Acidophiles: masters of acidic realms

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Abstract. *Galdieria sulphuraria* is a unicellular red alga that thrives in extreme acidic environments, such as geothermal sulfur springs, characterized by low pH, high temperatures, and toxic metal concentrations. This study investigates the unique adaptations, molecular defense mechanisms, and ecological roles of *G. sulphuraria*, while emphasizing its potential for biotechnological applications. The alga's exceptional metabolic flexibility allows it to function as a heterotroph, utilizing a diverse range of substrates and surviving in complete darkness. Its resilience is further supported by specialized membranes and proteins adapted to acidic and high-temperature conditions, as well as robust metal detoxification systems. Genomic analysis reveals evidence of horizontal gene transfer from extremophilic Archaea and Bacteria, enhancing its ability to tolerate harsh conditions and metabolize diverse compounds. Ecologically, *G. sulphuraria* plays a vital role in nutrient recycling in extreme habitats, while biotechnologically, it holds promise in biofuel production, wastewater treatment, and sustainable industrial processes. By examining this alga's extraordinary adaptability, the study expands our understanding of life's boundaries and its potential applications in Earth-based and extraterrestrial environments.

Key words: biotechnological applications, extremophiles, *Galdieria sulphuraria*, metabolic flexibility.

Introduction. Acidophiles are organisms that thrive in environments with extremely low pH, such as volcanic springs, acid mine drainage, and sulfuric hot springs (Arce-Rodríguez et al 2020; Hedrich & Schippers 2021). Among these extremophiles, the unicellular red alga *Galdieria sulphuraria* stands out for its remarkable versatility and resilience, thriving in conditions that would dissolve most forms of life. The aim of this study is to explore the unique adaptations, molecular defense mechanisms, and ecological roles of *G. sulphuraria*, a highly resilient acidophilic alga, while highlighting its biotechnological potential in applications such as biofuel production, wastewater treatment, and sustainable industrial processes. By examining its ability to thrive in extreme environments, the study seeks to expand our understanding of life's limits and uncover insights relevant to both Earth and extraterrestrial ecosystems.

Habitat and adaptations. Native to geothermal environments like the sulfur springs of Yellowstone National Park (Canelli et al 2023), *G. sulphuraria* (Figure 1) is uniquely adapted to survive in highly acidic conditions (pH levels close to 0) and extreme temperatures exceeding 50°C (122°F) (Pan et al 2021). These habitats are saturated with toxic metals and often devoid of other life forms, yet this alga not only survives but thrives (Kharel et al 2023a, b).

One of the key adaptations of *G. sulphuraria* is its ability to metabolize a wide variety of organic and inorganic substrates (Maamoun et al 2020). Unlike many algae that rely solely on photosynthesis, this organism exhibits remarkable metabolic flexibility, functioning as a heterotroph by absorbing nutrients directly from its environment. This allows it to persist in complete darkness or environments where photosynthesis is impossible due to the absence of light (Abiusi et al 2021).

