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Thermophiles: Masters of heat and their impact on humanity

Ada Szabelewska
Uniwersytet Gdański, Wydział Oceanografii i Geografii
Katedra Biologii Morskiej i Biotechnologii
E-mail: a.szabelewska@gmail.com

tutorka: dr Anna Toruńska-Sitarz
Uniwersytet Gdański, Wydział Oceanografii i Geografii
Katedra Biologii Morskiej i Biotechnologii

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Streszczenie

Środowiska ekstremalne charakteryzują się warunkami, które przekraczają granice tolerancji większości organizmów żywych. Określa się je mianem ekstremalnych, w odróżnieniu od ekosystemów wykazujących warunki sprzyjające wysokiej różnorodności form życia, jakimi są neutralne bądź bliskie neutralnemu pH, wysoka dostępność wody, oraz temperatura nie przekraczająca 40°C. Występowanie wyższej temperatury, klasyfikuje dane środowisko jako ekstremalne, a zamieszkujące je organizmy określane są mianem termofili. Wśród termofili zdecydowanie dominują mikroskopijne organizmy z domen Bakterii oraz Archeonów. Znani są również termofilni przedstawiciele bardziej zaawansowanych ewolucyjne taksonów. Istnienie termofili zostało odkryte pod koniec XIX wieku, kiedy po raz pierwszy opisano mikroorganizmy wykazujące wzrost w temperaturze przekraczającej 70°C. Dalsze badania nad termofilami przyniosły wiele przełomowych odkryć, takich jak odkrycie polimerazy Taq – termostabilnego enzymu wyizolowanego z bakterii *Thermus aquaticus*, które to zrewolucjonizowało technologię PCR (ang. *polymerase chain reaction* – łańcuchowa reakcja polimerazy). Procesy biokatalizy z użyciem enzymów pozyskanych od termofili są badane jako skuteczna, bardziej przyjazna środowisku alternatywa dla katalizy chemicznej, która używana jest w wielu gałęziach przemysłu. Ze względu na swoje ekstremalne przystosowania, termofile znajdują również zastosowanie w astrobiologii – dziedzinie zajmującej się spekulacjami i badaniami nad możliwością istnienia życia pozaziemskiego. Termofile mogą również przyczynić się do lepszego zrozumienia jednej z największych zagadek nauki – pochodzenia życia na Ziemi. Termofile stanowią niezwykłą grupę organizmów, która uświadamia nam i pomaga zrozumieć potęgę zdolności adaptacyjnych życia na naszej planecie, jak i – potencjalnie –

poza nią. Zestawiając analizę źródeł z osobistą refleksją, esej przedstawia termofile jako organizmy, których niezwykłe przystosowania mogą inspirować nie tylko biologów.

Abstract

Extreme environments refer to habitats with such harsh conditions that they exceed the tolerance limits of most organisms. They are classified as extreme in comparison to conditions found in most ecosystems, which support rich biodiversity, such as near-neutral pH, high water availability, and temperatures not exceeding 40°C. High temperature is one of the defining characteristics of some extreme environments. Organisms that thrive under high temperatures are known as thermophiles. This group mostly constitutes of microscopic Bacteria and Archaea, however there are also some examples of thermophiles from more evolutionary developed taxa. The existence of thermophilic microbes has been known since late 19th century, when bacteria growing above 70°C were described for the first time. With further research into these organisms came many scientific breakthroughs, such as the discovery of Taq polymerase – a thermostable enzyme isolated from bacterial species *Thermus aquaticus*, that revolutionized the PCR (polymerase chain reaction) technology – now a staple laboratory technique. Currently, biocatalysis processes with the use of thermostable enzymes are being investigated as a substitute for chemical catalysis used in industrial processing, which presents a more environmentally friendly solution in the era of climate change. Because of their extreme adaptability, thermophilic microbes are also among organisms studied to determine the possibility of existence of extra-terrestrial lifeforms. Thermophiles may also shed light on one of the biggest mysteries in science – the origins of life on Earth. These organisms represent a fascinating natural phenomenon, continually challenging and redefining the boundaries between habitable and uninhabitable environments. By combining source analysis with personal reflection, the essay presents thermophiles as organisms whose remarkable adaptations can inspire not only biologists.

