EXTREMOPHILES: FROM EXTREME ENVIRONMENTS TO SUSTAINABLE GLOBAL SOLUTIONS

PREETI CHAUHAN, ASHA SAHU*, SUDESHNA BHATTACHARJYA, K BHARATI, S R MOHANTY, NISHA SAHU, PAYAL BISWAS, SAVI GIROTHIA

ICAR-Indian Institute of Soil Science, Bhopal, Madhya Pradesh, India

*Corresponding Author, E-mail: ashaars.iiss@gmail.com

Can you imagine life far below the oceans's surface where sunlight never reaches, or in the deep sea with the pressure which could flatten a submarine or in the frozen desert of the Antartica? These places are so harsh that finding life in such environment appears impossible but even in these conditions the life persists. The tiny organisms that are invisible to the naked eye not only survive there but often thrive successfully.

Organisms which live in such extreme harsh condition are called extremophiles. These organisms can live in extreme hot niches (Figure 1), ice, high salt or acidic condition, and in places where there is high radioactivity and heavy metal content. Extremophiles are found in all three domains of life which are bacteria, archae and eukarya. Most of the extremophiles are microorganisms (a high proportion of these are archaea), but this group also includes eukaryotes such as protists (e.g., algae, fungi and protozoa) and multicellular organisms.

As it is difficult for commonly founded microorganism to live in such hard condition these organisms usually adapt to their environment either by adopting new mechanism or by altering those already in place. Table 1 lists out various extremophiles, their niches and how they adapt themselves and successfully thrives in the extreme environment.

Figure 1. Surajkund Hot Springs, Yamunotri, Uttarakhand

Table 1. Different type of Extremophiles, Their Niches and Adaptation

TYPE OF EXTREMOPHILES	THEIR NICHES	THEIR ADAPTATION
Thermophile	The places such as hot springs (Figure 1) and hydrothermal vents. They grow at a minimum 55ºC and optimally between 55ºC to 65ºC.	• Lipid membrane more saturated than mesophile. • Presence of a unique DNA gyrase enzyme that acts to introduce supercoils in DNA which helps in thermostability • High G+C content in the stems of tRNA (transfer RNA) and rRNA (ribosomal RNA. • Production of heat shock protein.
Hyperthermophiles	The places where temperature reaches above 65ºC or more.	• Presence of ether linkage in cell membrane. • Processes like homologous recombination take place in Hyperthermophilic archaea to repair damaged DNA. • Structure of membranes forms a lipid monolayer which is much more heat resistant than the lipid bilayer of mesophilic organisms.
Psychrophiles	These are present in cold environment like polar regions or deep sea etc. and grow at temperature below 15ºC optimally and can grow at temperature of 0 ºC.	• Produce antifreeze and ice-binding proteins • Higher amount of membrane unsaturated fatty acids • Some Psychrophiles contains genes for gas vehicle production, cell adhesion, rhodopsin and retinal biosynthesis. The formation of gas vesicles provides buoyancy and helps bacteria to float over the surface for carbon acquisition from primary sources, whereas rhodopsin helps in surviving under nutrient limited condition
Piezophile	These organisms require high hydrostatic pressure for growth and cannot grow at atmospheric pressure. These are found mostly in deep-sea or subsurface environments (crude oil reservoirs, mines etc.) where pressure is very high (e.g., 10 MPa to several hundred MPa).	• High unsaturated fatty acid in lipid membrane. • Compatible solutes help by displacing the water molecules bound to proteins that would otherwise lead to their denaturation. • Reduction in proline composition and increase in glycine as it has high conformational flexibility and protects proteins from denaturation.

