https://doi.org/10.47460/athenea.v4i12.54

Engineering prototype based on the study of extremophiles

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Received (01/11/2022), Accepted (11/05/2023)

Abstract. - This paper discusses engineering options for understanding how extremophile organisms might shed light on the possibilities of life on other planets. The study of extremophiles is responsible for the life that can exist in highly hostile environments on Earth, such as volcanoes, arid deserts, or domains with high salt concentrations. Engineering could be the essential tool to know unexpected life scenarios so that developments in this sense are proposed. The proposed prototype is generated from the analysis of extremophiles so that an engineering development suitable for adaptation to complex environments and valuable for the best human living conditions is possible. The main results show that a design with these characteristics presents more advantages than other technologies.

Keywords: Life, organisms, survival.

Prototipo de ingeniería basado en el estudio de extremófilos

Resumen: En este trabajo se analizan las opciones de ingeniería para comprender cómo los organismos extremófilos podrían arrojar luz sobre las posibilidades de vida en otros planetas. El estudio de extremófilos se encarga de examinar la vida que puede existir en entornos extremadamente hostiles en la Tierra, como volcanes, desiertos áridos o ambientes con altas concentraciones de sal. La ingeniería podría ser la herramienta clave para conocer escenarios de vida inesperados, de tal manera que se proponen desarrollos en este sentido. El prototipo propuesto se genera a partir del análisis de extremófilos, de manera que sea posible un desarrollo de ingeniería apto para la adaptación a ambientes difíciles y útil para las mejores de las condiciones de vida humana. Los principales resultados muestran que un diseño con estas características presenta ventajas importantes en comparación con otras tecnologías.

Palabras clave: Vida, organismos, supervivencia.

I. INTRODUCTION

Life on Earth has proven incredibly adaptable, finding ways to thrive in even the most inhospitable and hostile environments. From the deep ocean to arid deserts to active volcanoes, there is a surprising variety of organisms capable of surviving in extreme conditions. These organisms, known as extremophiles, have evolved unique mechanisms that allow them to withstand extreme temperatures, high pressures, intense radiation, and toxic levels of chemicals [1].

Extremophiles are true masters of adaptation, challenging our traditional notions about the limits of life. Some can survive in shallow temperatures, such as the polar regions, where intense cold seems incompatible with life. Others, instead, thrive in volcanic hot springs, where temperatures can exceed 100 degrees Celsius [2].

In addition to extreme temperatures, extremophiles have adapted to high-pressure conditions, such as the abyssal depths of the ocean, where the pressure reaches levels unimaginable to most organisms. These beings have also demonstrated a fantastic ability to survive in highly toxic environments, such as the saline waters of hypersaline lakes or acidic sources rich in heavy metals [3].

Understanding how extremophiles have evolved to survive in these harsh environments gives us valuable insights into the diversity of life on Earth. It may also have important implications in our search for extraterrestrial life. By studying extremophile adaptations and survival mechanisms, we can understand what life might be like on other planets or moons with similar conditions [4]. In this sense, extremophiles' existence shows life's fantastic ability to adapt and survive in environments that defy all expectations. These organisms not only expand the understanding of biodiversity on the planet itself but also invite reflection on the possibilities of life in seemingly inhospitable places in the vast universe.

The involvement of engineering in the study of extremophiles has been fundamental to understanding how these organisms survive in hostile environments. Engineers have developed specialized techniques and tools to collect samples of these organisms in their natural habitat, allowing for a more detailed analysis of their adaptations. In addition, they have applied bioengineering concepts to replicate extreme conditions in the laboratory and recreate the environments in which extremophiles live. These engineering approaches have provided valuable insights into these organisms' biological responses and survival mechanisms [5].

Engineering has also played a key role in developing technologies to study and analyze the DNA and proteins of extremophiles. By using genomic and proteomic sequencing techniques, engineers have managed to identify specific genes and proteins that play a crucial role in extremophile adaptations. These discoveries have allowed a better understanding of the molecular mechanisms underlying survival in hostile environments and laid the foundations for developing technological applications inspired by extremophile adaptations [6].

Another area in which engineering has contributed significantly is the application of extremophile adaptations in various fields, such as biotechnology and medicine. Extremophiles have been shown to possess enzymes and proteins with unique properties, capable of functioning in extreme conditions that would be harmful to conventional organisms. Engineers have taken advantage of these adaptations to develop more stable and efficient enzymes in industrial processes and explore medical applications, such as in the production of thermostable drugs and the search for therapies for diseases related to oxidative stress [7].

