al., 2022). These microneedles are often made from biodegradable materials that decompose naturally, reducing medical waste compared to traditional needles and syringes (Luo et al., 2023). They also offer a key advantage in drug delivery: they do not require refrigeration, minimizing the energy needed for cold chain storage and transportation. Moreover, microneedles are less invasive and painful than traditional needles, encouraging better adherence to treatment regimens and reducing the need for additional medical interventions (Van Oorschot et al., 2023). Additionally, microneedles enable targeted delivery of drugs and vaccines, which can enhance their effectiveness and reduce the amount of medication needed, thereby conserving resources (Zuo et al., 2024).

Inspired by the unique shape and pattern of dermal denticles on shark skin, Sharklet Technologies developed the Sharklet micropattern technology. This technology features millions of microscopic features arranged in a distinct diamond pattern, which inhibits bacteria from attaching, colonizing, and forming biofilms through the pattern alone, reducing the need for toxic chemicals or antibiotics and minimizing the environmental impact associated with their production and disposal. Sharklet micropatterned films are ideal for surfaces in healthcare settings, public restrooms, and other areas where bacterial inhibition is desired. The Sharklet Foley catheter uses this micropattern on the exterior of the tube to prevent bacterial colonization and migration on silicone elastomer, which may reduce catheter-associated urinary tract infections. Similarly, the Sharklet endotracheal tube uses this micropattern on the interior of the tube to prevent dangerous buildup of mucus and biofilm on tube surfaces, which may reduce the risk of ventilator-associated pneumonia. By preventing bacterial adhesion and biofilm formation on medical devices, Sharklet technology helps reduce hospital-acquired infections, leading to fewer medical interventions and less waste from disposable medical supplies. Additionally, surfaces treated with Sharklet technology are less prone to microbial degradation, which can extend product lifespan and reduce the need for frequent replacement (Sharklet Technologies, 2007).

The microscopic structures found in butterfly wings, peacock feathers, and beetle shells have inspired the creation of highly sensitive biosensors that detect changes in light, temperature, strain, and physical and chemical conditions. These biosensors can be used to develop non-invasive diagnostic tools that detect biomarkers in bodily fluids, such as sweat or saliva, enabling early disease detection and monitoring, leading to more effective treatments and reduced healthcare costs. By improving patient outcomes and minimizing the need for extensive medical interventions, these innovations contribute to the sustainability of healthcare systems (Kelly, 2021; Bodkhe et al. 2024). Moreover, the way electric fish generate electric fields to sense prey has inspired the development of catheters capable of navigating the intricate blood vessels, thereby reducing the need for contrast dyes during angiography (Kelly, 2021).

The unique nanostructure of gecko's feet has led to the development of surgical glues that are strong and biodegradable. These glues can be used to close surgical wounds, patch internal injuries, and graft and repair tissues (Kelly, 2021). Unlike sutures, staples, and bandages, which are typically made from non-biodegradable materials, these glues naturally break down in the body or the environment, eliminating long-term waste and the need for special disposal methods. Additionally, they are often packaged in minimal, eco-friendly materials, reducing medical waste and the environmental impact of medical procedures. This contributes to less pollution and resource depletion, making medical care more sustainable (Bio-MED Regulated Waste Solutions, 2024; Moshkid, 2024).

TRANSPORTATION

Biomimicry has led to the development of smarter, more efficient, eco-friendly, and sustainable transportation technologies. For example, inspired by the kingfisher's ability to dive into water with minimal splash and transition smoothly from air to water, Japanese engineers redesigned the front of the bullet train to mimic the kingfisher's long, narrow, streamlined beak. This innovation reduced air pressure changes, minimized the sonic boom, decreased noise, and lowered energy consumption by 10-15%, ultimately improving the train's efficiency (EarthSky, 2012). Similarly, the versatile F-16 Fighting Falcon was designed after the sparrow, granting it exceptional agility and maneuverability (Amhil, 2023).