Xerophile	These are capable of surviving in environments with low availability of water or low water activity. Generally, xerophilic organisms can grow at a values lower than xerotolerant organisms (aw below 0.8).	• Goes into reversible form of dormancy. • Produces EPS (extracellular polymeric substances) and biofilm which can hold water several times its weight. • Many energy-consuming processes, such as flagellar motility and chemotaxis are downregulated in cells under desiccating conditions. • Increased ratio of fatty acids that have tighter lipid packing order is thought to preserve the membrane.
Alkaliphiles	The microorganisms that require pH 9 or above for growth and development e.g. Soda lakes, alkaline soils	• Production of carotenoids in large quantities which helps in pumping protons near ATP synthases and cardiolipin, a glycerophospholipid that assists in retaining H+ near cell membrane to avoid diffusion to surrounding PH. • Presence of an Na+/H+ antiporter system
Acidophile	Those microorganisms that can thrive in acidic conditions at pH 2-3 optimally e.g. Acid mine drainage, volcanic areas.	• Acidophiles rely on impermeable cell membranes, proton transporter systems, cytoplasmic buffering, K+ ions and active proton extrusion strategies. • Once the pH drops below a certain level, to achieve intracellular pH homeostasis, A. thiooxidans, exports the excess protons out of the cytoplasm by upregulating the H+-ATPase activity and metabolising ATP.
Halophiles	These organisms grow at high salt concentration e.g. Salt lakes, salt mines, saline soils. These organisms are differentiated into different types on basis of the salt concentration such as slightly halophiles (bear salt concentrations of 0.2–0.85 M), moderately halophiles (tolerate salt concentrations of 0.85–3.4 M), and true halophiles (tolerate	• Have > 60% G+C content probably to avoid UV dimerization of thymidine in such habitats. • Presence of two or more large plasmids and presence of multiple replication origins. The presence of mega plasmids assists in adaptation to excessive salt conditions. • The ability of halophiles to produce secondary metabolites such as red–orange carotenoids, gas vesicles and higher cytoplasmic KCl concentration facilitate their adaptive responses.

	salt concentrations between 3.4 and 5.1 M).	
Radiophile	Microorganism that thrives in the presence of radiation (Ultraviolet Light, Gamma Rays, and X-rays) and huge oxidative stress such as uranium mines, radioactive waste areas etc.	• Homologous recombination and non-homologous end joining repair breaks. These organisms often contain multiple copies of their genome (4–10 copies). This provides template redundancy for DNA repair. • High Antioxidant Concentration like Manganese. • Compact and Tightly Coiled DNA Structure which Minimizes diffusion of broken DNA ends.

APPLICATIONS OF EXTREMOPHILES

Extremophiles have various applications in the diverse fields and some of them are illustrated in Figure 2.