Engineering involvement in the study of extremophiles has been essential to advancing our understanding of these organisms and their adaptations. From sample collection in extreme environments to genomic and proteomic analysis, engineering has provided crucial tools and knowledge to unravel the secrets of life in extreme conditions. In addition, the application of extremophile adaptations in different fields has opened up new technological and medical possibilities, taking advantage of the unique ability of these organisms to survive in challenging environments. Likewise, engineering is projected as a tool to solve an infinity of social, industrial, and scientific problems.

II. DEVELOPMENT

An extreme environment is an environment that exhibits physical, chemical, or biological conditions that are considerably different or more extreme compared to the usual requirements that support life on Earth. These environments can be hostile, difficult to inhabit, and pose significant challenges to living organisms. Some examples of extreme environments include [8]:

High temperatures: Places with extremely high temperatures, such as volcanic lava flows or hot springs, where organisms must deal with intense heat.

Low temperatures: Polar regions, glaciers, or cold underground environments, where temperatures can drop below freezing, presenting challenges to survival.

High pressure: The deep ocean, where the hydrostatic pressure is exceptionally high, exceeds sea-level pressure.

Acidic or alkaline environments: Places with extremely low or high pH, such as acidic lakes generated by volcanic activity or alkaline waters.

Saline environments: In regions with high salt concentrations, such as saline lakes or salt flats, salinity is much higher than in typical aquatic ecosystems.

Radiation: Places with high radiation levels, such as areas near radioactive sources or environments exposed to cosmic radiation in space.

Nutrient scarcity: Environments with limited resources, such as deserts or arid regions, where water and nutrients are scarce.

Absence of light: Underground or deep environments in the ocean, where sunlight cannot penetrate, creating conditions of total darkness.

These extreme environments present unique challenges to life. Still, they are also home to an incredible diversity of extremophile organisms that have evolved specialized adaptations to survive those harsh conditions. Studying these organisms and their adaptations provides valuable information about the limits of life on Earth and the possibilities for life in other extreme environments, including planets and planets in the solar system.

In this sense, extremophiles have evolved to survive and thrive in extreme environments inhospitable to most living things. These organisms exhibit various adaptive characteristics that allow them to cope with extreme conditions, such as extremely high or low temperatures, high pressures, severe acidity, high salt concentrations, lack of oxygen, and intense radiation. Their adaptations include enzymes and proteins stable under extreme conditions, resistant cell membranes, DNA repair mechanisms, and specialized metabolism.

Extremophiles are classified into different categories depending on the extreme environment in which they can survive. Some examples are thermophiles, which thrive in high temperatures; psychrophiles, which are found in icy environments; halophiles, adapted to high concentrations of salt; acidophiles, which can survive in highly acidic environments; and alkalophilic, which are found in highly alkaline environments. In addition, some extremophiles can withstand extreme radiation, pressure, or dryness [9].

The life forms of extremophiles can vary widely. Some extremophiles are single-celled microorganisms, such as bacteria and archaea, that can inhabit extreme environments such as hot springs, saline lakes, or hydrothermal vents on the ocean floor. Other extremophiles are multicellular organisms, such as some fungi, lichens, and algae, that can adapt to extreme conditions in polar regions, deserts, or volcanic environments. Even extremophiles capable of surviving in harsh conditions in outer space have been discovered, raising the possibility of life on other planets or moons.

Extremophile research has important implications in various fields. Studying their adaptations can provide valuable information for understanding the evolution and diversity of life on Earth. In addition, extremophiles have proven to have practical applications in biotechnology, as their stable enzymes and proteins can be used in industrial and medical processes. It is also investigated whether extremophiles could provide clues about the possibility of life on other planets since their adaptations could be relevant for survival in extraterrestrial environments. [10] Finally, it is necessary to recognize that extremophiles have evolved unique adaptations to survive in extreme environments. Their classification is based on the types of harsh conditions they can tolerate. Extremophiles can be single-celled microorganisms or multicellular organisms, and their study has implications for understanding life on Earth, biotechnology, and the search for life on other planets.

Extremophiles are found in various parts of the planet, such as volcanic hot springs, polar regions, arid deserts, deep oceans, hypersaline environments, and highly acidic or alkaline environments. Some examples of extremophiles include:

Thermophilic: They are organisms that can survive and reproduce in very high temperatures, even above 100 degrees Celsius. They are found in hot springs and underwater hydrothermal vents.