Introduction

Before we start the discussion on thermophiles, we first need to place them within the broader, arbitrary category they belong to, namely – extremophiles. The name "extremophile" is given to any organism, that lives outside the boundaries of environmental conditions that are optimal for the majority of lifeforms, but most significantly humans. These *non-extreme* conditions are, among others, near-neutral pH, high water availability, and temperatures not exceeding 40°C. The term "Goldilocks zone", which references the classical tale *Goldilocks and the Three Bears*, was adapted to describe environmental conditions necessary to support human life, that just like in the tale are not too cold or hot, but just right for us. Extremophiles are therefore defined though the lenses of what is considered normal by human standards and by what they are in relation to us. While it is a very functional term, that presents an easy-to-understand definition, it also inherently links their existence with something that is extreme, or even unnatural. It fails to include a most crucial aspect of extremophilic lifeforms, which is that in these "extreme" environments, they actually thrive. For an abyssal fish, that lives at the depth of 8 000 m and pressure of ~12000 psi, that is a perfect environment. When brought up to the surface – where hydrostatic pressure is optimal for humans – its tissues deform to an unrecognizable extent. From the point of view of organism that occupy the habitats outside of our Goldilocks zone, it is we humans that are extremophiles.

Among extremophiles, organisms that thrive at high temperatures are known as thermophiles (literally – heat lovers). Across different definitions, one constant is the inclusion of a minimal temperature of an organism's habitat that makes it a thermophile. However, these temperature values, as well as the description of thermophiles activity under them differ between definitions. Urbieta *et al.* (2015), describes thermophiles as organisms whose optimum growth temperature is over 55°C. According to Ferrera and Reysenbach (2007), they are organisms that grow best at above 45°C. Brock (2001) defines them as ones that reproduce at high temperatures, the minimum of which depends on the group of organisms taken under the consideration. Some researchers also differentiate organisms that can survive at temperatures above 45°C as moderately thermophilic (Arbab *et al.*, 2022). Overall, we can conclude that a to be a true thermophile, an organism needs to survive, grow and reproduce at temperatures exceeding at least 45°C. Very commonly, a term hyperthermophile is used to distinguish the species that truly mastered the craft of living at high temperatures. At first, they were defined as organism that grow in boiling water, so a temperature around 100°C (Brock, 2001). Today however, the line between thermophiles and hyperthermophiles is typically set at 80°C (Ferrera & Reysenbach, 2007; Stetter, 2006; Berenguer, 2023).

The discovery of thermophiles came at the dawn of bacteriology, in the 19th century. During his study of Seine River bacterial communities in 1888, Pierre Miquel isolated a bacterium which grew at temperatures up to 75°C. For several years afterward, however, thermophile studies were mainly focused on aspects regarding food bacteriology, and environmental research was mainly suspended. At that time, temperature of 60°C was considered a high maximum for thermophilic organisms (Brock, 2001). Important milestones in the research of thermophiles came in the second half of 20th century, when the thermal habitats of USA's Yellowstone National Park drew the attention of bacteriologists, and the diversity of thermophiles was beginning to be unearthed. For the first time, the boundary of temperature at which life can persist was pushed further in 1965, when Thomas D. Brock reported a bacterium living in temperatures up to 88°C in the Octopus Spring of Yellowstone National Park (Brock, 2001). The first instances of microbes sustaining life at temperatures near-boiling point and over, were reported in the 1980s, when Karl O. Stetter and Wolfram Zillig discovered them in Icelandic hot springs and mud pools (Stetter, 2006). As for the microbial studies in general, the development of environmental omics broadened the horizons of the thermophilic biodiversity research. This technology eliminates the need for culturing, which can often be challenging in case of extremophiles.

