Biomimetic
Manufacturing and Healthcare:

Sustainable Pattern, Algorithm, and Assembly

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Abstract

Nature, a master of efficiency and sustainability, has honed her designs through billions of years of evolution. Biomimetic manufacturing and healthcare, inspired by these elegant solutions, offer a promising path towards a more efficient and sustainable future. This paper explores the application of nature's patterns, algorithms, and assembly strategies in both manufacturing and healthcare, highlighting their potential to revolutionize these fields. This review focuses on the new applications of nature inspired innovations in manufacturing and healthcare. For the Manufacturing Industries, we focus on (1) Pattern, (2) Self Healing, (3) Additive Manufacturing, as well as (4) Energy and Environment. Our focuses of Biomimetics' healthcare applications are (1) Membrane (2) Peptide Assembly, (3) Synthesis, and (4) Surfaces and Adhesion. Related topics in biomimetics-based computing and other applications will be discussed in an effort to provide a more complete perspective of biomimetics across the spectrum of different areas that are key to our life and society.

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Hummingbird inspires Drones. (A Public Domain Image from Pixabay)

1. Overview

The 21st century faces unprecedented challenges in both manufacturing and healthcare. Our current practices, driven by a linear "take-make-dispose" model and resource-intensive processes, are pushing the limits of our planet's resources and contributing to environmental degradation, pollution, and climate change. Increasing healthcare costs are placing pressure on individuals and governments, straining healthcare systems and limiting access to essential care. Growing populations and increasing life spans are placing unprecedented demands on healthcare systems, creating a need for innovative and sustainable solutions. The need for a paradigm shift is evident. We must move beyond unsustainable practices and embrace innovative approaches that prioritize resource efficiency, waste reduction, and environmental responsibility.[1]

This is where biomimetics emerges as a promising solution. By harnessing the wisdom of nature, a master of efficiency and sustainability, we can develop new technologies and processes that are not just effective but also environmentally friendly and resource-saving. By mimicking nature's patterns, algorithms, and assembly strategies, we can create a more sustainable future for both manufacturing and healthcare. Nature has spent billions of years honing its designs through evolution, resulting in a vast array of ingenious, efficient, and sustainable solutions. From the intricate architecture of a spider web to the self-cleaning surface of a lotus leaf, nature offers a blueprint for innovation that we can learn from and adapt. Nature's vast diversity offers a constant source of inspiration for new ideas and technologies. Biomimetics can help us break away from conventional thinking and develop novel solutions that were previously unimaginable.[1-3] **Figure 1** listed a number of examples that inspire current and future biomimetic technologies.[1-3] Spider silk, especially the dragline, is among the toughest materials known to mankind. The eyes of dragonfly provide paradigms for futuristic detectors. Whale fins and owl wings can help us design and improve drones, flying robots, and airplanes. Gecko foot and lotus leaf serve as models for wet adhesives and self-cleaning surfaces. Butterfly wings utilizes optics principles instead of or in addition to dye. Kingfisher inspired bullet trains, and the Velcro design originated from the plant Burdock.

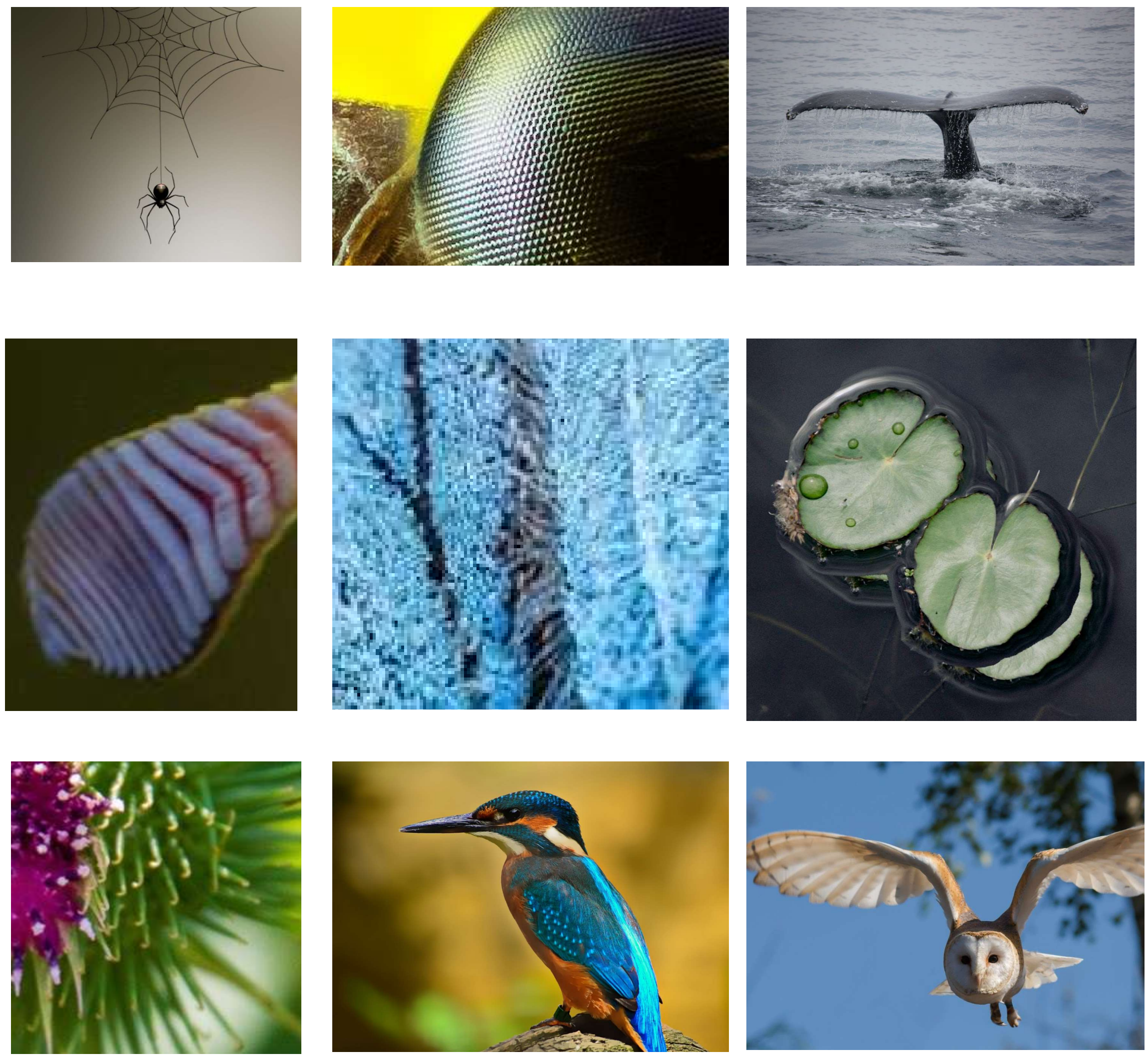


Figure 1. Inspirations for Biomimetic technologies. **Top Row**: Spider silk dragline, Dragonfly eye, Whale Fin. **Middle Row**: Gecko Foot, Butterfly, Lotus leaf. **Bottom Row**: Burdock with hooks, Kingfishers, Owl (Public domain pictures from Pixabay related to biomimetics.)

By embracing biomimetics, we can move beyond the limitations of our current practices and tap into a wellspring of sustainable solutions. (**Figure 2**) More and more researchers are joining the effort.[1-3] For example, in the field of space applications, the biomimetics-related publications are skyrocketing, as shown in **Figure 3**. By learning from nature's wisdom, we can create a future where manufacturing and healthcare are not just effective but also environmentally friendly, resource-saving, and beneficial for all living things. This potential for innovation and a sustainable future drives our exploration of biomimetic solutions in the following sections. For the Manufacturing Industries, we focus on (1) Pattern, (2) Self Healing, (3) Additive Manufacturing, as well as (4) Energy and Environment. Our focuses of Biomimetics' healthcare applications are (1) Membrane (2) Peptide Assembly, (3) Synthesis, and (4) Surfaces and Adhesion. Related topics in biomimetics-based computing and other applications will be discussed in an effort to provide a more complete perspective of biomimetics across the spectrum of different areas that are key to our life and society.