Halophiles: They are organisms adapted to highly saline environments, such as salt lakes or saline. They can tolerate much higher salt concentrations than most life forms could support.

Acidophiles: These organisms can live and grow in highly acidic environments, such as abandoned mines or acidic lakes generated by volcanic activity.

Alkalophiles: These are organisms adapted to highly alkaline environments, such as water lakes or alkaline sources. They can survive in high pH conditions.

Piezophiles: These organisms can withstand high hydrostatic pressures, such as those in the deep ocean.

The study of extremophiles is of great scientific interest, as it allows us to understand the diversity of life on Earth and the biological adaptations that allow survival in extreme conditions. In addition, these organisms could provide clues about the possibilities of life on other planets or moons in the solar system that present similar environments.

A. Extremophiles and engineering

Engineering can play an essential role in studying extremophiles and their applications. Here are some ways engineering can contribute:

Instrumentation and sensor design: Engineering can contribute to the design and development of specialized instruments and sensors for detecting and sampling extremophiles in their natural environment. These devices can be used to collect data and samples in extreme habitats and facilitate the study of these organisms.

Culture and maintenance technologies: Engineering can contribute to developing technologies and systems that enable the cultivation and maintenance of extremophiles in controlled laboratory environments. This helps researchers study and better understand the biological adaptations of these organisms and how they survive in extreme conditions.

Applications in biotechnology and medicine: Extremophiles possess unique adaptations and special enzymes that allow them to survive in extreme environments. Engineering can take advantage of these features for applications in biotechnology and medicine. For example, extremophile enzymes can be used in industrial processes that require extreme conditions, such as chemical production or bioremediation of contaminants.

Engineering can contribute to the study of extremophiles through instrumentation design, culture technologies, applications in biotechnology and medicine, space research, and materials design. These contributions help to understand extremophiles better, their adaptations, and their potential applications in various fields.

B. Contributions of engineering in the study of extremophiles

Some contributions of engineering in the study of extremophiles are mentioned below:
Remote sampling instrumentation: Robotic systems and drones equipped with specialized instrumentation have been developed to take samples and measure in remote and hard-to-reach locations, such as polar regions, acidic lakes, or hydrothermal vents on the ocean floor. These advances allow detailed information to be obtained without exposing researchers to the dangers of these extreme environments.

DNA sequencing technologies: Engineering has contributed to developing high-throughput, low-cost DNA sequencing technologies. This has facilitated the study of extremophile genes and genomes, providing crucial information about their adaptations and survival mechanisms under extreme conditions.

Bioremediation: Engineering has used extremophiles to develop bioremediation technologies to clean and decontaminate environments contaminated by toxic compounds or industrial waste. Some extremophiles can tolerate and break down hazardous chemicals, offering sustainable and efficient solutions for environmental remediation.

Bioengineering and nanotechnology: Bioengineering and nanotechnology have combined to develop sensors and drug delivery systems inspired by extremophile adaptations. For example, scientists have designed heat- and radiation-resistant materials and nanomaterials for drug transport and controlled release under extreme conditions.

Applications in space exploration: Extremophile studies have influenced the design of equipment and technologies used in space exploration. For example, research into radiation-resistant bacteria has developed protective materials for satellites and spacesuits. In addition, extremophiles provide valuable information about the conditions in which life might exist on other planets or moons, guiding space mission planning, and the design of probes and rovers.

These examples show how engineering has contributed to studying extremophiles and life in extreme environments. Advances in engineering continue to expand our knowledge and practical applications in this fascinating field.

C.Statistics of the extremophiles

It is estimated that there are thousands of species of extremophiles on Earth, adapted to a wide range of extreme conditions. These include bacteria, archaea, fungi, algae, and other microorganisms. In addition, scientists have verified that life exists in hot springs, in hydrothermal vents on the ocean floor, where temperatures can exceed 350 degrees Celsius. Communities of extremophiles have been discovered that survive in these extreme conditions based on chemosynthesis.

Extremophiles have been found in highly radioactive environments, such as the pools of highly contaminated water at the Chornobyl nuclear plant. These organisms can tolerate levels of radiation that would be lethal to most life forms. Life has also been found in acidic environments, such as Dallol Acid Lake in Ethiopia; extremophiles have been found able to survive at extremely low pH and high concentrations of acidic minerals. In addition, it has been observed that these species have adapted to salinity and are found in saline environments such as salt lakes and salt flats. For example, Lake Retba in Senegal, known as Pink Lake, is home to extremophiles adapted to high salinity and extreme conditions.