As organisms adapted to high-temperature conditions, thermophiles are naturally found in a wide range of hot habitats. They are mainly associated with geothermal environments, such as hot springs, mud pots and deep-sea hydrothermal vents (Ferrera & Reysenbach, 2007; Fig. 1, Fig. 2). The place most known for its vast diversity of thermophiles is probably the Yellowstone National Park, which is extremely abundant in various geothermal structures. Recent findings, however, indicate that thermophiles are distributed more widely across diverse environments than previously believed, making their biogeographical characterization increasingly complex. These organisms have been found in places such as deep gold mines, sediments and oil reservoirs. They even occupy niches in places we wouldn't expect to find heat-loving organisms, such as in Iceland (Cockell *et al.*, 2015). Certain conditions can create the so-called microenvironments, that sustain thermophilic lifeforms. These are sun-warmed rocks and melt ponds, that are heat up by sunlight to high temperatures during polar days (Cockell *et al.*, 2015). Thermophiles have also been found in the variety of man-made places and constructions, often ones we wouldn't expect to sustain life. They inhabit hot water supply systems and reservoirs, compost piles, bioreactors, coal piles and even nuclear and geothermal power plants (Ferrera & Reysenbach, 2007; Urbieta *et al.*, 2015; Fig. 3). It is fascinating that even though we think of these organisms as extreme and how alienating the environments in which they live seem to us, it is very possible that in our day-to-day lives, we are constantly in close proximity to thermophilic communities, that live in the water pipes of our homes. A study led by Wilpiszeski *et al.* (2019), which employed citizen science to collect samples from domestic water heater across USA, showcased the vast diversity of thermophilic microbes residing within household systems.

Fig. 1. Grand Prismatic Spring of the Yellowstone National Park
(James St. John, 2013) CC BY 2.0

