Review Article

Exploring Extremophiles: From Environmental Diversity to Next-Generation Biotechnology

Shivani Mehra, Manjusha Pal and Shikha Thakur*

Department of Biotechnology, School of Applied and Life Sciences, Uttaranchal University, Dehradun, Uttarakhand, India

*Email-Id: patho.shikha@gmail.com

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Abstract

Extremophiles are the microorganisms that survive in extreme environmental conditions such as high and low temperature, salinity, pH, pressure and radiation. Their extraordinary physiological and molecular adaptations including stable enzymes, specialized membrane structures, effective DNA repair systems and unique metabolic pathways, which enable them to survive where most of the life forms cannot. The extremophiles biological diversity highlights their significance for evolution and their ability to sustain biogeochemical cycles in hostile conditions. The group of extremophiles has drawn a lot of attention in recent years due to its biotechnological potential. They can be used in industrial biocatalysis, environmental remediation and bioenergy production because of the exceptional stability and activity of their enzymes, known as extremozymes. The discovery and application of novel extremophiles and their functional biomolecules have significantly expanded as a result of these recent discoveries as well as advancements in metagenomics, genome mining and synthetic biology. These technologies have made it viable to identify microorganisms that were previously unable to be grown and develop robust microbial systems for industrial application. Extremophiles are becoming one of the most important sources of sustainable innovation and combine latest biotechnological techniques. Their distinct characteristics leads them in the next-generation biotechnology, with potential solutions to the global problems in industries, energy, and environmental management.

Keywords: Bioremediation, bioenergy, biotechnology, extremophiles, extremozymes, metagenomics

Introduction

Extremophiles are microorganisms that can survive under environmental conditions that were previously been considered incompatible with life (Pikuta et al., 2007). These life forms are found in the ecological conditions of extreme temperature, pH, salinity, pressure, radiation or desiccation such as hydrothermal vents, hypersaline lakes, acidic mine drainages, polar ice and deep-sea trenches (Oarga, 2009). The identification of extremophiles essentially transformed the understanding of the life on earth and revealed that microbial life is likely to endure and are

adaptable than previously believed (Pikuta et al., 2007). Their ability to endure and operate in extreme conditions has opened new avenues in microbiology, biotechnology and astrobiology as extremophiles have become primary biological resources for scientific and industrial innovation (Rawat et al., 2024). Extremophiles have gained major scientific concern after thermophilic microorganisms in hot springs and hydrothermal vents were discovered during the late twentieth century (Miroshnichenko & Bonch-Osmolovskaya, 2006). The most notable results was the identification of thermophilic archaea which can grow at temperatures higher than 100 ℃ (Amend & Shock, 2001). Extremophiles are classified into various categories based on the environmental stress that they endure such as thermophiles and hyperthermophiles (high temperature), psychrophiles (low temperature), halophiles (high salinity), acidophiles and alkaliphiles (extreme pH), barophiles or piezophiles (high pressure), and radiophiles (high radiation) (Rekadwad et al., 2023). Each group possesses their own physiological and molecular adaptations that enable them to sustain cellular stability and metabolic activity in extreme condition (Jaenicke, 1991).