These examples demonstrate extremophiles' ability to adapt and survive in extreme conditions, showing their importance in understanding the limits of life on Earth and their potential in scientific, industrial, and medical applications.

III. METHODOLOGY

The methodological process was composed of the phases described in Figure 1, where it can be seen that the six stages include an evaluation of the adaptations and their use for engineering development.

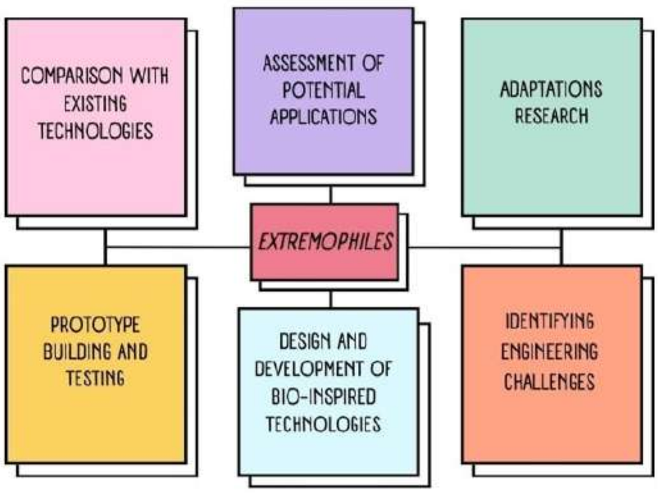

Fig. 1. Phases of implementation of the proposal.
Source: Authors.

Extremophile adaptations research: A comprehensive review of the scientific literature was conducted to identify critical adaptations of extremophiles to the extreme conditions in which they live. The structures, physiological mechanisms, and biochemical responses that allow them to survive were recognized.

Identification of engineering challenges: Different challenges or problems could be addressed by applying technologies adapted to extreme conditions, such as high temperatures, pressures, radiation, or aggressive chemical environments.

Design and development of bioinspired technologies: with the information collected, a proposal was designed for training in bioinspired technologies that can work in conditions similar to those of extremophiles. This training proposal for engineers aims to recognize the importance of survival in extreme environments and the need for innovation in the search for life on exoplanets.

Construction and testing of prototypes: The structure of a prototype water filtration system resistant to extreme conditions is proposed.

Comparison with existing technologies: The performance of the proposed bioinspired technology is compared with existing technologies in terms of efficiency, resistance, and adaptability to extreme conditions.

Evaluation of potential applications: The potential applications of the technology developed in fields such as medicine, industry, space exploration, or environmental protection are evaluated.

IV. RESULTS

The study of extremophiles allows us to know some characteristics for developing engineering systems that can be adaptive and facilitate scientific exploration in environments that are difficult for humans to access. Table 2 shows the features found in the detailed review carried out.

Tabla. 1. Characteristics of extremophiles.

Adaptation	Structure	Physiological Mechanism	Biochemical Response
Thermostability	Thermostable proteins	Stabilization of protein structures	Production of thermosetting proteins
Hyperthermophilic	Hyperthermophilic enzymes	Stability and activity at high temperatures	Adaptation to protein structure
Cryptobiosis	Spore formation	Suspension of metabolism and dehydration	Production of cell protectors
Dehydration	Protective proteins and lipids	Protection against dehydration	Accumulation of protective compounds
Halotolerance	Compatible solute carriers	Regulation of osmotic balance	Accumulation of compatible solutes
Radio tolerance	DNA repair enzymes	DNA damage repair	DNA protection and repair
Extreme pH	Proton pumps	Internal pH regulation	Internal pH control
Extreme pressure	Adaptations in membranes	Stability of cell structure	Modification of membrane lipids
Chemosynthetic metabolism	Enzymes and enzyme systems	Energy production from inorganic compounds	Adaptations in metabolic pathways

Fuente: Propia.

On the other hand, it was found that there are different challenges and problems in the development of technologies in engineering. Table 3 shows the main challenges encountered in the existing documentation.

Tabla. 2. Problems and challenges for the development of technologies.