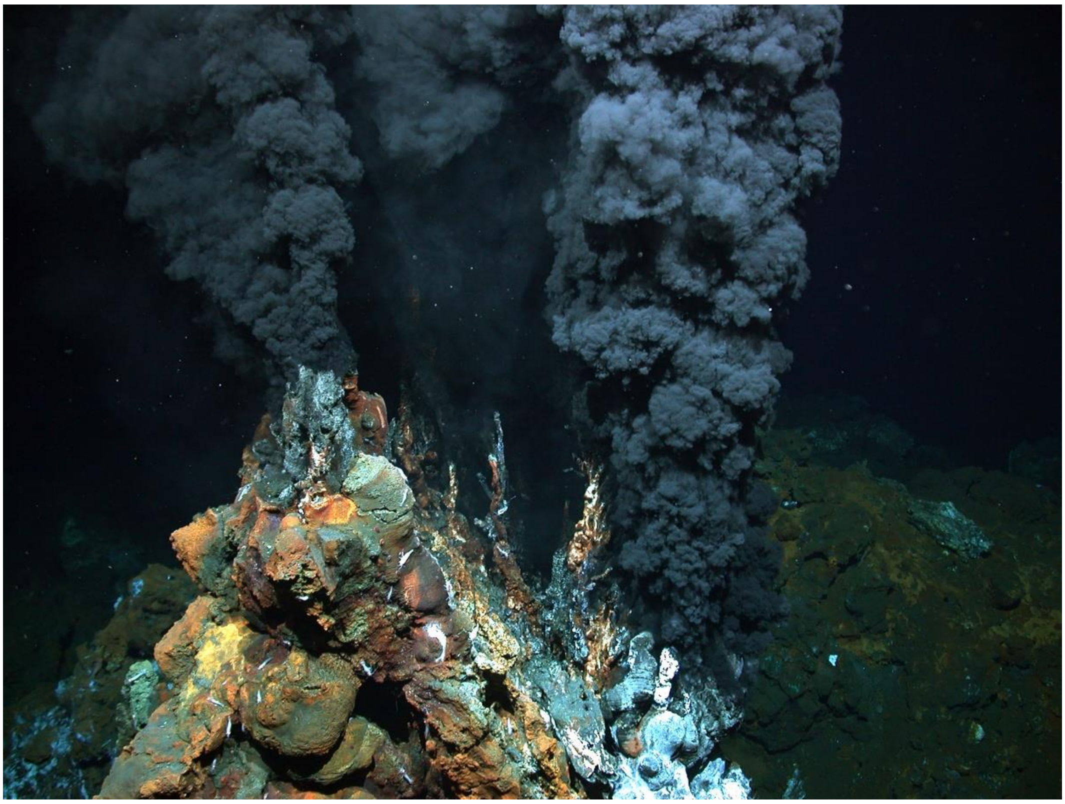

Fig. 2. Deep-sea hydrothermal vents of the Mid-Atlantic Ridge
(Marum, 2015), CC BY 4.0

Fig. 3. A Nuclear Power Plant
(Dean Calma, 2004), CC BY 2.0

Importantly, in many of these habitats, high temperature is only one of the hostile conditions that these microbes endure. Hot springs where thermophile reside, for example, often exhibit extreme pH values, being strongly alkaline or acidic. Organisms inhabiting such places can also be referred to as alkaliphiles and acidophiles, respectively. Overall, thermophiles seem to emerge wherever high temperature persists. It is hard to determine whether they occupy these niches, some of which are completely artificial, due to population spreading or rather by rapidly evolving and adapting to new conditions.

Among thermophilic organisms, we can find representatives from all three domains of life – Eukarya, Bacteria and Archaea (Ferrera & Reysenbach, 2007). Eukaryotes constitute the smallest group among thermophilic organisms and consist of fungi and microalgal species as well as amoebas and ciliates (Davila *et al.*, 2025). The upper limit of optimum growth temperature for them is 62°C, in case of some fungal species, and no hyperthermophilic Eukaryotes have been described (Ferrera & Reysenbach, 2007). Eukaryotic thermophiles utilize same life strategies as their mesophilic counterparts. Thermophilic algae are photoautotrophs, whereas thermophilic fungi are heterotrophs, that decompose organic matter, often performing fermentation and organic carbon oxidation. There are also a few cases of invertebrates that live in high temperature environments; however, little is known about the nature of their adaptations to such conditions. Among them, the most well-described is the Pompeii worm (*Alvinella pompejana*) – a deep-sea polychaete found at hydrothermal vents in the Pacific Ocean (Grzymski *et al.*, 2008; Fig. 4). These polychaetas can sustain extreme heat due to their symbiosis with thermophilic microbes; therefore, it could be debatable if they should be classified as "true" thermophiles. Most literature concerning thermophilic eukaryotes doesn't include these animals.

Fig. 4. Pomepii worm
(Olivier Dugornay, 2002), CC BY 4.0

The diversity of bacterial and archaeal thermophiles is far greater than that of eukaryotes. Thermophilic organisms can be found across all major groups of bacteria. There are also whole taxonomic units, for which thermophily is one of the defining qualities, such as the phylum Thermotogota or family Thermales (phylum Deinococcota) (Farrell, 2024; LPSN accessed on 1st July 2025). Many bacterial thermophiles adopt life strategies that cannot be found among eukaryotes. Purple and green sulphur bacteria, which often inhabit thermophilic environments, are anoxygenic photo-autotrophs that rely on reduced sulfur compounds as electron donors in their photosynthetic processes. Some of other metabolic pathways, such as denitrification (performed by e.g. *Aquifex* genus), are meaningful for potential industry applications of these organisms. Within bacterial thermophiles, we can also find cyanobacterial species, which same as algae, are oxygenic photoautotrophs, however they are able to withstand much higher temperatures (Fig. 5, Fig. 6).

Archaea include the most extreme thermophiles known to science, capable of thriving at the highest recorded temperatures. The record holder, that can reproduce at the temperature of 122°C is an archaeal species *Methanopyrus kandleri* (Takai *et al.*, 2008; Fig. 7). Historically, archaea were mainly associated with all sorts of extreme environments, and terms “archaea” and “extremophiles” were almost synonymous. Further research proved however that not all archaea are extremophiles, and that not all extremophiles are archaea. To this day, however, extremophilic archaea remain disproportionately represented relative to other domains of life. It could be argued though, that it is the extreme environments that have been more intensively studied for archaeal diversity than 1) other domains of life 2) non-extreme environmental niches.