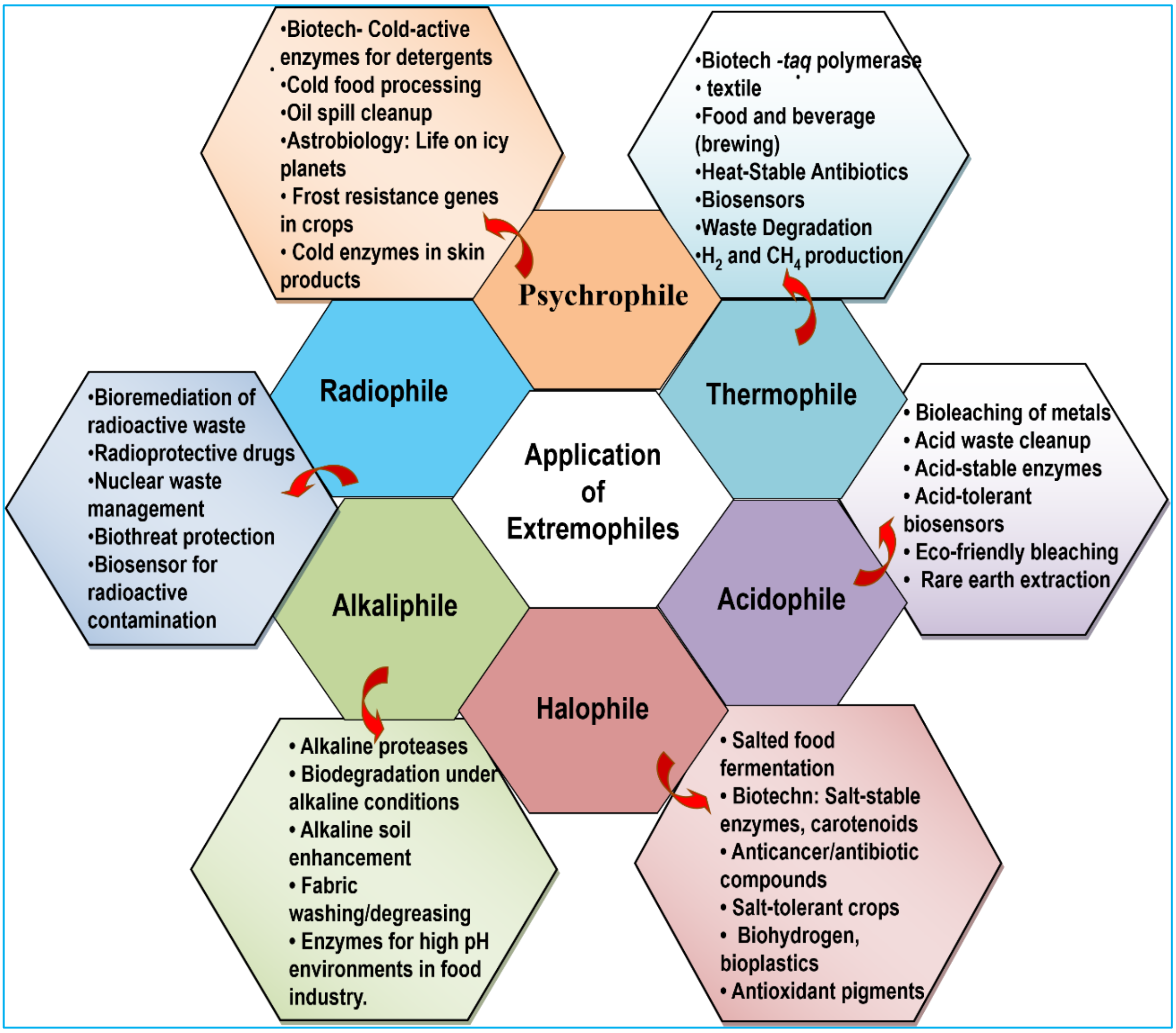

Figure 2. Application of various Extremophiles (**Source:**

EXTREMOPHILES AND SUSTAINABILITY

With the global resources being reduced and steadily increasing population of humans, the world's concern has shifted to issues of sustainability which was encapsulated and formalized by the United Nations with the adoption of 2030 agenda for sustainable development and presentation the 17 sustainable development goal (SDG) in 2015. The SDGs that are supported by extremophiles are listed in Table 2.

Table 2. Extremophiles in Sustainable Development Goals (SDGs) of UN

SDGs	Role of extremophile in SDGs
3 GOOD HEALTH AND WELL-BEING	This SDG incorporates many elements relating to communicable and non-communicable human diseases. Although there has not been significant contribution by extremophiles but extremoenzymes like taq polymerase has been used for detection of disease and Bacterioruberin, a rare C50 carotenoid synthesized by most haloarchaea a cytotoxic effect on human breast cancer lines. Novel C50 carotenoids from Natrialba sp. M6 demonstrate antiviral activity against hepatitis viruses (HCV, HBV).
7 AFFORDABLE AND CLEAN ENERGY	Extremophile and Extremoenzymes are used in production of bioethanol, biohydrogen and help in methanogenesis, degradation of lignocellulosic material, liquid organic hydrogen carrier synthesis and microbial fuel cell.
9 INDUSTRY, INNOVATION AND INFRASTRUCTURE	Extremoenzymes has great potential for industrial application due to ability to withstand harsh conditions example Sulfolobus acidocaldarius are being used for production of archaeal liposomes (archaeosomes), which can serve as delivery systems for vaccines and for trehalose production(sugar that protects cells and protein in extreme conditions) and Thermophilic sugar isomerases which can be used for the synthesis of new nutraceuticals as sugar-free products which could combat chronic diseases such as diabetes, obesity and hypertension.
12 RESPONSIBLE CONSUMPTION AND PRODUCTION	Extremophiles are being used for making products like Bilurubin (Bioelectricity), PHAs (Biodegradable Plastic) and Amino Acids, Biofuels etc.
14 LIFE BELOW WATER and 15 LIFE ON LAND	These goals address the conservation, restoration and sustainable use of marine and terrestrial ecosystems. a significant proportion of global marine, freshwater and terrestrial ecosystems are polluted by industrial and urban wastes (e.g., petroleum, mining waste, agricultural runoff and hazardous chemicals) which can be reduced by Bioremediation like Bioprecipitation, Bioaccumulation, Biotranformation etc. which are performed by extremophiles very efficiently than the native population of the microorganisms present there due to the adaptation they have acquired in the course of their evolution.

CONCLUSION

Extremophiles not only provide valuable insights into the origin and evolution of life on early Earth but also represent a powerful resource for sustainable biotechnology. Their unique adaptations enable the development of innovative solutions to resource depletion while minimizing ecological harm. Thus, Extremophiles serve as both a bridge to our planet's past and a key to addressing present and future environmental challenges.

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