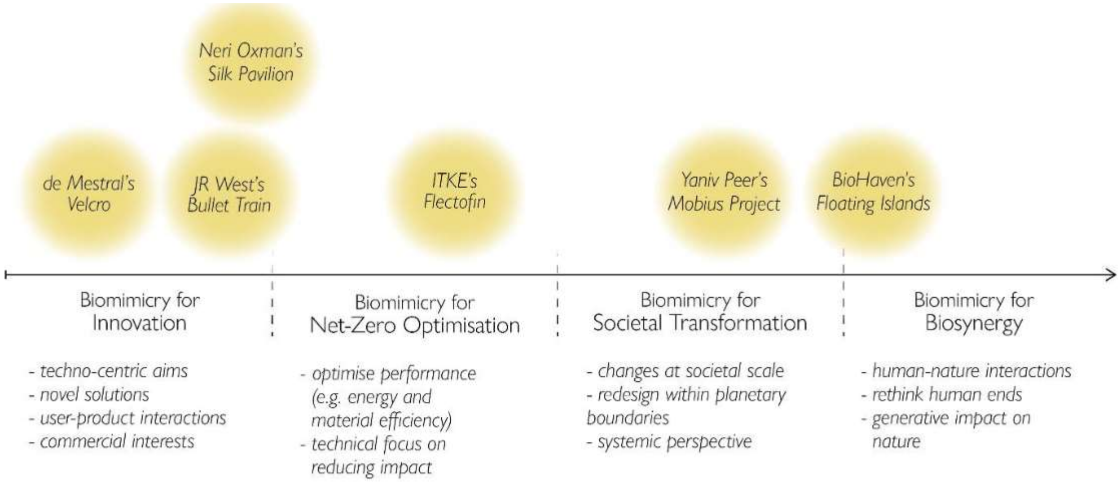


Figure 2. First dimension (x-axis) of the Biomimicry for Sustainability framework, with general criteria for each category. The varying placement of the examples in the vertical direction is arbitrary, for visual purposes only. (Figure and Caption from reference [2], without change, under CC-BY License.[4])

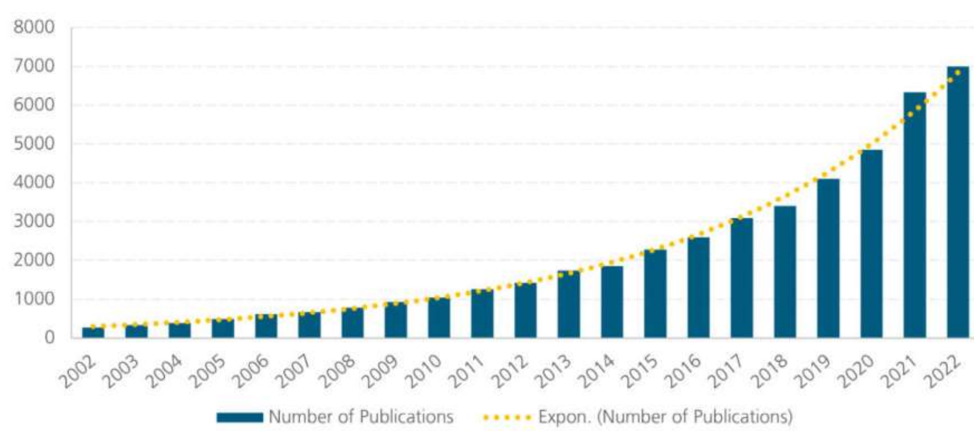


Figure 3. Graph indicating the exponential increase in the number of publications published related to the topic of biomimetics for aerospace applications. Keyword search was conducted using the ScienceDirect database with the following key words: (biomimetics OR bionics OR bio-inspired OR bioinspired) AND (aerospace OR space), from 2002 to 2022 (State 10.10.2022). Note that the number of publications in 2022 can be anticipated to increase slightly until the end of the year. (Figure and Caption from reference [3], without change, under CC-BY License.[4])

2. Manufacturing

2.1 Nature Pattern

Nature, in its boundless creativity, paints a canvas of structures with remarkable properties. From the delicate yet potent spider web to the sturdy honeycomb, natural patterns embody a symphony of strength, efficiency, and adaptability.[1-3,5] This inherent brilliance is beckoning the world of manufacturing to break free from the constraints of traditional design and embrace nature's blueprints. For example, the humble honeycomb, a hexagonal masterpiece crafted by bees, offers a potent lesson in structural efficiency.[1-3,5] By distributing stress evenly across its interconnected hexagons, it maximizes strength while minimizing material usage. This principle is inspiring the development of lightweight, yet incredibly strong panels for aircraft and vehicles. As another example, trees, with their intricate networks of branches, are nature's masters of surface area maximization.[1-3,5] Their fractal branching patterns spread out like delicate fingers, capturing sunlight and nutrients with remarkable efficiency. This design logic is finding its way into heat exchangers and solar panels that maximize heat transfer or light absorption, leading to more efficient systems. **Table 1** highlights some fascinating nature patterns.[5]

Table 1. Nature patterns, inspired and adapted from reference [5]

Patterns	**Examples**
Spiral	Nautilus
Stripes	Zebra skin, Royal Angelfish
Dots	Leopard skin
Cracks	Palm Trunk
Fractal	Tree
Tiling	Honeycomb
Bubbles	Living cells, soap foam
Waves	Dune
Symmetry	Crystals, Ice, Starfish
Chaos	Tornado Vortex, Meanders, Turbulent Flow

2.2 Self-Healing

Self-healing materials can be used for both manufacturing and healthcare. Within the domain of manufacturing, self-healing materials hold immense promise for enhancing product lifespan and minimizing environmental impact.[6-9]

The integration of microcapsules containing healing agents within composites allows for autonomous crack repair, extending the operational life of critical infrastructure like wind turbine blades, concretes, and pipelines.[6] This not only reduces maintenance costs but also minimizes the need for constant replacements, mitigating waste generation and promoting a circular economy. Intrinsic Self-Healing Polymers (SHP) may work alone or be combined with extrinsic mechanisms to benefit a wide range of applications from coating, sensors, electronics, wound treatment, targeted drug delivery for diseases, to automobiles, and aerospace.[7]

2.3 Biomimetic 3D printing

Mimicking the hierarchical structures of bone, the intricate vascular networks of leaves, or the adaptive camouflage of butterfly wings, biomimetic printing allows us to engineer materials with unprecedented biocompatibility and functionality (**Figure 4**).[11-15] Instead of conventional plastic filaments, biomimetic printing may rely on specially formulated "bioinks." These concoctions combine living cells, such as stem cells or tissue-specific cells, with biocompatible polymers, hydrogels, or other supportive materials.[15] This cell-laden ink serves as the building block, meticulously deposited layer by layer to create intricate 3D structures. The applications of biomimetic printing are as diverse as life itself. Researchers are constructing functional skin grafts, mimicking the multi-layered structure of our natural barrier. Blood vessel networks vital for tissue survival are being printed, paving the way for organ transplantation advancements. Bioprinted bone scaffolds with intricate internal architecture hold promise for treating fractures and promoting bone regeneration.[15]

Bioprinted robotic limbs with embedded sensors and artificial muscles mimic the dexterity and adaptability of their natural counterparts. Researchers are even exploring the creation of miniature bioprinted drones inspired by insects, with applications in environmental monitoring and search and rescue missions. Despite its immense potential, several hurdles remain before biomimetic printing reaches its full potential. Ensuring the long-term viability and functionality of printed tissues and organs is a significant challenge. Additionally, scaling up the printing process while maintaining cell viability and precision is an ongoing research pursuit.