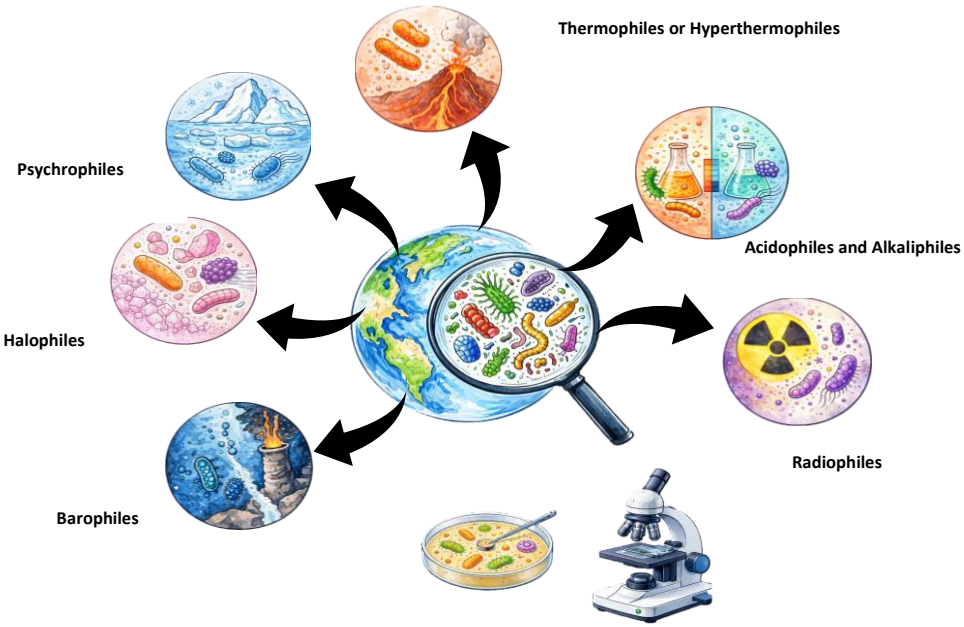

Figure 1: Bacteria in Various Environmental Conditions

Extremophiles survive in harsh conditions due to their specialized biochemical and structural adaptations (Brininger et al., 2018). These include stable enzymes, modified membrane lipids, efficient DNA repair mechanism, and protective molecules such as compatible solutes and heat-shock proteins (Sottile & Nadin, 2018). These adaptations have the benefit that they maintain the functionality of cellular components despite existing in conditions that would denature proteins

or disrupt membrane in most organisms (Jaenicke, 1991). Molecular biology and genomics research have revealed that extremophiles have unique metabolic pathways and genetic characteristics which enable them to exploit minimal nutrients and sustain energy generation in harsh conditions (Rampelotto, 2024). These discoveries have significantly contributed to our understanding of microbial evolution and the processes supporting life in the stressful environmental conditions (Guan et al., 2017).

Ecological significance of extremophiles has become highly valuable in biotechnology due to the extraordinary stability of their enzymes commonly known as extremozymes (Raddadi et al., 2015). These enzymes function effectively in conditions that normally inhibit conventional biological catalysts such as high temperature, high salinity, or extreme pH (Lowe et al., 1993). Among the most well-known examples is the thermostable DNA polymerase derived from the thermophilic bacterium *Thermus aquaticus* which revolutionized the field of molecular biology through its use in the polymerase chain reaction (PCR) (Terpe, 2013). With its ability to provide strong catalytic activity in harsh industrial environment, extremozymes are now widely applied in various industrial sector including food processing, pharmaceuticals, biofuel production, textile manufacturing and detergents (Sarmiento et al., 2015). Recent advances in high-throughput sequencing, metagenomics, and genome mining have further enhanced the discovery of novel extremophiles and their functional genes (Han et al., 2024). There are various extreme environments that remain unexplored and modern omics technologies enable scientists to study microbial communities directly on environmental samples, without the need of traditional cultivation (Han et al., 2024). Extremophiles are also being explored in bioremediation, bioenergy production and biomining, where their resilience allows them to exist in environments that are unfavourable to conventional microorganisms (Sepe et al., 2025).

Diversity of extremophiles

Extremophiles constitute a diverse group of microorganisms which can survive and thrive in environments that are fatal to most life forms. These microorganisms thrive in environmental conditions with extreme temperature, salinity, pH, pressure and radiation. Most extremophiles are bacteria and archaea, but some fungi and microalgae also known as extremotolerant. Their distinct physiological adaptation allows them to colonize ecosystem that were initially consider as hostile and they play significant roles in global biogeochemical cycles. The major group of microorganisms are thermophiles and hyperthermophiles, psychrophiles, halophiles, acidophiles and alkaliphiles and barophiles or piezophiles as discuss in table 1.

Table 1: Major group of microorganisms

Types of Extremophiles	Environmental Conditions	Habitat	Feature of adaptation	Example of Microorganism	References
Thermophiles	Temperature is high (45-80°C)	The habitat is hot springs, hydrothermal vents, volcanic soils.	Heat-stable enzymes, thermostable proteins, saturated membrane lipids	*Thermus aquaticus* *Pyrococcus furiosus*	Stetter, (2013)
Psychrophiles	Temperature is low (<15°C)	The habitat is polar ice caps, glaciers, deep oceans, permafrost.	Cold-active enzymes, flexible protein, unsaturated membrane lipids	*Psychromonas ingrahamii* *Colwellia psychrerythraea*	Carré et al., (2022)
Halophiles	Salinity is high (3-30% NaCl)	The habitat is salt lakes, solar salterns, saline soils.	Compatible solutes, salt-stable proteins	*Halobacterium salinarum* *Haloferax volcanii*	Oren, (2011)
Acidophiles	pH is low (<3)	The habitat is acid mine drainage, sulfuric hot springs.	Proton pumps, acid-stable enzymes	*Acidithiobacillus ferooxidans* *Sulfolobus acidocaldarius*	Madigan et al., (1997)

Alkaliphiles	pH is high (>9)	Habitat is soda lakes and alkaline soils	Alkaline-stable enzymes, sodium ion transport systems	*Bacillus alcalophiles* *Natronobacterium gregoryi*	Horikoshi, (2006)
Barophiles (Piezophiles)	Hydrostatic pressure is high (>10 MPa)	Found in deep-sea trenches, ocean sediments	Pressure-resistant membranes and enzymes	*Shewanella benthica* *Colwellia marinimaniae*	Jørgensen and Boetius, (2007)

The extremophilic nature of microbes is the indication of the remarkable ability of microorganisms to colonize and survive in previously hostile conditions (Kumar et al., 2022).

