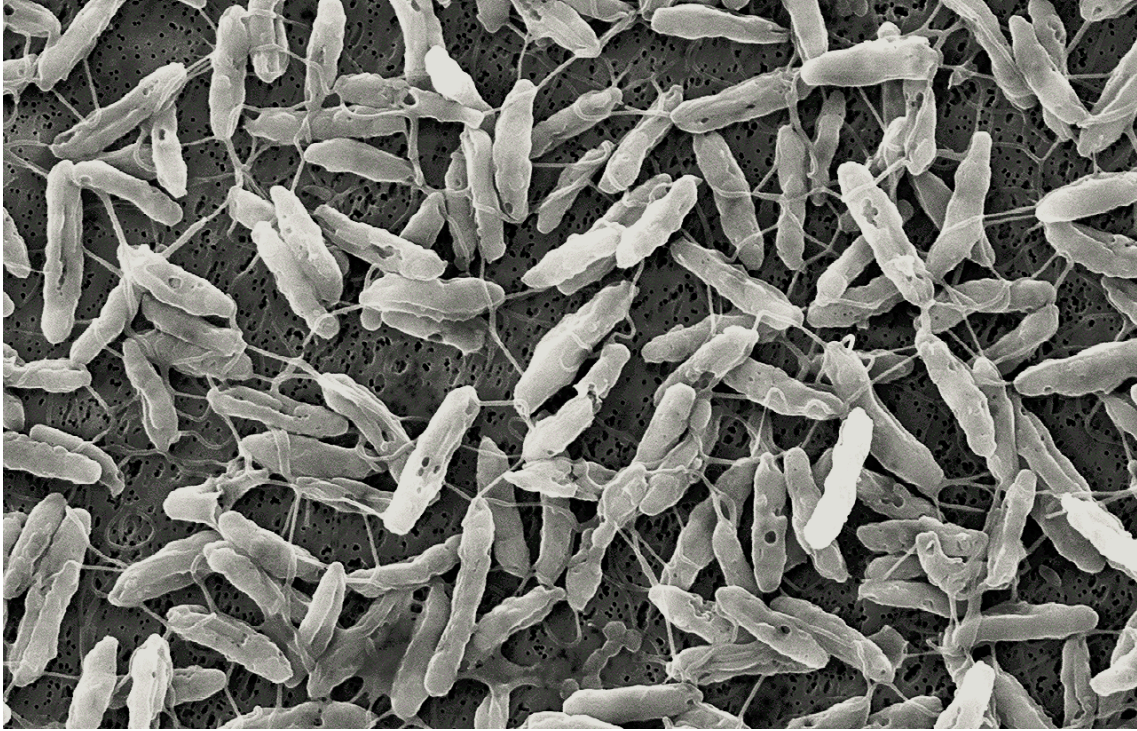


Extremophile Hero: Duna (*Dunaliella acidophila*)

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Claim to Fame: one of the most acidophilic (acid-loving) microalgae known

Duna is a microbe that thrives in highly acidic aquatic environments that can have a pH value as low as 0.1. This unique ability, combined with its potential for biotechnological applications, makes it a subject of great interest in scientific research and industry. As studies continue to uncover new aspects of its biology and applications, this microalga may become an important resource in fields ranging from natural pigment production to environmental sustainability and astrobiology.

Duna (*Dunaliella acidophila*) is a single-celled green alga belonging to the phylum Chlorophyta and the order Chlamydomonadales.

Like other species of the genus, it lacks a rigid cell wall and instead possesses a flexible external membrane as the cell envelope, which provides the ability to adapt to extreme environmental conditions. The absence of cell wall allows Duna to rapidly adjust its volume and shape in response to changes in osmotic pressure caused by freshwater input, which lowers osmotic pressure, or inputs in salt or other osmotically-active substances, that increase osmotic pressure.

Duna is motile – swims – using two equal-length flagella that act as a propeller and enable it to move freely in aquatic environments.

It contains chloroplasts, organs of photosynthesis responsible for capturing the energy of sunlight to power the conversion of carbon dioxide into sugars. These are the starting materials for the production of all cellular compounds and components, and hence of life. Duna's chloroplasts have high concentrations of light-capturing photosynthetic

pigments, including chlorophylls and carotenoids. These pigments, particularly β -carotene, give Duna species their characteristic coloration, which can range from green to orange, depending on environmental conditions.

What is special about extreme acidity and how does it affect biological systems?