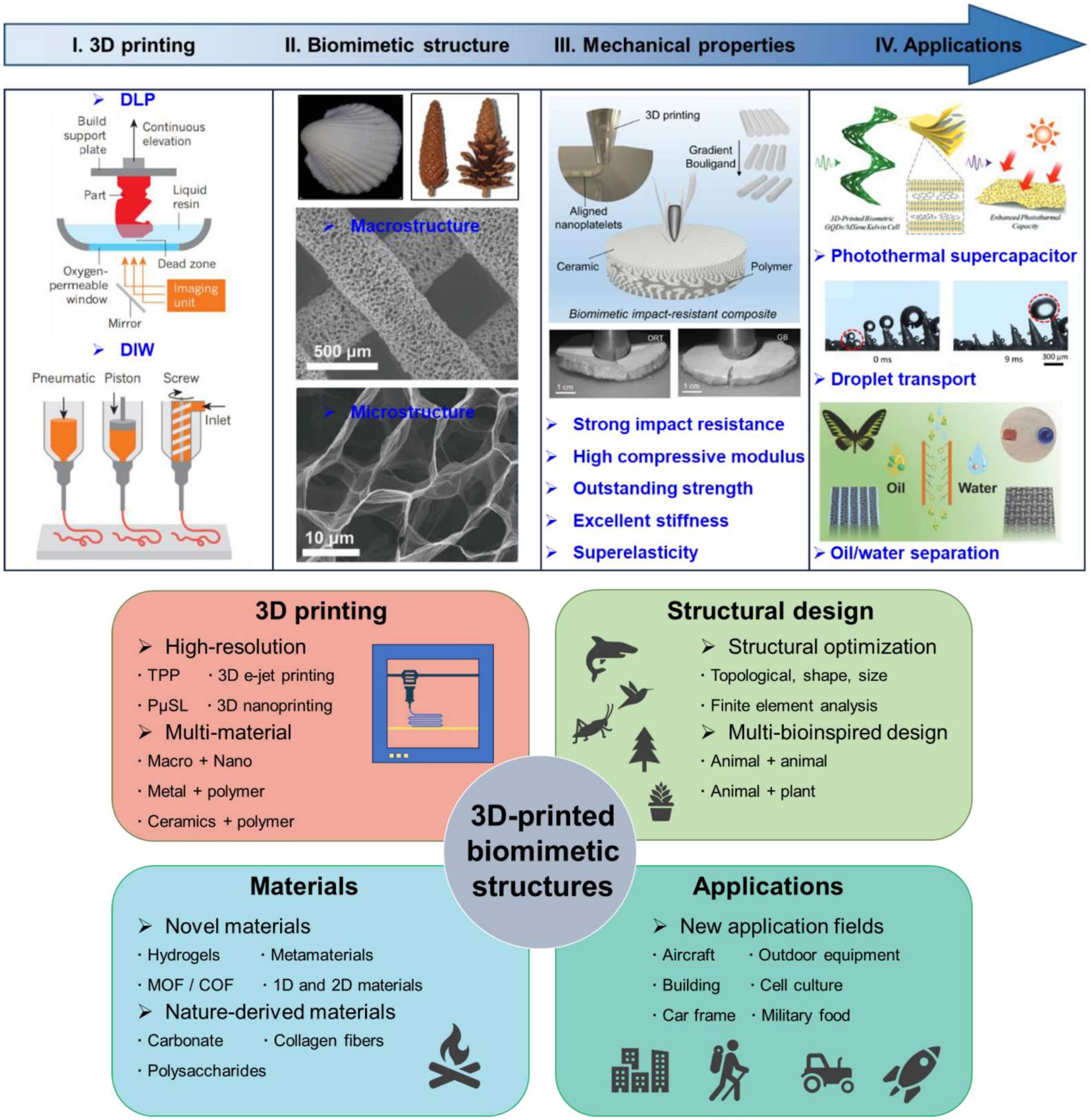


Figure 4. Top: Overview of this article regarding the perspective of 3D-printed biomimetic structures for energy and environmental applications. **Bottom**: Remaining challenges and further development directions for biomimetic 3D printing. (Figure and Caption from reference [11] without change, under CC-BY License[4].)

2.4 Energy and Environment

In the wake of global warming connected to human activities and the race to capture carbon dioxide, it is important to note that ecosystems operate in closed loops, where organisms decompose and recycle waste back into valuable nutritions or life-supporting resources.[16-21] Biomimicry draws inspiration from these principles, guiding us towards circularity in material design, production, and consumption.

Carbon capture, the act of snatching CO_2 from the atmosphere or emission sources before it warms the planet, has emerged as a critical weapon in the battle against climate change. Its diverse arsenal comprises several tactics, each tackling CO_2 at different stages. **a)**. Direct Air Capture (DAC) is offering a way to directly address the existing stock of atmospheric CO_2 . **b)**. Flue Gas Capture (FGC) prevents it from entering the atmosphere in the first place. **c)**. Bio-Energy with Carbon Capture and Storage (BECCS) is growing specialized plants to absorb CO_2 . Once captured, the CO_2 may be stored in reservoirs, or embark on a second life through mineralization, storage, and utilization as described in the following.[16-22] (**1**) Mineralization: Transforming CO_2 into stable carbonate minerals, mimicking nature's rock formation processes, offers permanent storage while potentially creating useful building materials (**Figure 5**). This process involves reacting it with alkaline minerals like calcium or magnesium, transforming it into stable carbonate minerals like limestone. These mineralized forms of CO_2 are essentially locked away, safely tucked away underground or incorporated into building materials, preventing them from re-entering the atmosphere. (**2**) Geological Storage: Deep underground formations, like depleted oil and gas reservoirs, offer vast potential for long-term CO_2 storage. (**3**) Utilization: Captured CO_2 can be repurposed into various products, such as synthetic fuels, plastics, or even fertilizers, adding value to the capture process. How to capture and sequester CO_2 efficiently and cost effectively at a large scale remains challenging.

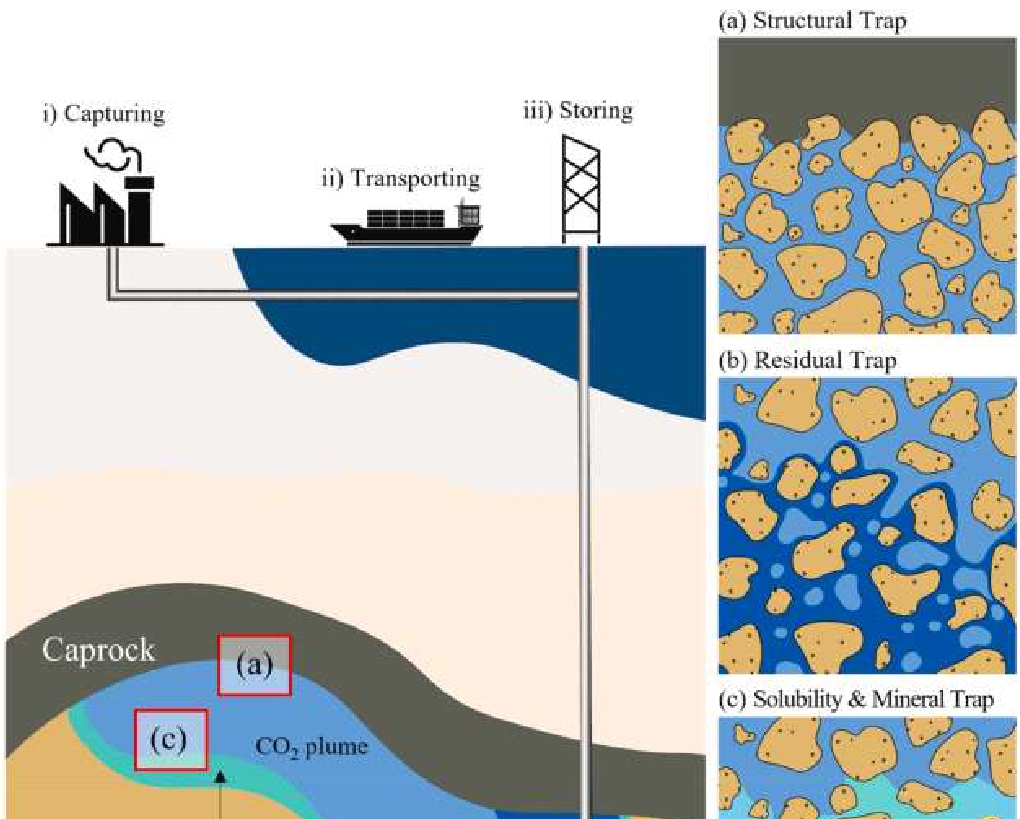


Figure 5. CCS procedure and CO_2 trap mechanism. (a) Structural trap, (b) Residual trap, (c) Solubility & Mineral trap. (Figure and Caption from reference [22] without change, under CC-BY License[4].) CCS refers to Carbon Capture and Storage.

Nature excels at turning waste into resources, which sets an ultimate model for **upcycling** of modern wastes including plastics derived from petroleum refinery.[23-27] Microbes decompose fallen leaves, insects like dung beetles recycle animal waste, and coral reefs build their intricate structures from calcium carbonate extracted from seawater. Biomimicry draws inspiration from these natural processes, guiding us towards upcycling waste plastic into valuable new materials and resources.[23-27] A number of approaches can contribute to the process. (1) Researchers are mimicking enzymes, creating engineered counterparts or even harnessing naturally occurring ones to deconstruct waste plastic into its molecular building blocks. (2) Some bacteria possess the remarkable ability to degrade and even "eat" plastic. Biomimicry can inspire us to cultivate and utilize these "plastic-munching" microbes to biodegrade plastic waste in controlled environments. (3) Biomimetic upcycling can incorporate self-healing mechanisms into recycled plastics, extending their lifespan and minimizing the need for constant replacements. (4) Plastic waste may also be converted into fuels like ethanol or even biodiesel, mimicking nature's energy-storing processes. (5) Waste plastic can be transformed into durable building materials like bricks or insulation panels, reducing construction's reliance on virgin materials.

Biodegradable polymers come with two main categories: naturally occurring polymers, and synthetically produced counterparts.[28-32] Examples of the former include polysaccharides like cellulose (found in plants) and proteins like collagen (found in animals). These naturally biodegradable materials have been used for centuries, from biodegradable packaging made from wood pulp, dissolving sutures made from silk protein, to bone scaffolds that promote natural tissue regeneration. The realm of synthetic biodegradable polymers is equally exciting.