To improve aerodynamics and reduce aircraft drag, Lufthansa Technik and BASF developed AeroSHARK, a functional surface film inspired by the microscopic structure of shark skin. When applied to the aircraft's outer skin, AeroSHARK improves fuel efficiency and reduces CO_2 emissions, helping Lufthansa meet its sustainability goals of achieving a neutral CO_2 balance by 2050 and cutting net CO_2 emissions by 50% by 2030. (Lufthansa Group, 2023). Similarly, Nissan, inspired by the synchronized movements of schools of fish, created anti-collision safety features: Intelligent Brake Assist and Forward Collision Warning. McLaren's designers, also taking inspiration from nature, emulated sailfish's scales on the interior of the ducts that channel air to the engine of its P1 supercar, boosting airflow by 17%, thereby increasing power and efficiency (Ward, 2016).

AGRICULTURE

In agriculture, efficient and sustainable farming practices have been developed by emulating natural ecosystems. Integrated Pest Management (IPM) reduces reliance on chemical pesticides by mimicking the chemical signals used in insect communication to trap pests and disrupt their mating patterns, thereby lowering pest populations (Friuli, 2022). Similarly, No-Till Farming emulates natural processes by avoiding plowing and leaving crop residues on the field to improve soil structure, reduce erosion, increase organic matter, and foster healthier ecosystems (Burleson, 2020).

In 2011, Australian engineer Edward Linacre drew inspiration from the Namibian desert beetle to create Airdrop, a self-powered irrigation system that cools air to condense water, which is then delivered to plant roots (Biomimicry Institute, 2012). Similarly, Japanese scientists developed a robot drone that collects and transfers pollen between flowers, mimicking the bee's cross-pollination process (Klein, 2017).

According to Wikipedia, polyculture – such as the Three Sisters (maize, beans, and squash) of indigenous American agriculture, the rice-fish systems in Asia, and the diverse mixed cropping systems in Nigeria – involves growing multiple crop species together, mimicking the biodiversity of natural ecosystems. This practice reduces vulnerability to pests and diseases, thereby decreasing reliance on chemical pesticides and herbicides. It prevents soil erosion and maintains soil health. It also enhances resilience to environmental changes and boosts productivity (Garrett, 2023).

Another sustainable practice is permaculture. Drawing inspiration from the diversity and resilience of natural ecosystems, Permaculture is a holistic approach that integrates land, resources, people, and the environment through mutually beneficial synergies to create no waste, closed-loop systems similar to those in nature. It is multidisciplinary, encompassing agriculture, water harvesting and hydrology, energy, natural building, forestry, waste management, animal systems, aquaculture, appropriate technology, economics and community development. Permaculture emphasizes working with nature and designing solutions that benefit all forms of life. It can be applied in both rural and urban settings and is particularly relevant for rehabilitating and rethinking settled areas and agricultural lands (The Permaculture Research Institute, 2022).

ENGINEERING & TECHNOLOGY

Biomimicry has led to numerous innovations in engineering and technology. One of the earliest and most notable instances of biomimicry is Velcro, invented by Swiss engineer George de Mestral in 1941. Intrigued by the tiny burrs that clung to his dog's fur during a hunting trip, de Mestral examined the burrs under a microscope. He observed that the loops in the fur allowed the burr's hooks to attach securely. This natural adhesion inspired him to develop a similar gripping mechanism, which he named Velcro (Li, 2017; Micro Photonics, 2016). Since its invention, Velcro has transformed the fastener industry and become a staple in everyday life (Micro Photonics, 2016).

Another remarkable example is the development of artificial spider silk by researchers at Cambridge University. This synthetic silk is strong, stretchy, energy-absorbing, and biodegradable. It can be used to enhance helmets, parachutes, bulletproof vests, and airplane wings. Compared to traditional silk farming, the production of artificial spider silk requires fewer resources, such as water and land, without the need for harsh chemicals or high temperatures, thus generating fewer greenhouse gas emissions and reducing carbon footprint. Additionally, artificial spider silk breaks down naturally without leaving harmful residues, reducing environmental impact. Products made from this material also tend to have a longer lifespan, reducing the need for frequent replacements and thus lowering overall resource consumption (Matchar, 2017; University of Cambridge, 2017).

The adaptive camouflage abilities of animals like cuttlefish inspired the development of dynamic camouflage coatings. These coatings can change color and pattern in response to environmental conditions, reducing the need for multiple layers of paint or coatings, minimizing the use of harmful chemicals and reducing waste. By adapting to their surroundings, dynamic camouflage coatings can also help regulate temperature, reducing the need for heating and cooling, leading to energy savings. Additionally, these coatings protect surfaces from environmental damage, extending product lifespan and decreasing the frequency of replacements or the need for repainting. Ultimately, they help conserve resources and reduce the environmental impact associated with manufacturing and applying traditional coatings (Fu et al., 2024; Crawford et al., 1999, Ask Nature 202).

