International Journal of Science and Research (IJSR)
ISSN: 2319-7064
SJIF (2022): 7.942

Nature's Blueprint: Using Biomimicry for Advanced Water Management and a Sustainable Future

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Abstract: ***Access to freshwater is vital to human survival and the development of human societies. However, sustainable management of freshwater resources is a growing challenge, especially in the face of increasing consumption and changing weather patterns due to climate change. By mimicking adaptations of various flora and fauna, it is possible to create new efficient and sustainable tools for water conservation and management. This paper looks at three such structures – elytra of Namib desert beetles, aquaporin membrane proteins, and whale baleen – and examines how these structures have inspired new technologies for water collection and conservation.***

Keywords: freshwater management, water conservation, climate change, biomimicry technologies, sustainable water solutions

1. Introduction

Access to freshwater is essential to human life. Indeed, the earliest civilizations grew around the banks of mighty river systems – the Nile, Tigris - Euphrates, the Indus, and the Yangtze to name a few. However, as the population of humans has continued to grow, our consumption of freshwater has also greatly increased – not only for domestic needs but also for industrial applications and agriculture.

Global water consumption is estimated to be about $4x10^{12}$ m^3 per year (Ritchie and Roser). That is approximately $500m^3$ per person per year or 1300 litres per person per day. However, the overwhelming majority of this goes into agriculture and industrial use – roughly 87%. Even so, the UN estimates that in 2022, 2.2 billion people did not have daily access to safe drinking water, and 3.6 billion did not have access to safely managed sanitation facilities (UNESCO). This is below the expected progress to meet the UN's Sustainable Development Goal of ensuring availability as well as sustainable management of water & sanitation for all people by 2030 (UN Department of Economic and Social Affairs)

Another phenomenon that has accompanied the growing consumption of freshwater is the rate at which groundwater is being extracted from the Earth, largely to meet agricultural and industrial needs.$9x10^{11}$ m^3 of groundwater is estimated to be extracted every year, or roughly $1/4^{th}$ of all freshwater consumed globally, an amount that is believed to be unsustainable in the long run (Pointet).

Evidently, access to safe drinking water is poor across much of the world, and this is before we have begun to face the full brunt of climate change and the changes in patterns of precipitation that will follow. While many countries are turning to physical processes like desalination to shore up their supplies of freshwater, these consume a large amount of energy and can only be used in places with access to the sea. There is an urgent need to identify and develop mechanisms to ensure that more people are able to access safe drinking water in energy - efficient and sustainable ways.

The process of observing and replicating biological structures and activities in human contexts is known as biomimicry, and it has been used to great effect in many fields. Some modern examples include:

- Hook and loop fasteners, which mimic how grass burrs stick to the fur of animals • Oleophobic and hydrophobic coatings on glass surfaces – car windshields, smartphone screens etc., which mimic how to water plants and waterfowl keep their leaves/feathers clean and dry.
- Swimsuits with microfins to streamline the flow of water over a swimmer's body and allow the swimmer to swim faster and use less energy, mimicking the rough skin of sharks.

Extraction and management of water resources is something that various species on our planet have evolved to carry out with great efficiency in particular niches. Physiological developments, such as waxy coatings and the Crassulacean Acid Metabolism (CAM) photosynthetic cycle in desert plants, have been studied in great detail. By understanding other biological developments related to water management, we may be able to develop energy - efficient systems to extract and manage freshwater. This paper examines several examples of water extraction and management from the natural world, which may be used to develop biomimetic systems to collect and manage freshwater efficiently.

Condensation & collection of water – inspired by Namib desert beetles

The Namib desert which runs along the Atlantic coast in southwestern Africa is one of the most arid places on Earth, with the region receiving under 50mm of precipitation per year (Seely). Precipitation in the Namib desert is largely in the form of fog that occasionally blows in from the Atlantic Ocean and condenses on rocks and the sparse vegetation of the region. Several hundred species of beetles have evolved to survive in these harsh conditions, most of which drink water that condenses onto vegetation.

However, a few species are able to condense water from the fog onto their shells (elytra) which they then drink. While each of these species appears to use different mechanisms to condense and collect water, one species *Physosterna cribripes* has gained prominence among materials researchers. It has a characteristic bumpy surface on its elytra, with the peaks of the bumps being smooth and hydrophilic, while the valleys are hydrophobic. Water condenses onto the bumps until it grows heavy enough to slide into the valleys, where it can collect against the hydrophobic coating until the beetle drinks it (Guadarrama - Cetina et al.).

P. cribripes has inspired significant advancements in the field of biomimicry for water condensation, focusing on the beetle's unique ability to collect water in arid environments through its back's hydrophobic - hydrophilic pattern. Al - Beaini explored the feasibility of using zinc oxide surfaces patterned after the beetle's back to enhance condensation, highlighting the material's non - toxicity and capability for photoinduced hydrophilicity. Similarly, Song and Bhushan investigated bioinspired triangular patterns with varying wettability to improve the performance of water collection systems, utilizing a low temperature to promote water condensation.