Degradable polymers were synthesized from renewable resources like cornstarch and bacteria, mimicking the breakdown mechanisms found in nature. These bioplastics offer a diverse range of properties, from water-resistant packaging to sturdy bioresorbable medical implants, and microbes, such as bacteria and fungi, recognize the unique chemical bonds within these materials and can break them down readily into harmless byproducts like water, carbon dioxide, and compost. **Table 2** highlights some important biopolymers and their functions.[28-32]

Table 2. Biodegradable polymers to inspire.[28-32]

Biopolymer Assemblies	Function(s)
Enzymes	Degrading and feeding microbes or other organisms
Poly(peptides)	Structurel, catalysis, and immune activity
Poly(nucleic acids)	Information storage, transmission
Poly(saccharides)	Energy storage with structural role, Cellular communication
Mangrove Roots	Desalination
Kidney	Bio-filtering
Cell stacks of electrical eels	Energy Storage
Muscle	Actuator
Eye	Visual Sensor
Brain	Memory, Perception, Decision, Consciousness

Furthermore, nature is a veritable cornucopia of energy sources we often overlook. From sunlight to wind, movement to heat, biomimicry offers a range of **energy harvest** blueprints to tap into these underutilized resources:[33-39] (1) Inspired by the graceful sway of palm trees, researchers have developed flexible energy harvesters mimicking their movements. Imagine wind farms with flapping "leaves" generating electricity, harnessing even the gentlest breezes. (2)Waves crash with immense power, a potential energy source waiting to be unleashed. Biomimetic devices inspired by fish fins and jellyfish bells extract this energy, powering coastal communities or even underwater sensors. (3) Imagine tiny sensors on birds' wings, harvesting energy from their graceful flight. This technology translates to drones or wind turbines mimicking bird wings, generating power from natural air currents.

Additionally, from the towering redwoods storing solar energy in their cellulose fibers to the humble dandelion dispersing its seeds on a puff of wind, nature is a master of **energy storage**. Biomimicry unlocks these secrets, guiding us towards innovative storage solutions based on natural principles:[40-49] (1) Imagine batteries inspired by electric eels, storing vast amounts of energy in sleek, compact bodies. Researchers are studying eel muscle structures and electrical properties to design next-generation batteries with higher capacities and faster charging times. (2) Look at the humble cactus, storing water in its spongy tissues to survive arid conditions. Biomimetic supercapacitors mimic this design, using porous materials inspired by nature to achieve rapid energy storage and release, perfect for high-demand applications like electric vehicles. (3) Red tide algae store energy in the form of sugar molecules. Now, bio-inspired flow batteries are being developed, using similar sugar solutions to store large amounts of energy for long periods, paving the way for grid-scale storage solutions.

3. Healthcare

3.1 Biomimetic Membrane

Biomimetic membranes are a type of membrane inspired by nature's own membranes, such as those found in plants and animals.[1, 50] They are designed to mimic the specific properties and functions of these natural membranes, offering a range of potential benefits for various applications. **Figure 6** and **7** show the layered structures of amniotic membranes and their potential inspiration for biomimetic applications.[50]

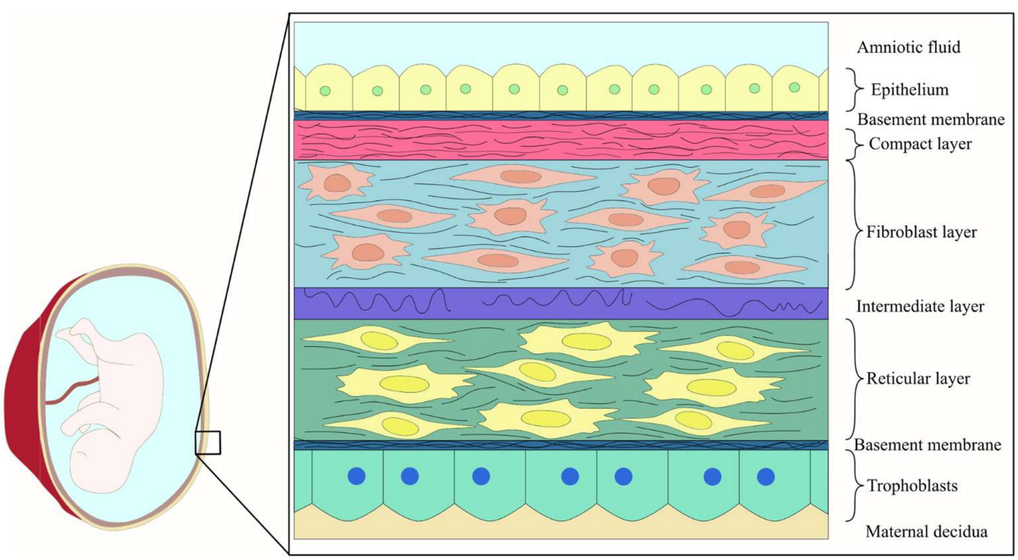


Figure 6. Schematic representation of fetal membrane structure. (Figure and Caption from reference [50] without change, under CC-BY License [4].)

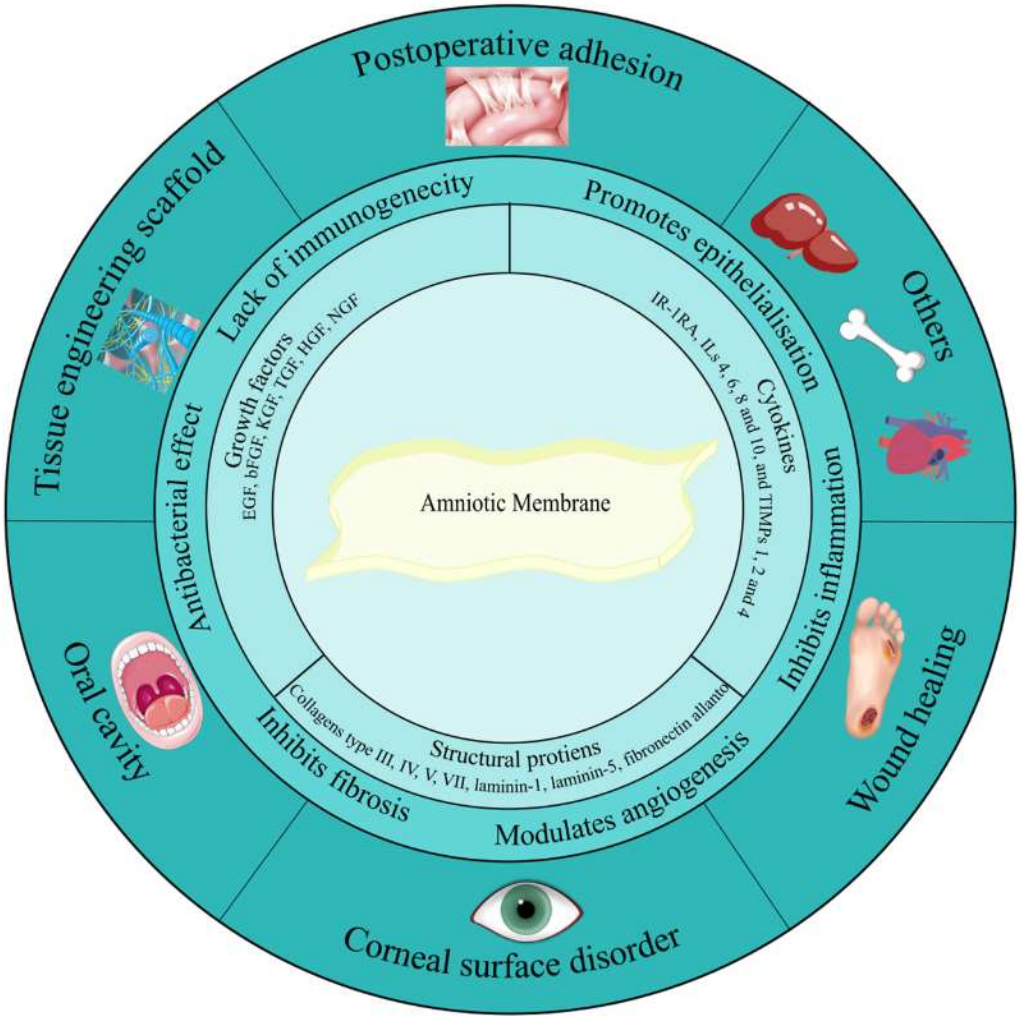
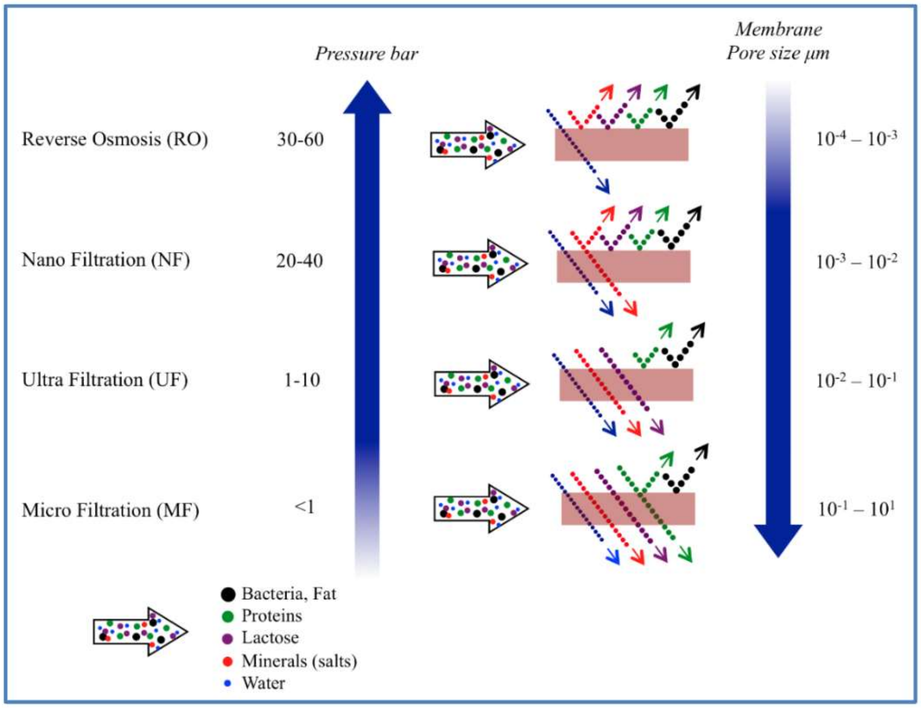