Fig. 5. Green and pink microbial mats formed by thermophilic bacteria, in the hot spring of Yellowstone National Park
(adapted from: Ferrera & Reysenbach, 2007; modified: cropped)

Fig. 6. Microbial community, dominated by thermophilic bacteria in the creek of Yellowstone National Park
(adapted from: Ferrera & Reysenbach, 2007; modified: cropped)

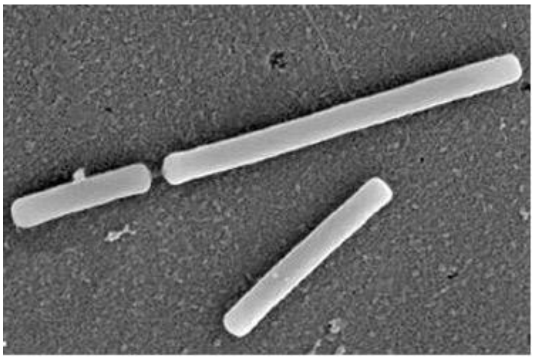

Fig. 7. Methanopyrus kandleri, viewed with the laser scanning microscope
(adapted from: Schopf et al., 2008 modified: cropped)

Showcasing the vast diversity of prokaryotes can be challenging, however one way to do it is with the number of their registered genomes. According to the GOLD database, 241 990 bacterial genomes have been registered (GOLD Database, 2025). In comparison, in the case of archaea it is only 2 857 (GOLD Database, 2025). The vast overrepresentation of bacterial genomes may be because archaeal genome sequencing is far more demanding. Verma *et al*. examined these data in relation to thermophily in 2022. At that time, out of 190 868 registered bacterial genomes, 468 were of thermophiles (0,25%). In case of Archaea, thermophily was far more frequent – out of 1930, 159 were genomes of thermophiles, making them around 8% of all registered genomes. Aside from the differences in the contribution of thermophiles within bacteria and archaea, these numbers showcase just how dynamically the field of genomics develops, with how the numbers of registered genomes grew rapidly over the span of only 3 years.

Mastering heat – thermophilic adaptations to extreme temperatures

One of the most interesting aspects of studies on thermophiles relates to their adaptations that enable survival at extreme temperatures. There is no single defining trait by which an organism can be classified as a thermophile. It is rather a set of adaptations at different molecular levels, that all together constitute the thermophilic nature of these organisms. I want to discuss these adaptations starting from the genomic level, through gene expression, proteins, metabolism and finally morphologic features, focusing on bacterial and archaeal thermophiles.

Genetic information is of course what dictates and allows for thermophiles to thrive at high temperatures, encoding specific genes and therefore functions. Because of that, a very important aspect of thermophilic adaptations is the protection of that information. Elevated temperatures increase the susceptibility of DNA to degradation through mechanisms such as double strand breaks, denaturation, and deamination. Therefore, thermophiles have evolved specific adaptation to counteract DNA thermal damage. While specific trends in genome architecture and sequence composition are common among these organisms, such features are not exclusive to thermophiles and do not, by themselves, confer thermophily. In many thermophiles we can observe genome reduction, as well as higher ploidy – they tend to possess shorter genomes, that are in more copies, in comparison to their mesophilic counterparts (Wani *et al.*, 2022; Verma *et al.*, 2022). Shorter genomes are less susceptible to degradation and mutation, while possessing multiple genome copies reduces the risk of completely losing genetic information. Additionally, within thermophilic genomes, higher GC-content is often observed

(Hus & Bocian, 2017). The guanine-cytosine base pairs form three hydrogen bonds between each other, in comparison to the two between adenine and thymine, allowing for a more stable secondary DNA structure. Another important aspect is the various DNA-protecting enzymes such as topoisomerases, that are present in all kinds of lifeforms, however in thermophiles we can observed their increased expression and activity (Hus & Bocian, 2017).