Extreme acidity is one of the harshest environmental conditions for life. High concentrations of hydrogen ions (H^+) present in acidic environments disrupt normal biological functions in most organisms. These effects include:

- **protein denaturation:** acidic conditions cause proteins to lose their shape and function, leading to metabolic failure in most life forms.
- **disruption of cellular membranes:** high concentrations of H^+ ions can destabilize lipid bilayers, the structural components of the cell envelope, making cells more permeable and prone to leakage.
- **interference with metabolism:** many biochemical reactions rely on specific pH ranges to function correctly. In highly acidic environments, enzymatic activity is severely hindered or completely halted.
- **oxidative stress:** acidic conditions often lead to increased production of reactive oxygen species, which can damage DNA, proteins, and lipids within cells.
- **inhibition of photosynthesis:** most photosynthetic organisms struggle to maintain efficient light-harvesting and electron transport chain function under acidic conditions, leading to reduced energy production.

Despite these challenges, *D. acidophila* has evolved specialized mechanisms to counteract these effects, making it a prime example of an acidophilic extremophile.

Where is extreme acidity to be found on Earth? Can It Be Visited?

Extremely acidic environments are scarce and can be caused by natural phenomena (i.e. geothermal areas and exposed metal sulfides) or of anthropogenic origin, generally associated with metal and coal mining. These ecosystems are especially interesting because, in general, the low pH of the water is the consequence of microbial metabolism and not a condition imposed by the environment as is the case in many other extreme environments (temperature, radiation, pressure, etc.).

Extreme acidic environments, moreover, can vary greatly in temperature (from $<0^{\circ}C$ to $>80^{\circ}C$) and contain much higher concentrations of dissolved solutes and heavy metals than neutral pH environments. Therefore, the challenges for biota growing in these sites are greater than just coping with external hydronium ion (H^+) concentrations, which can be as much as four to seven orders of magnitude greater than those present in neutral waters.

Acidic environments have two main origins that differ significantly in their physicochemical characteristics and, consequently, in their microbial ecology. They can originate from geothermal and volcanic activity, or be related to the oxidation of metallic sulfide deposits present in the Earth's crust. Environments with extremely low pH, such as acid mine drainage sites, volcanic lakes, and certain acidic hot springs, are home to acidophilic organisms. Some of these locations, such as the Rio Tinto in Spain, volcanic lakes, as well as geothermal areas, can be visited, although safety precautions are necessary due to their harsh conditions.

How does Duna manage to live under such conditions and what are its special features?

To survive in such harsh environments, Duna has developed several biochemical and physiological adaptations:

- **membrane stability:** The plasma membrane contains a unique lipid composition that enhances its resistance to acidic conditions, preventing damage from high concentrations of hydrogen ions.
- **acid-resistant enzymes:** The enzymes have evolved to maintain stability and functionality at extremely low pH levels, allowing essential metabolic processes to continue.
- **carotenoid accumulation:** The production of β -carotene and other carotenoids acts as a protective mechanism against oxidative stress, shielding cellular components from free radical damage.
- **osmotic regulation:** The alga effectively regulates intracellular ion concentrations, maintaining homeostasis despite extreme environmental fluctuations.
- **efficient proton pumps:** Specialized proton pumps actively expel excess hydrogen ions from the cytoplasm, preventing acidification of the internal cellular environment.
- **chloroplast adaptations:** Its photosynthetic machinery has been fine-tuned to operate efficiently in acidic conditions, ensuring that energy production remains stable.

Biotechnological Applications

The unique properties of Duna make it an attractive candidate for various biotechnological applications. Some of the potential uses include:

- **natural pigment production:** Its ability to accumulate high concentrations of β -carotene makes it a valuable source of natural pigments. β -carotene is widely used in the food, cosmetic, and pharmaceutical industries as a colorant and a precursor to vitamin A.
- **acidophilic enzyme production:** The acid-tolerant enzymes found in this species could have industrial applications, particularly in processes that require stable enzymatic activity at low pH levels. These enzymes could be useful in food processing, biofuel production, and pharmaceutical manufacturing.
- **extremophile research:** Studying these species helps scientists understand how life can adapt to extreme conditions. This knowledge can be applied in astrobiology to explore the possibility of life on other planets with acidic environments, such as Venus or certain moons of Jupiter and Saturn.
- **bioremediation:** Acidophilic microalgae may play a role in bioremediation efforts to neutralize acidic wastewaters generated by industries such as mining and chemical manufacturing.
- **biosensors:** Acid-tolerant organisms can be used in the development of biosensors that detect and monitor pH changes in industrial and environmental settings.
- **sustainable agriculture:** Research on acidophiles could lead to the development of acid-resistant crops, improving agricultural sustainability in regions with acidic soils.

Duna is a super hero of highly acidic extreme environments!