Figure 7. Amniotic membrane components, characteristics, and applications. Amniotic membrane is rich in growth factors, cytokines, and structural proteins. These biological factors have given AM its unique features such as antibacterial effect, anti-inflammatory activity, anti-scarring, and anti-fibrosis potential. Due to these suitable features, nowadays AM is widely utilized as a therapeutic option in the treatment of various diseases related to the urinary tract, oral cavity, skin, stomach, larynx, head and neck, ocular surface, pelvic, and abdominal surgery. Additionally, it has been used as a natural scaffold in TE. (Figure and Caption from reference [50] without change, under CC-BY License.[4])

Some key characteristics for biomimetic membranes include the following.[1, 50] **1**). High selectivity and permeability: They can selectively allow certain molecules or ions to pass through while blocking others, making them ideal for filtration and separation processes. For example, biomimetic membranes can be used to purify water by removing salt and other contaminants. **2**). Self-assembly and repair: Some biomimetic membranes are designed to self-assemble into complex structures, mimicking the way natural membranes form. They can also self-repair to some extent, which can extend their lifespan and reduce maintenance costs. **3**). Biocompatibility and sustainability: Biomimetic membranes are often made from natural or biodegradable materials, making them compatible with living organisms and minimizing their environmental impact.

These features make biomimetic membranes a promising technology for a variety of applications,[1, 50] such as the following. **1**). Water purification: Biomimetic membranes can be used to filter out contaminants from water, providing clean drinking water for people in areas with limited access to safe water. **2**). Drug delivery: Biomimetic membranes can be used to encapsulate drugs and deliver them to specific targets in the body, improving the effectiveness of treatment while reducing side effects. **3**). Tissue engineering: Biomimetic membranes can be used to create scaffolds for growing new tissues, which has potential applications in regenerative medicine and organ transplantation. **4**). Sensors and biosensors: Biomimetic membranes can be used to create sensitive sensors that can detect specific molecules or ions, making them useful for environmental monitoring, medical diagnostics, and other applications.

For water filtration membranes, Aquaporin-inspired membranes incorporate natural or synthetic counterparts of aquaporins,[51-52] which are natural water channels found in cell membranes. They can efficiently filter water while rejecting salt and other impurities. Bioinspired membranes for desalination can mimic the structure of mangrove roots or fish gills to a certain degree, which allow them to extract fresh water from seawater.[51-52] They have the potential to make desalination more efficient and energy-saving. (**Figure 8**)



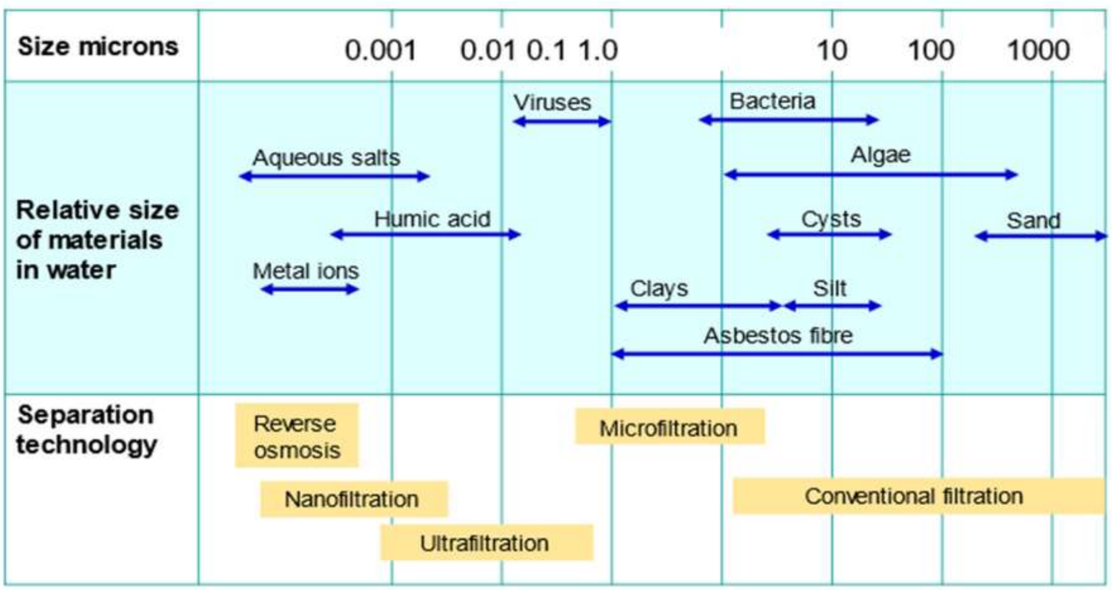


Figure 8. Top: All pressure-driven membrane techniques (Figure and Caption from reference[51] without change, under CC-BY License.[4]) **Bottom**: Membrane processes and application. (Figure and Caption from reference[52] without change, under CC-BY License[4].)

3.2 Biomineralization and Peptide Assembly

Biomineralization and biomimetic mineralization involve self-assembly of biomolecules and inorganic minerals, which can result into 0 to 3 dimensional structures such as nanoparticles, nanoclusters, nanofibers, nanotubes, nematic films, nanoarrays, gels, helical superstructures, and chiral superstructures.[53] These biomimetic assemblies can have tremendous impacts on chiral optics, biomedicine, sensors, and catalysis, in applications ranging from solar cells, electronics and composite materials, filtration and wound healing, to drug delivery and tissue engineering. [53]

As an extraordinary example of biomineralization, nacre, the inner layer of many mollusk shells, is a remarkable natural composite made up of 5%vol. organic and 95%vol. inorganic material.[54] It's lightweight, yet incredibly strong, with an estimated toughness 3 orders of magnitude higher than regular aragonite. This impressive blend of properties comes from its protein-guided mineralization and polycrystalline microstructure: a brick-and-mortar arrangement of tiny calcium carbonate platelets held together by an organic glue.

As another extraordinary example of biomineralization, bone is the main structural unit in vertebrates, and collagen mineralization towards bone growth is of intense interest in treating orthopedic diseases, bone grafts, and fighting cancers.[55] In natural bones, mineralized collagen usually contains a majority of (95%) calcium phosphate (hydroxyapatite, or HAP) with magnesium ions, carbonate, chloride, fluoride, citrate etc, with seven levels of hierarchical structures and HAP platelets' c-axes [0 0 1] aligned parallel to the (type 1) collagen fibril.[55] HAP mineralized collagen serve as the building blocks of natural bone and dentin, which may include intrafibrillar and extrafibrillar mineralization.[56] Involved biomineralization theories include size exclusion, capillary effects, electrostatic interaction, Gibbs-Donnan equilibrium, protein induced liquid precursor, as well as interfacial crystallization.[56] To efficiently achieve the desired outstanding toughness and anisotropy of natural bones remains challenging. [57]

Sometimes connected to biomineralization, peptide assembly is a fascinating phenomenon where short chains of amino acids, called peptides, spontaneously organize into defined structures with unique properties.[58-59] This self-assembly process, driven by intermolecular interactions between the peptides, opens exciting possibilities for creating innovative materials and tools with applications in various fields. Peptide self-assembly can be used in a range of end applications such as catalytic peptides, metallo-nanozyme, photosensitive enzyme, drug delivery, immunotherapy, photodynamic therapy, antibacterial and hemostasis, wound healing, cell culture scaffold, semiconductor, as well as piezoelectrics. The assembled structures can be in the form of hydrogel, nanofiber, nanosheet, nanosphere, nanobelt, nanorod, nanotube,and vesicle.[58] Peptides assemblies can target 3D scaffolds, functional fibrils, biomineralization and hybrid materials, membrane stabilization, liquid-liquid phase separation (LLPS), as well as membrane disruption and drug delivery.[59]

Driving forces[60] of peptide assembly may involve intrinsic and external factors.(**Figure9**) External conditions include pH values, temperature, and solvents. Intrinsic factors may include the following: 1). Hydrophobic interactions: Amino acids with hydrophobic side chains cluster together to minimize contact with water, driving peptide chains to assemble into specific configurations. 2). Hydrogen bonding: The formation of hydrogen bonds between peptide backbones and specific side chains contributes to structural stability and organization. 3).