The Asian Arowana's cycloid scales have inspired scientists to create multifunctional ZnO nanostructures. These nanostructured coatings offer adjustable light refraction and reflection. They can be used in solar energy harvesting, enhancing solar panel efficiency and reducing reliance on non-renewable energy sources. Additionally, the unique surface properties of these nanostructures enable the creation of self-cleaning surfaces, reducing the need for harmful cleaning chemicals. Their damage-tolerant mechanical properties also make them highly durable, extending products lifespan and reducing waste (Sun, 2015).

The seahorse's highly maneuverable tapered tail has inspired scientists to develop robots capable of grasping objects with diverse curvatures. These robots could be used in environmental applications, such as river and ocean cleanup, to efficiently collect floating debris (Zhang, 2022; Lewis, 2022).

In the realm of mobile technologies, such as drones, flying robots, and autonomous vehicles, there is a growing demand for miniaturized, lightweight cameras with a wide field of view (FoV). Inspired by fisheye, researchers at the Center for Nanoparticle Research in Korea have developed a novel miniature camera with comparable optical characteristics: a wide FoV of 120°, minimal optical aberrations, depth of field ranging from 20 cm to infinity, and facile visual accommodation. It has successfully captured high-quality images across wide angular directions and varying distances, opening up new opportunities for next-generation mobile electronics. Unlike traditional wide-angle cameras, which require multiple bulky lenses to correct distortions, the fisheye-inspired miniature camera uses fewer lenses and materials, reducing energy consumption during both manufacturing and operation. Its compact and lightweight design also lowers the overall weight of devices, such as drones and mobile devices, contributing to reduced fuel consumption and improved battery life (Kim, 2020; Ma, 2020; Yirka, 2020).

Inspired by the hydrodynamics of the bumpy structure on humpback whale fins, scientists at Harvard University developed innovative turbine blades that improve efficiency by 20%, reduce noise by over 2 decibels, decrease fatigue loads by 6-8%, extend the lifespan of turbine components by 25% and the overall lifetime of the wind turbine by 3 to 6 years (Hamilton, 2008; Quinn, 2018). John Dabiri at Caltech drew inspiration from the vortex patterns created by fish while swimming and designed vertical axis wind farms with fin-shaped turbines. These wind farms are more space, cost, and energy-efficient, generating 10% more energy per turbine (Hezaveh, 2018).

Lily Impeller, an innovative mixer designed by Jayden D. Harman at PAX Scientific in 1996, was inspired by natural fluid flow geometry and is used in municipal water treatment plants, achieving remarkable efficiency by reducing energy consumption by 80%, noise by 75%, and the need for disinfectants by 85% (Ajayi, 2023). The Eco-Machine at the Omega Center for Sustainable Living is a full-circle wastewater treatment system inspired by natural water purification processes in wetland ecosystems. Powered by solar and geothermal energy, it uses plants, bacteria, microorganisms, gravel, and sand to purify water without relying on chemicals, thereby enhancing biodiversity and promoting sustainability (Tackett, 2018).

CONCLUSION

Human activities have significantly altered Earth's ecosystems and biodiversity, breaching six of the nine critical planetary boundaries. This degradation of the environment urgently calls for sustainable development and a reduction in human impact. After billions of years of evolution, nature holds the key to reducing anthropogenic impacts on the environment. Drawing inspiration from nature's time-tested solutions, biomimicry offers a promising pathway for creating innovative, sustainable, efficient, and resilient solutions to complex challenges faced by humans.

Being inherently interdisciplinary and multidisciplinary, biomimicry fosters close collaboration among diverse disciplines and promotes holistic problem-solving. Although it has inspired numerous innovations, biomimicry remains a relatively new and under-explored field. To unleash its full potential, it is crucial to integrate biomimicry into educational curricula. This integration will ignite students' curiosity, bridge the gap between classroom learning and the natural world, enhance critical thinking skills, and cultivate a mindset dedicated to environmental stewardship and sustainable development.

By emulating nature's brilliance, we can create a more sustainable and harmonious world, achieve the Sustainable Development Goals, and ensure a healthier planet for future generations.

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