Recent studies have pushed the boundaries of this technology further. Boylan et al. developed a beetle - inspired biphilic quasi - liquid surface (QLS) that significantly enhances heat transfer and water harvesting rates by facilitating rapid droplet growth and removal. This surface combines hydrophilic and hydrophobic patterns to mimic the beetle's natural water collection efficiency but with added enhancements for practical applications in steam environments.

In another study, Do et al. addressed the challenge of atmospheric water harvesting by mimicking the water collection mechanisms of tree frogs and desert beetles. They fabricated surfaces with varying wettability, including superhydrophilic and biphilic properties, to optimize condensation and water collection on cooled window glass. This approach not only enhances condensation efficiency but also promotes sustainable water collection in environments facing water scarcity.

High - efficiency reverse osmosis using Aquaporins

First discovered in 1988, aquaporins are a class of membrane proteins found throughout the biological world (Isaksson). These proteins selectively allow the passage of water into a living cell and exclude other dissolved molecules. They are found in large numbers in tissues that selectively absorb water, such as renal tissues, root tissues etc. Their efficiency in allowing the passage of water and excluding other solutes has inspired the development of water purification processes that use synthetic aquaporin - like molecules.

Recent advancements in the field of water purification using aquaporins and related technologies have shown significant progress in addressing the challenges of water scarcity and pollution. Nguyen et al. introduced a novel desalination technology that utilizes membranes with entrapped air layers, achieving high water permeability and near - complete solute rejection, which surpasses the performance of traditional commercial membranes. This method demonstrates a promising approach to overcoming the trade - off between water permeability and selectivity in membrane technologies.

Kausar describes sustainable polymer membranes using facile techniques that are effective or various water treatment processes including desalination and dye removal. These membranes not only show good performance but also have positive environmental impacts due to their sustainability and potential for recycling through mechanical, chemical, or thermal processes.

Liu et al. propose a high - efficiency purification method using a low - pressure Janus membrane with electrically induced multi - affinity, capable of removing a wide variety of contaminants, including organics and heavy metals, with high efficiency and significantly lower energy consumption compared to traditional methods. The ability of these membranes to achieve 100% regeneration of performance through electro - induced switching of interfacial affinity marks a sustainable advancement in drinking water purification.

Chen et al. have explored the use of Metal Organic Framework (MOF) - based nanocomposite membranes that show high rejection rates for organic carbon and pollutants like trimethoprim in wastewater treatment, demonstrating excellent mechanical stability and resistance to fouling.

These findings collectively highlight the ongoing innovations in membrane technology and materials science that are enhancing the efficiency, sustainability, and applicability of water purification systems.

High - efficiency water filtration – inspired by whale baleen

Baleen whales are aquatic mammals that feed by filtering out krill and other microscopic animals from seawater. The sizes of these organisms range from 10μm to 5mm. Whales have specialized feeding structures called baleen, which allow efficient capture of krill, as well as efficient removal for feeding. It has been found that filtration takes place at low pressures, while a small volume of high - pressure water is sufficient to dislodge krill out of the baleen and into the whale’s gut. (Dama - Fakir et al.)

This is relevant to water purification systems because microscopic debris in the 10μm to 1mm range needs to be filtered out before water can undergo chemical treatment or reverse osmosis. Conventional water filtration systems often get clogged with filtered debris and need to be removed for cleaning or disposed entirely, which is either slow, expensive, or both. Research into baleen - like filters has been going on for some time now. Baleen Filters, an Australian company, was the first to commercialize a water filter that mimics the filtering action of whale baleen, and their filters have been deployed in several water treatment plants, both for municipal water treatment and for treating industrial effluents (Dama - Fakir et al.).

Recent advancements in the field of high - efficiency water filters inspired by baleen whales have focused on understanding and mimicking the natural filtration mechanisms of whale baleen. Werth et al. explored the capture rates of various types of plastics by baleen tissue and the threat plastic debris posed to whales. They found that expanded polystyrene foam

and other microplastic particles are effectively trapped, which highlights the potential for developing synthetic filters based on baleen structures. Similarly, Potvin and Werth investigated

Paper ID: SR24805194911 DOI: https://dx.doi.org/10.21275/SR24805194911

the hydrodynamics generated by the baleen mats, discovering that porosity and permeability are crucial factors in the filtration process, which can be applied to enhance the design of water filters. Ongoing research into the hydrodynamics within the oral cavity of baleen whales can also advance the design of filtering chambers to be more efficient (Zhu et al.)

These findings suggest that both the structural properties of baleen and the material composition of filters are critical to enhancing filtration efficiency, offering valuable directions for future research and development in water filtration technologies inspired by natural systems.

2. Conclusion

The examples discussed above are only some ways in which biomimetic structures can be created to improve access to fresh water and ensure proper treatment of wastewater for reuse. Much work remains to be carried out in developing appropriate materials to carry out biomimetic functions, such as the hydrophobic - hydrophilic material of the *P. cribripes* elytra or whale baleen.

However, the fact that such mechanisms already exist in nature and are quite efficient for their purpose shows us that efficient new alternatives can be developed for human use. These mechanisms provide yet another reason for us to ensure the safety of all biological niches. Discovering new species and how they adapt to their environment will undoubtedly hold valuable lessons for humanity on how to be more efficient and reduce our ecological footprint while also providing a better quality of life to all people.

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