Adaptation mechanisms

Extremophiles survive and thrive in harsh environmental conditions with a range of highly specialized physiological and molecular adaptations (Rampelotto, 2024). The mechanism enables them to maintain cellular integrity, metabolic activity and genetic stability even they are exposed to extreme temperature, pH, salinity, pressure and radiation. Extremophiles have been identified by significant molecular adaptations particularly in terms of protein structure and enzyme stability (Rao et al., 2022). They produce enzymes known as extremozymes that are resistant to harsh environments (Littlechild, 2015). Psychrophiles produce flexible enzymes that remain active at low temperatures and thermophiles have compact, rigid enzymes with strong ionic interactions that prevent them from denaturing at high temperature (Feller, 2013).

Extremophiles modify the structure of their cell membranes to maintain stability so psychrophiles utilize unsaturated lipids to maintain the membrane fluid, whereas thermophiles contain rigid saturated lipids (Russell, 2007). Barophiles also modify the properties of membrane in response to high hydrostatic pressure, which in required maintain the normal functions of cells (Yano et al., 1998).

It is essential to adjust to chemical stressors. Both acidophiles and alkaliphiles can survive in extremely acidic or alkaline environments by controlling the internal pH through ion transport systems and membrane impermeability (Mamo, 2019). Protein stability at high salinity is achieved by halophiles storing suitable solutes or ions in response to osmotic stress (Saum & Müller, 2008).

Radiophiles have antioxidant mechanisms and efficient DNA repair systems to avoid radiation damage (Ranawat & Rawat, 2017). Stress-sensitive genes and molecular chaperones support the genomic and metabolic adaptability of extremophiles, which protects their survival in survival in several harsh environments simultaneously (Evgen'ev et al., 2014).