Electrostatic interactions: Charged amino acid side chains attract or repel each other, influencing the assembly pattern and overall charge of the resulting structure. 4). π-π stacking: Aromatic side chains can stack to form planar or 3D assemblies, further stabilizing the assembled structure.

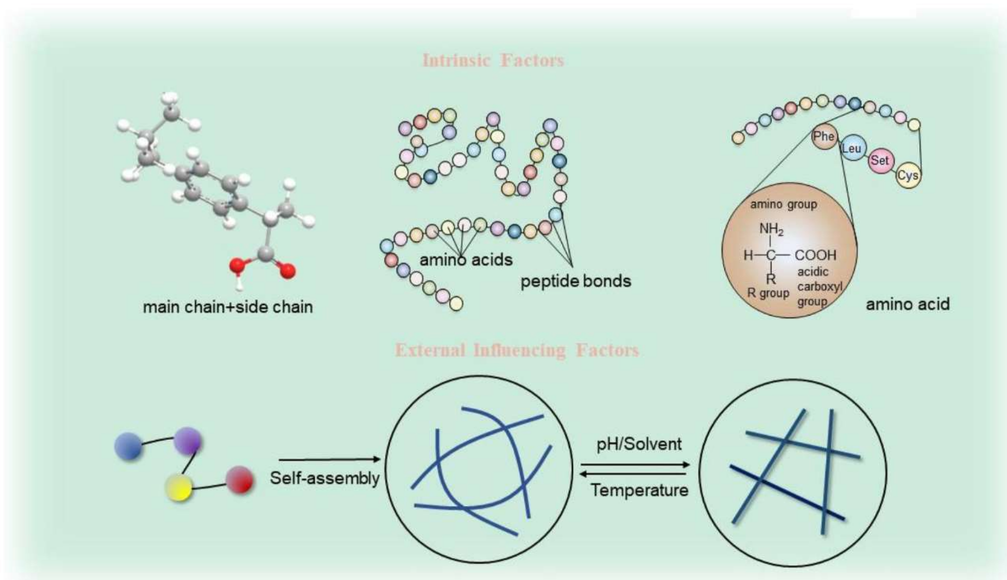


Fig. 2. Factors of influencing self-assembly.

Figure 9. Factors of influencing self-assembly. (Figure and Caption from reference [60] without change, under CC-BY License[4].)

Figure 10 demonstrates a wide range of peptide assembly types.[61] These include but are not limited to the following. 1). Fibrous Assembly: Peptides often assemble into elongated structures like nanofibers or gels, driven by interactions along their long axes. These structures can be used as biocompatible scaffolds for tissue engineering or as drug delivery vehicles. 2). Sheet-like Assembly: Peptides can form flat sheets or membranes through side-by-side interactions. These sheets find applications in biomimetic membranes and sensors. 3). Spherical Assembly: Under specific conditions, peptides can organize into spherical structures like micelles or vesicles. These nanocapsules can be used for encapsulating and delivering drugs or imaging agents.

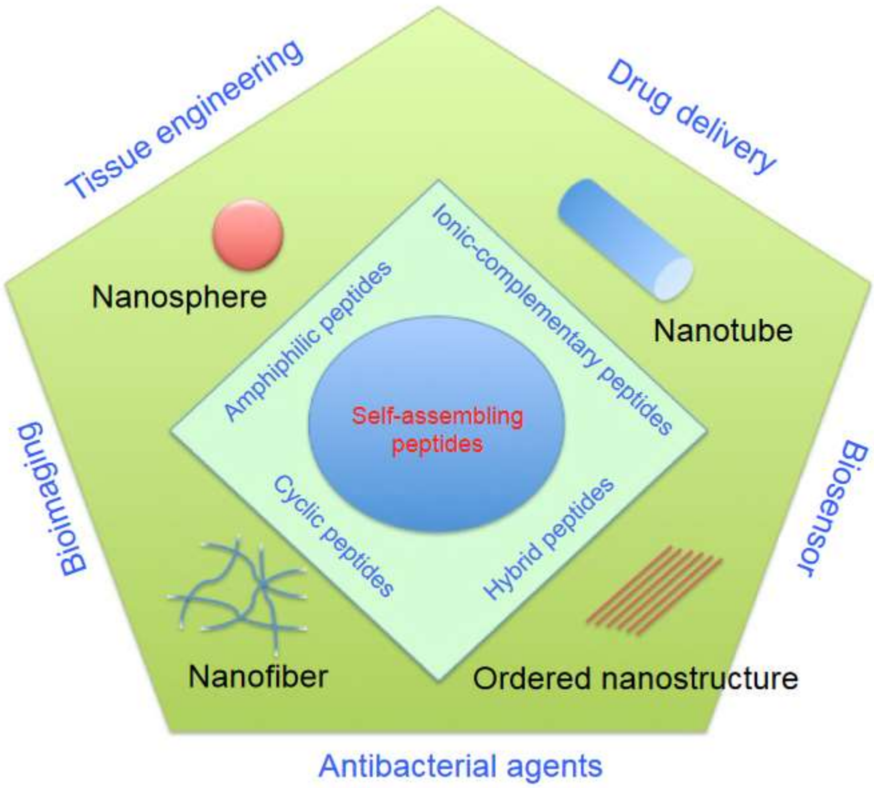


Figure 10. Schematic illustration of various nanostructures (nanosphere, nanotube, nanofiber, and ordered nanostructure) formed by self-assembling peptides (amphiphilic peptides, ionic-complementary peptides, cyclic peptides, and hybrid peptides) and their applications in tissue engineering, drug delivery, bioimaging, and biosensors. (Figure and Caption from reference [61] without change, under CC-BY License.[4])

In terms of applications, peptide assemblies may be used for:[58-61] 1). Biomaterials: Peptide assemblies can be designed for biocompatibility and controlled degradation, making them ideal for tissue engineering scaffolds, wound healing materials, and drug delivery systems. **Figure 11** provides an example for using peptide assemblies for drug delivery. 2).

Nanomaterials: The precise and predictable nature of peptide assembly allows for the creation of nanomaterials with tailored properties for electronics, photonics, and catalysis. 3). Biosensors: The ability of peptides to interact with specific molecules makes them useful for designing sensitive biosensors for diagnostics and environmental monitoring.

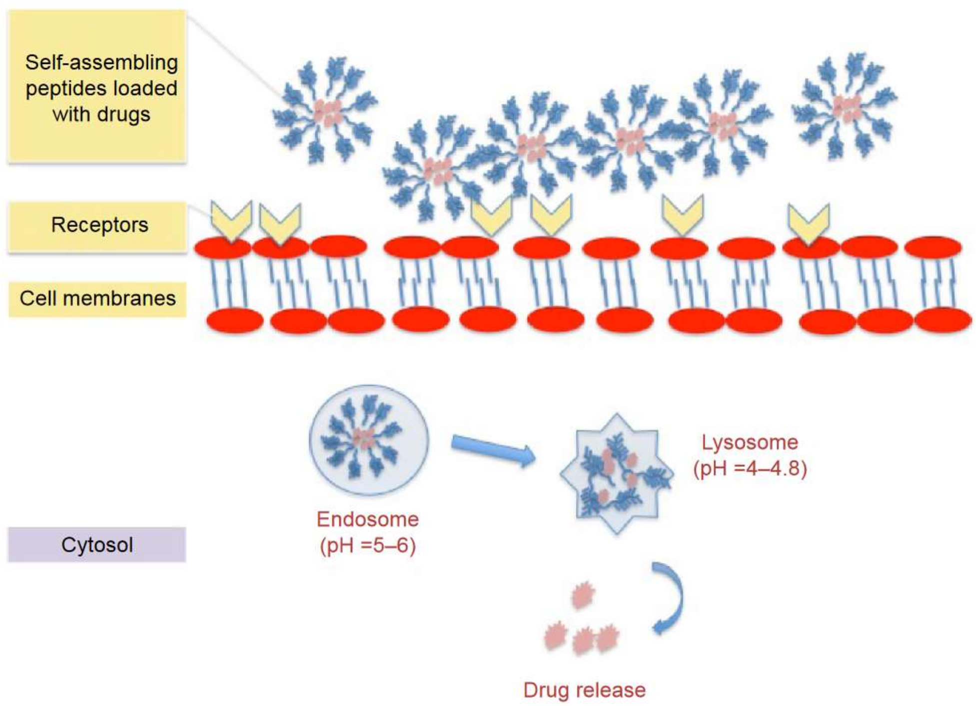


Figure 11. Schematic illustration of cell-membrane interactions and drug release of the drug-loaded self-assembling peptides. (Figure and Caption from reference [61] without change, under CC-BY License[4].)