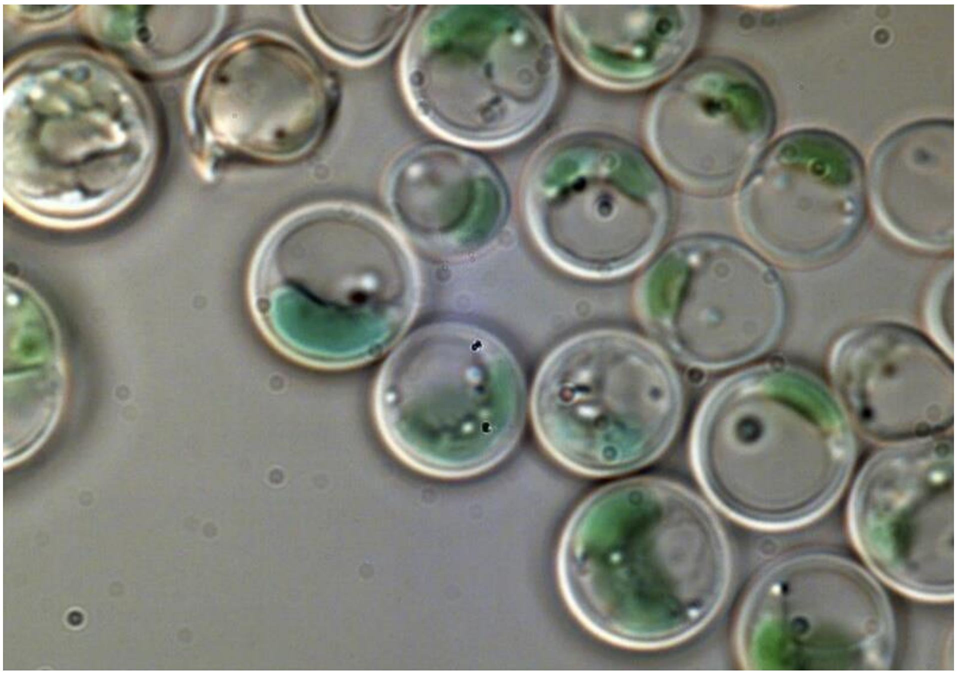

Figure 1. The extremophile protist *G. sulphuraria*, a mixotrophic species of thermoacidophilic red algae, here growing under illumination. Light micrograph, Rappaport & Oliverio (2023) courtesy of Gerald Schöenknecht (Oklahoma State University, Heinrich-Heine-Universität Düsseldorf).

Molecular defense mechanisms. The cell membrane and protein structures of *G. sulphuraria* are engineered for resilience (Vítová et al 2022). Its membranes are enriched with specialized lipids that remain stable in acidic conditions, while its proteins are uniquely folded to resist denaturation caused by heat and acid. Additionally, this alga employs robust metal detoxification systems, using chelating molecules and efflux pumps to neutralize and expel heavy metals (Kharel et al 2023a, b).

Its genome reveals a fascinating history of horizontal gene transfer from Archaea and Bacteria that share its extreme habitat. These borrowed genes contribute to its ability to tolerate acidity, detoxify metals, and metabolize diverse substrates. This genetic borrowing exemplifies how extremophiles adapt by integrating useful traits from their microbial neighbors.

Other acidophilic species. Microorganisms such as *Acidithiobacillus ferrooxidans* and *Ferroplasma acidarmanus* are known for their ability to oxidize iron and sulfur, making them essential in bioleaching processes for metal recovery. Archaea like *Sulfolobus acidocaldarius* thrive in hot, acidic springs, exhibiting remarkable resilience to high temperatures and low pH. *Leptospirillum ferrooxidans* plays a key role in the oxidation of ferrous iron in acidic mine drainage systems, while *Acidiphilium cryptum* demonstrates metabolic versatility by utilizing a variety of organic compounds in low-pH environments. These acidophiles highlight the extraordinary adaptability of life in extreme conditions and have significant ecological and industrial applications.

Ecological and biotechnological importance. Beyond its scientific appeal, *G. sulphuraria* holds significant ecological and biotechnological importance. In its natural environment, it plays a crucial role in nutrient recycling within extreme ecosystems. Additionally, its metabolic flexibility and ability to produce valuable compounds like phycocyanin and antioxidants position it as a promising candidate for various biotechnological applications (Wan et al 2021). Researchers are investigating its potential in biofuel production, wastewater treatment, and the development of sustainable industrial processes.

Conclusions. *Galdieria sulphuraria* exemplifies the extraordinary adaptability of life in extreme environments. By thriving in acidic, metal-rich, and thermally challenging habitats, this alga challenges our understanding of the limits of biology. Its unique adaptations and potential applications underscore the importance of studying extremophiles - not just for unraveling the mysteries of life on Earth but also for exploring possibilities beyond our planet.

Conflict of interests. The authors declare that there is no conflict of interest.

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