Surviving the Extremes: How Proteins and Enzymes Adapt to Alien-like Conditions

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ABSTRACT

Life thrives in some of the most extreme environments on Earth, offering valuable insights into how organisms might survive in extraterrestrial conditions. Extremophiles and their enzymes, adapted to these harsh ecosystems, hold great promise for green biotechnology, enabling sustainable and eco-friendly industrial processes. Antarctica's hypersaline Deep Lake (-18°C to +11.5°C, 21– 28% salt) and the brine pools of the Red Sea (23°C to 68°C, 26–33% salt, high metal content) are prime examples of extreme habitats that mimic alien-like conditions—characterized by high salinity, temperature extremes, and low water activity. Microbial enzymes from these environments exhibit remarkable stability and activity under conditions resembling those found on icy moons like Europa or the subsurface oceans of Mars. A cold- and salt-tolerant β-galactosidase from *Halorubrum lacusprofundi* in Deep Lake, identified through culture-dependent methods, reveals key adaptations to hypersaline, subzero environments. Meanwhile, Single Amplified Genome (SAG) analysis of the Red Sea brine pools uncovered an alcohol dehydrogenase and carbonic anhydrase from uncultured microbial dark matter, shedding light on survival strategies in extreme conditions. These enzymes were expressed in a halophilic system, purified, and structurally and functionally characterized. Notably, purified enzymes retained activity under extreme temperatures, high salt concentrations, and organic solvents demonstrating their robustness in conditions inhospitable to most biomolecules. Structural studies, including X-ray crystallography and molecular dynamics simulations, provide critical insights into how extremozymes maintain stability and function in extreme conditions— leveraging increased surface acidity and fine-tuned flexibility to endure high salinity and temperature

DOI: 10.21467/abstracts.177 ISBN: 978-81-984081-3-6 (eBook), 978-81-984081-9-8 (Paperback)

fluctuations. These findings pave the way for engineering enzymes with enhanced properties for green biotechnology, bio-based industries, and sustainable innovations.

Keywords: Extremophiles, Extremozyme, Halophiles, Polyextremophiles, Thermophiles, Sustainability

How to Cite

Ram Karan, Dominik Renn, Shubham Pandey, Bhavna Parmar, Jorg Eppinger, Stefan Arold, Thorsten Allers, Magnus Rueping, “Surviving the Extremes: How Proteins and Enzymes Adapt to Alien-like Conditions”, *AIJR Abstracts*, pp. 55-56, Mar. 2025.