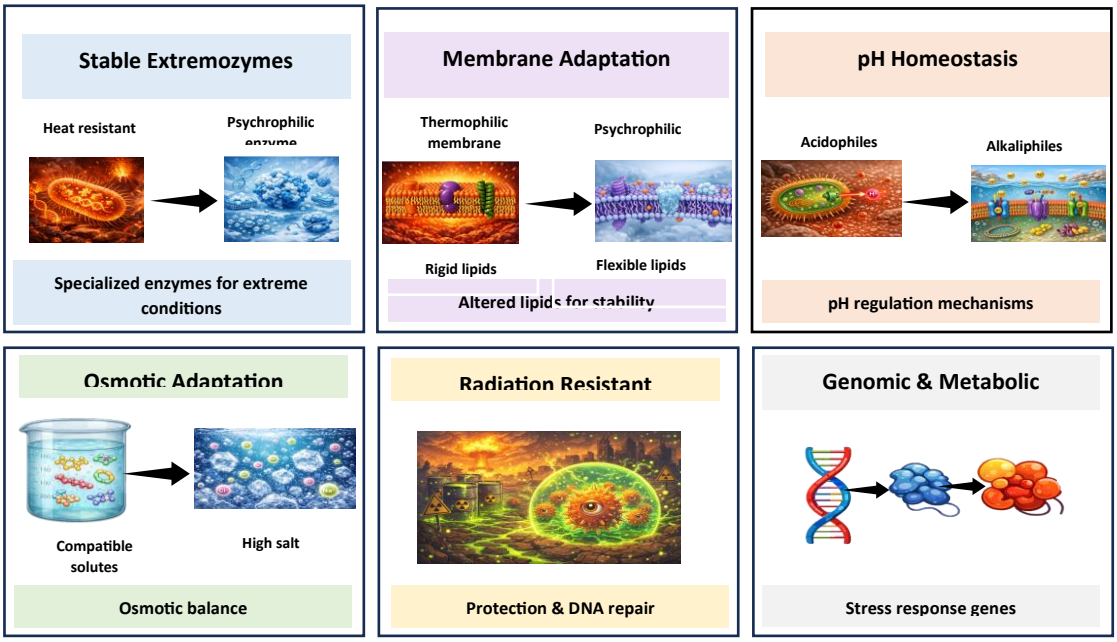

Figure 2: Mechanism of extremophiles in harsh condition

Next-generation applications

Extremophiles and their biomolecules are emerging as potent biotechnological tools in the next generation, in areas where traditional biological systems fail (Sepe et al., 2025). Their natural stability in extreme conditions enables their useful integration into novel industrial and environmental applications, which enhance the efficiency, sustainability, and economy. Industrial biocatalysis has been revolutionized by extremozymes, which operate at extreme temperature, pH, and salinity, thus, leading to low process control conditions and low contamination risks (Zhou et al., 2011). Extremozymes are being employed in the pharmaceutical, food, textile and detergent industrial sector to enhance the product stability and reaction rates (Kakkar & Wadhwa, 2022). For example, thermostable enzymes have enable the application of high temperature in the starch conversion and bioethanol production process and alkaliphilic enzymes have broad application in detergent formulations to provide performance in alkaline environments (Fujinami & Fujisawa, 2010). These applications are not just efficient in operations, but also contribute to more sustainable and environmentally friendly industrial processes (Jena et al., 2020). Extremophiles is important in environmental remediation especially in industrial wastewater purification and in

remediation of polluted ecosystems (Swaminaathan et al., 2024). Their capacity to thrive in adverse and toxic mediums enables them to eliminate contaminants including heavy metals, hydrocarbons, and synthetic dyes in conditions in which other microorganisms do not work (Tripathi et al., 2023). This renders them useful tools of bioremediation efforts that are geared towards rehabilitating polluted environment (Pande et al., 2020). Extremophiles are also being studied in the context of the bioenergy sector with regards to their role in the production of biofuels like biohydrogen, biomethane and advanced bioethanol (Sarkar, 2022). Their metabolic mechanisms are also modified to work effectively across the extremes, which allows sustained and stable bioenergy production even in the harsh industrial environment. This provides viable options of sustainable power (Yadav et al., 2025). Synthetic biology and genome engineering have increased the pace of exploitation of extremophiles (Ye et al., 2023). The technologies of metagenomics and gene editing allow utilizing new genes and metabolic pathways present in extremophiles and express them in engineered systems (Gallo et al., 2021). This has created new prospects of creating strong microbial platform that is able to generate high-value product, pharmaceuticals and bio-based products on the harsh process environments (Liu et al., 2025).

Future prospects

The future of the field of extremophiles research is already determined by exceptional recent advancements in metagenomics, genomics mining and innovative biotechnology techniques that enable the exploration of currently unexplored microbial diversity (Rampelotto, 2024). Genome mining is another technology that speeds it up as it allows the in-silico discovery of functional genes and biosynthetic gene clusters that relate to stress tolerance, enzyme production, and secondary metabolites (Lee et al., 2020). Using the most sophisticated bioinformatics, one can forecast the functions, stability and even applications without necessarily having to do a lot of growing up of the enzymes (Suplatov et al., 2015). This strategy has greatly increased the range of repertoires of extremozymes which are applicable in industrial biocatalysis, pharmaceutical and environmental technologies (Espina et al., 2022). Genetic engineering integrated with synthetic biology transforming how extremophilic characteristics are applied (Rehman et al., 2026). Extremophile derived genes can now implanted into well-known microbial hosts to produce engineered strains that are capable of functioning under extreme process conditions (Vavitsas et al., 2022). CRISPR-Cas technologies and other technologies are able to edit the genome with maximum regulation of metabolism and producing high-value of compounds (Dudeja et al., 2025). These developments are resulting in emergence of strong microbial cell that can be used in industry (Nielsen et al., 2022). Extremophile genes have been susceptible to transfer into established microbial hosts and produce engineered strains that can operate in extreme process environments

(Gallo et al., 2021). Such technologies as CRISPR-Cas systems provide accurate genome editing, which allows optimizing metabolic pathways and enhancing the synthesis of high-value compounds (Das et al., 2024). These development are leading to the emergence of powerful microbial cell factories to industrial purposes (Clomburg et al., 2017). Machine learning and artificial intelligence are emerging tools that are becoming critical in the prediction of protein structure, enzyme stability, and functional structures in extreme conditions (Niazi, 2025). These technologies are efficient in enzyme discovery and design and less time and cost are used in conducting experiments (Bunzel et al., 2018). Combined with high-throughput screening methods, they make it possible to shorten the time spent to identify attractive candidates to be used in biotechnology (Zeng et al., 2020).

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