Peptide assembly is a dynamic field with immense potential to revolutionize various technological advancements; nevertheless, there are many challenges in the field:[58-61] 1). Controlling assembly: Predicting and precisely controlling the assembly process remains a challenge, requiring further research into peptide design and environmental factors. 2). Scaling up production: Efficient and cost-effective methods for large-scale production of peptide assemblies are needed for broader commercialization. 3). New functionalities such as energy harvesting and bioinspired robotics.

3.3 Biomimetic Synthesis

Biomimetic synthesis takes inspiration from natural chemical processes such as the ones involved enzymes to create molecules and materials,[63-67] which can be distinguished different from synthesis of biomimetic materials.[68] This approach, driven by sustainability and efficiency, holds immense potential for revolutionizing various industries, from pharmaceuticals to materials science. Nature, through billions of years of evolution, has perfected intricate pathways to synthesize complex molecules and structures with remarkable properties in a cyclable, efficient, and sustainable way.

The key to biomimetic synthesis lies in understanding the intricate chemistry of nature's machinery. This includes:[63-67] **1**). Enzymes: As nature's master catalysts, enzymes accelerate specific chemical reactions with unmatched efficiency and selectivity. Understanding their mechanisms paves the way for designing synthetic catalysts that mimic their power. **2**). Metabolic pathways: Nature builds complex molecules through a series of carefully orchestrated chemical steps. Deciphering these pathways allows us to replicate them in the lab, using readily available and sustainable starting materials. Successful examples of biomimetic synthesis range from natural products such as tropinone, alkaloids, cyclic steroid ring, carpanone, spirotryprostatin B, endiandric acid, to nanomaterials.[63-67]

3.4 Surfaces and Adhesion

Nature is a master of adaptation, constantly innovating to solve challenges with elegance and efficiency. One remarkable area where nature excels is adhesion, in both dry and wet conditions. From a mussel that sticks to wet surfaces, a gecko defying gravity on a wall to a spider spinning a web that catches even the most delicate insects, nature showcases an incredible variety of adhesive strategies.[69-80]

Biomimetic surfaces and adhesion is a rapidly growing field that seeks to unlock these natural secrets and apply them to human-made technologies. By mimicking the structures and materials used by plants and animals, scientists are developing new adhesives, coatings, and even robots with unprecedented sticking power. The key principles that inspire biomimetic adhesion include the following.[69-80] **1)**. Micro and Nanotopography: Many natural adhesives rely on intricate surface features on a microscopic or even nanoscopic scale. These features, like the tiny hairs on a gecko's foot or the bumps on a lotus leaf, act as tiny hooks or springs that interact efficiently with complementary surfaces, creating a strong, yet reversible, bond. **2)**. Directional and Switchable Adhesion: Some natural adhesives, like those found in mussels, can stick better in one direction than another. This directional adhesion allows them to cling to rough surfaces while still being able to detach easily when needed. **3)**. Superhydrophobicity: Some surfaces, like lotus leaves, repel water and other liquids so effectively that they become almost completely self-cleaning. This superhydrophobicity can also be used to create surfaces with low friction, making them ideal for applications like drag reduction in airplanes or self-cleaning coatings. **4)**.

Biocompatibility: Many natural adhesives are made from biocompatible materials, meaning they are compatible with living organisms and pose minimal risk of harm. This makes them ideal for applications in healthcare, such as wound dressings and surgical adhesives.

Natural adhesions are often complex and poorly understood.[1, 69-80] How to accurately replicate the complex structures and materials found in nature on a large scale and at an affordable cost remains a challenge for humanity. The potential applications of biomimetic surfaces and adhesion may range from wet and medical adhesives, sensors to robotics. [1, 69-80] **1**). Bionic robots with gecko-inspired climbing abilities or mussel-inspired underwater adhesion could revolutionize tasks like inspection and maintenance in difficult-to-reach areas. **2**). Biocompatible adhesives inspired by nature could be used for wound closure, drug delivery, and even tissue engineering. **3**). Self-cleaning surfaces inspired by lotus leaves could stay clean with minimal maintenance, reducing the need for cleaning chemicals and water. **4**). Superhydrophobic coatings inspired by fish scales could reduce drag on airplanes and ships, leading to increased fuel efficiency. **5**). Sensitive surfaces that mimic the adhesive properties of insects could be used to develop new sensors for environmental monitoring and medical diagnostics that require unprecedentedly precise and accurate measurements.

4. Nature's Algorithms

4.1 Bio-Inspired Computing

Bio-inspired computing is a fascinating field that draws inspiration from the natural world to solve computational problems.[81-86] Imagine a computer program that mimics the efficient foraging behavior of ants, or an algorithm that solves complex problems as gracefully as a flock of birds in flight. Some approaches used in bio-inspired computing include the following.[81-86] **1**). Evolutionary Algorithms: These algorithms mimic the process of natural selection, where populations of solutions "evolve" over time through mutation and selection. The fittest solutions, those that best solve the problem at hand, are more likely to survive and reproduce, leading to progressively better solutions over generations. **2**). Swarm Intelligence: This approach draws inspiration from the collective behavior of social insects like ants and bees. These algorithms involve large numbers of simple agents that interact with each other and their environment, leading to the emergence of intelligent collective behavior. **3**). Artificial Neural Networks: These computational models are inspired by the structure and function of the human brain. They consist of interconnected nodes, or neurons, that process information and communicate with each other. Artificial neural networks are able to learn and adapt from data, making them powerful tools for pattern recognition, prediction, and optimization. **4**). Fuzzy Logic: This approach handles uncertainty and vagueness, similar to how humans make decisions. Fuzzy logic allows computers to work with imprecise information, such as "hot" or "cold," rather than just binary values like 0 or 1. **5**). Fractal Geometry: This branch of mathematics describes complex shapes that are self-similar at different scales. Fractals are found in nature everywhere, from coastlines and snowflakes to plants and mountains. Bio-inspired computing can utilize fractal geometry to create efficient algorithms for searching and optimizing complex systems.

The potential applications of bio-inspired computing may include but not limited to the following exciting examples.[81-86] **1**). Optimization: Solving complex problems in logistics, scheduling, routing, planning, and resource allocation. **2**). Machine Learning: Developing algorithms that can learn from data and make accurate predictions, such as in image recognition and supply chain forecasting. **3**). Robotics: Designing robots with efficient movement and adaptation capabilities, inspired by animals like insects and birds. **4**). Medical Diagnosis: Analyzing medical data to identify diseases, guide treatments, and predict patient outcomes. **5**). Drug Discovery: Designing new drugs and therapies by simulating molecular interactions beyond the current limitations of theories and computational power.

While the potential of bio-inspired computing is immense, there are still significant challenges to overcome.[81-86] One challenge is how to bridge the gap between the biological inspiration and the actual computational implementation. Another challenge is how we can scale up bio-inspired algorithms to handle large and complex datasets. As researchers continue to develop new algorithms and applications, we can expect to see bio-inspired computing play an increasingly important role in solving some of the world's most pressing challenges.

4.2 Neuromorphic Computing

The human brain, with its 100 billion neurons and intricate network of connections, is the most powerful information processing system on Earth, and neuromorphic computing aims to emulate the architecture and workings of the human brain to achieve computing breakthroughs.[87-90] Although it is also a bio-inspired computing, neuromorphic computing is discussed here in a separate section due to its enormous potential and unique characteristics. Neuromorphic computing uses artificial neurons and synapses to perform computations in a parallel (instead of sequential), event-driven manner, mimicking the brain's natural way of processing information.[87-90]

Unlike traditional computers that rely on sequential processing and binary logic, neuromorphic computers embrace a different paradigm.[87-90] They operate on spikes, rapid changes in voltage that mimic the way neurons communicate, and utilize analog circuits to capture the nuances of neural activity. This shift brings several advantages: **1**). Energy efficiency: Neuromorphic computers can potentially achieve orders of magnitude greater energy efficiency than traditional computers, especially for tasks like pattern recognition and real-time data processing. **2**). Adaptability: Inspired by the brain's plasticity, neuromorphic systems can learn and adapt to new information on the fly, making them ideal for handling complex, dynamic environments. **3**). Fault tolerance: Damage to individual neurons or synapses in a neuromorphic system doesn't necessarily cripple the entire system, just like brain damage doesn't always lead to complete cognitive loss. This inherent fault tolerance is crucial for robust and reliable computing.