Challenges/Problems	Description
Selection of suitable extremophiles	Identify and select the most relevant extremophiles adapted to the extreme conditions targeted.
Transfer of adaptations	Understand how to transfer extremophile adaptations to the design of human technologies efficiently.
Extreme condition replication	Design and create laboratory environments or test conditions that accurately simulate extreme natural conditions.
Strength and durability	Develop solid and durable materials and components that can withstand extreme conditions without degrading quickly.
Efficiency optimization	Improve the efficiency of bioinspired technologies to make them competitive with conventional methods.
Scalability and mass production	Adapt manufacturing processes to enable large-scale production of bio-inspired technologies.
Regeneration and maintenance	Design regeneration and maintenance mechanisms to extend the life and effectiveness of extremophile-based technologies.
Integrity and security	Ensure the integrity and safety of extremophile technologies, avoiding possible negative impacts on the environment and human health.
Economic cost	Develop bioinspired technologies that are economically viable compared to conventional alternatives.
Technology transfer	Overcome the challenges of effectively transferring bioinspired technology to industry and implementation in different contexts.

Fuente: Propia.

Based on these premises, the design of a technological engineering prototype is proposed, which includes the characteristics described and allows the generation of an engineering development suitable for use. In this sense, a water filtering system that applies to different scenarios is proposed.

This prototype would filter water in environments with high salinity concentrations, such as saltwater bodies or saline. It is inspired by the adaptations of extremophiles that can survive in highly saline environments. In addition, the operating mechanism is composed of a filtration system, which consists of a compact device that uses a combination of materials and bioinspired filtration techniques to remove salt and other impurities from water. It also uses a specialized membrane inspired by extremophile adaptations, which has a porous and selective structure that allows the passage of water while retaining salt ions and other impurities. This membrane mimics natural transformations, such as ion transport channels in extremophiles.

The filtered water is collected in a separate container, ready for use. It may include an additional sterilization or disinfection mechanism to ensure the water is free of harmful microorganisms. To maintain the efficiency of the filtration system in the long term, it is proposed to include a membrane regeneration mechanism. This mechanism removes accumulations of salt and other impurities from the membrane to restore its filtration capacity. This can be done using techniques such as washing with concentrated saline solutions or applying pulsed electrical currents to remove obstructions.

A system with these features is expected to have the following benefits:

- It can be used where salt or saline water is the only available source or where freshwater resources are limited.
- It can be applied in marine environments, desalination plants, expeditions in arid regions, or emergency situations where access to drinking water is needed.
- The prototype's bio-inspired technology offers an efficient, low-cost, and energy-efficient solution compared to conventional desalination methods.
- Table 4 compares with existing technologies, showing high efficiency and possible scalability, thus offering an opportunity for robust engineering development.

Tabla. 3. Problems and challenges for the development of technologies.

	Prototype filtration resistant to extreme conditions	Reverse osmosis	Evaporative distillation	Electrodialysis
Retention efficiency	Loud	Loud	Loud	Variable
Energy consumption	Low	High	High	Variable
Cost of operation	Low	High	Moderate	Variable
Maintenance requirements	Low	Moderate	Moderate	Variable
Installation area	Small	Big	Big	Moderate
Use of chemicals	Low	Moderate	Low	Moderate
Adaptability to extreme conditions	Loud	Casualty	Moderate	Moderate
Scalability	Possible	Possible	Possible	Possible
Applications	Marine environments, arid regions, emergencies	General	General	Specific

Fuente: Propia.

CONCLUSIONS

1. A water purification system based on the study of extremophiles can convert seawater into drinking water, allowing fresh water supply in coastal areas where water scarcity is an issue.

2. It can also be used in areas with little availability of fresh water since the system can filter water from wells or underground sources with high levels of salinity, providing a source of drinking water for the local population.

3. It is expected that, during expeditions in remote regions or camps in isolated areas, the system can provide drinking water by filtering local sources such as rivers, lakes, or springs with high concentrations of mineral salts.

4. In natural disasters or emergencies where the drinking water supply is affected, the proposed system can be used to purify contaminated or saline water, providing a safe water source for human consumption.

5. The water this system filters can be used in industrial and agricultural activities where quality water is required, such as crop irrigation or water supply for industrial processes.

6. Another functionality of the proposed system is for use in long-duration space missions, where access to fresh water is limited. The water filtration system is resistant to extreme conditions and can be used to recycle and reuse water, ensuring the supply of drinking water for astronauts.

A more in-depth study is necessary to define the possible adaptations that the proposed system could have so that its usefulness can be broad and diverse and can offer a resource as valuable as filtered water.

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