The neuromorphic approach holds immense potential to revolutionize artificial intelligence, robotics, and our understanding of the brain itself.[87-90] **1**). Advanced AI with capabilities (such as natural language processing, image recognition, and movement) that better mimics human skill and adaptability. **2**). Brain-computer interfaces to seamlessly translate thoughts and intentions into digital commands, for people with disabilities or human capability augmenting. **3**). Neuroscience research on the brain's complex inner workings, the mysteries of consciousness and how we think. Scaling up neuromorphic systems to handle large datasets and complex tasks requires further technology advancements, particularly in hardware development and efficient algorithms. Additionally, bridging the gap between biological inspiration and computational implementation remains a complex endeavor.

5. Outlook

Figure 12 highlighted four different levels of biomimicry, each with increasing focus on sustainability and societal transformation.[62] **1**. Biomimicry for Innovation: This is the most basic level, focused on using nature's designs to solve technical problems and improve economic performance. Examples include Velcro and the Bullet Train. **2**. Biomimicry for Net-Zero Optimization: This level aims to reduce the environmental impact of existing designs, but doesn't necessarily address underlying unsustainable systems. An example is ITKE's Flectofin, which optimizes building energy consumption. **3**. Biomimicry for Societal Transformation: This level focuses on using biomimicry to fundamentally change societal systems and behaviors towards sustainability. Examples include Yaniv Peer's Mobius Project, which aims to transform urban spaces into hubs for food production, waste management, and community building. **4**. Biomimicry for Biosynergy: This is the most advanced level, going beyond sustainability to create a "co-creative partnership" with nature. It questions our current desires and goals, seeking to align them with nature's own ends. An example is BioHaven's Floating Islands, which improve water quality and biodiversity. **Table 3** is an attempt to collect some of the biomimetic examples in different applications.[1-3, 62] As we demonstrated here, biomimicry can be used for various levels of a wide range of purposes, from technical innovation to societal transformation. Different levels of biomimicry address sustainability in different ways, with biosynergy offering the most holistic approach. Moving towards biosynergy requires questioning our current goals and aligning them with those of nature.

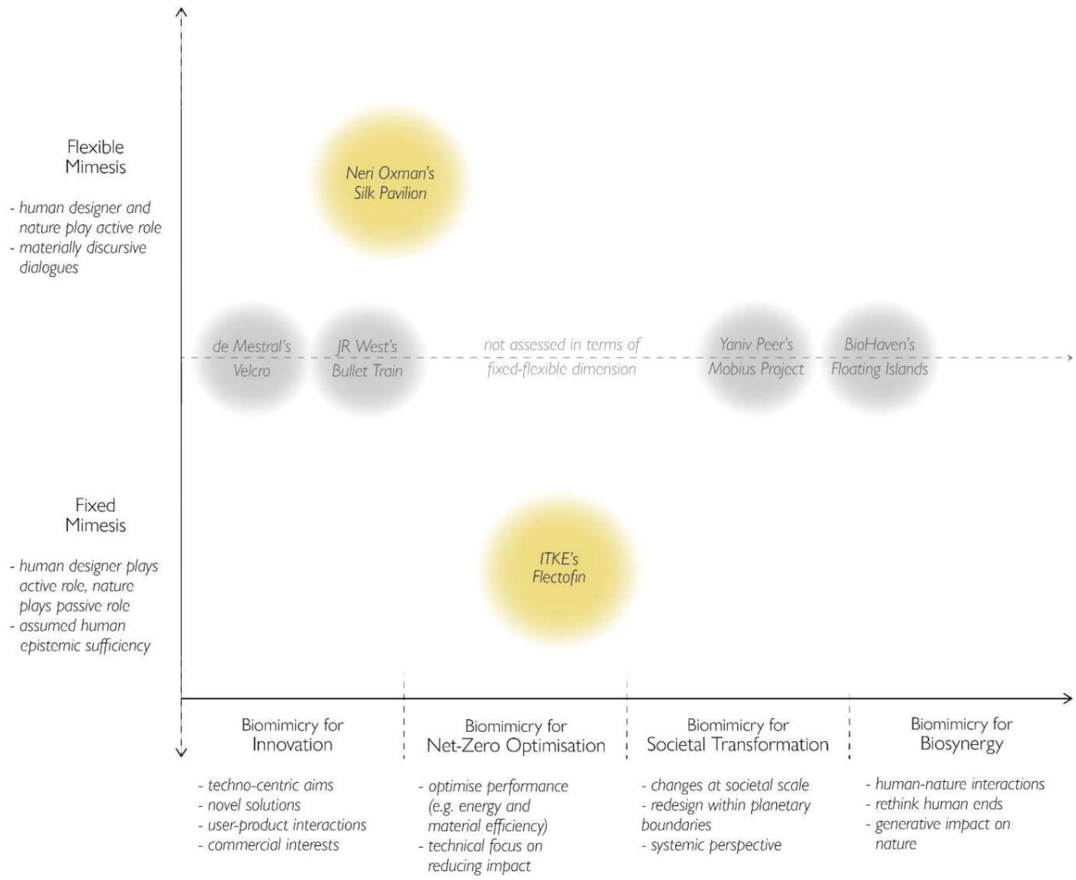


Figure 12. Biomimicry for Sustainability Framework with two examples (in yellow) assessed based on both dimensions. General criteria for each category included. The black and white examples have not been assessed in relation to the vertical range, as indicated by the dotted line. (Figure and Caption from reference [62] without change, under CC-BY License.[4])

Table 3. A list of biomimetic examples from Agriculture to Aeronautics, and beyond [1-3, 62], organized by application fields

Invention	**Inspiration**	**Field**
Bio-inspired AI	Nature optimization and evolution	Artificial intelligence
Self-cooling buildings	Termite Mount	Architecture
Umbrella and Pavilion	Tree	Architecture
Desert water harvesting	Desert insects	Agriculture
Water-efficient irrigation	Desert plant root structures	Agriculture
Crop pollination robots	Pollination of bees and butterflies	Agriculture
Shark skin airfoils	Textured shark skin	Aeronautics
Bird-inspired flight control	Bird eyesight and wing control	Aeronautics
Superhydrophobic coatings	Lotus leaves	Aeronautics, Architecture
Bionic bird wings	Flapping wings of birds	Aeronautics
Noise-canceling headphone	Owl ear structure and feathers	Acoustics
Self-healing materials	Self-repair of bone and spider silk	Construction
Artificial nose, e-nose	Nose	Diagnosis
Bioremediation	Microorganism	Environment
Biodegradable packaging	Leaves and fruit peels	Environment
Sensors with display	Light generation of fireflies	Environment
Artificial leaves	Photosynthesis in plants	Energy
Biofuel from algae	Metabolic processes of algae	Energy
Bio-inspired solar collection	Butterfly wing and light absorption	Energy
Antimicrobial surfaces	Insect exoskeleton, natural defense	Hygiene and Healthcare
Gecko-inspired adhesives	Reversible grip of geckos	Medical, robotics, climbing
Spider silk sensors	Sensitive nature of spider silk	Medical, environmental
Bio-inspired drug delivery	Seeds, bacteria dispersal	Medicine
Regenerative scaffolds	Bone and healing processes	Medicine
Medical or wet adhesives	Mussel and wound-healing	Medicine, Marine
Energy storage	Electric eels	Manufacturing
Saw	Sawgrass	Manufacturing
Biodegradable plastics	Fungal or bacterial decomposition	Materials science
Underwater robots	Jellyfish propulsion,hydrodynamics	Marine and underwater
Bio-conductive interfaces	Neurons and brain tissue	Neuroscience
Bionic prosthetics	Muscle and nerve interaction	Prosthetics
Rescue Robots	Ant navigation, obstacle avoidance	Robotics

Collaborative robot swarm	Bees and birds	Robotics
Adaptive clothing	Chameleons and thermoregulation	Textiles and wearable
Self-regulating textiles	Polar bears and desert animals	Textiles
Bullet train	Kingfisher	Transportation
(Soft) Robotics	Animals and Insects	Various
Biomimetic water filters	Shark gills and fish bladders	Water purification
Self-cleaning surfaces	Lotus leaves and spider silk	Windows, solar panels, medical devices

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Conflicts of Interest

The author declares no conflict of interest.

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