Genetic information is translated from the DNA into proteins, however along the way is temporarily stored in the form of mRNA, which, without adding the impact of high temperature, is already more unstable than the DNA molecules. Therefore, to ensure proper functioning of the cell, protection of RNA is just as vital as the protection of DNA. The discovered protection mechanisms regarding RNA involve post-transcriptional modifications of these molecules. Some nucleosides are changed into their alternative forms via processes like methylation of ribose or the nucleobase, which ensures higher stability of the mRNA during transportation and translation. Another mechanism observed in some bacterial thermophiles is the stabilization of both DNA and RNA by low-molecular weight polyamines, such as spermine and spermidine (Hus & Bocian, 2017).

Similarly to DNA, proteins of thermophiles, often referred to as thermostable proteins, are unique at both structural and conformational levels. Overall, one of the most important aspects of these proteins is that they are more tightly bound than their non-thermostable counterparts. At the structural level, this is achieved by higher share of charged amino acids which form ion bonds between each other (Hus & Bocian, 2017). Additionally, less thermolabile amino acids, such as histidine and glutamine are present in thermostable proteins, which lowers the chances for their degradation (Hus & Bocian, 2017). At the tertiary structure level of thermostable proteins, we can observe higher numbers of salt bridges formed between cysteine amino acid residues, which also results in more tightly bound molecules (Hus & Bocian, 2017). Thermostable proteins are often hydrophobic, which further contributes to their ability to sustain their native structures at high temperatures. As in all organisms, in thermophiles, molecular chaperones such as heat shock proteins, assist in the correct folding of proteins (Hus & Bocian, 2017). It is a vital function, as the right conformation is the most essential part of the proper functioning of proteins. Among thermophiles however, we can observe greater numbers of these compounds, to counter the influence that high temperature poses on proteins, which in the presence of heat are more prone to misfolding and formation of aggregations.

The metabolic pathways of thermophiles are often the same as those of mesophiles, with the exception being the thermostable enzymes that catalyse the metabolic reactions. Their co-factors however are often unchanged, despite their low stability at high temperatures (Hus & Bocian, 2017). Even though heat is generally associated with faster metabolism, it has been demonstrated that in case of some thermostable enzymes, the temperature optimal for their host is not necessarily their own optimum, and they are more efficient at lower temperatures (Hus & Bocian, 2017). Additionally, in the case of some reactions such as sugar degradation, it has been reported that thermophilic species utilize alternative metabolic pathways, that do not require thermolabile substrates. This showcases the great extent of thermophilic adaptability, as these are very conserved processes across different lifeforms.

Finally, thermophiles also exhibit morphological adaptations to heat. The lipid membrane, alongside the cell wall, constitutes the barrier between the organism and the environment. Ensuring its integrity, which is susceptible to high temperatures, is crucial for the functioning of the cell. In the membranes of thermophiles, we can observe fatty acids that are longer, more saturated, and more branched, which all contribute to a more rigid structure, allowing it to more efficiently counter the high temperature of the environment (Hus & Bocian, 2017). Maintaining the integrity of lipid membranes seems to be one of the trickier parts of withstanding heat, as it is hypothesized, that eukaryotes cannot live at temperatures higher than 62°C due to their inability to form thermostable organelle membranes under these temperatures (Rappaport & Oliverio, 2024).

Overall, the thermophilic adaptations to high temperatures are largely strategies that mesophiles also exhibit, however either only under certain circumstances or to a lesser extent. Before conducting the research on these adaptations, I personally expected to learn about processes that are completely new or alien to other forms of life. The fact that these are similar mechanisms, is somehow even more impressive, as it shows the power of adaptation and evolution that allow for life to exist in environments that seem so hostile to it.

Thermophiles and the origin of life

The life on Earth is thought to first appear between 4.4-4.2 billion years ago, and its origins remain one of the biggest questions in all of science. One of its aspects is the issue of *the Last Universal Common Ancestor* (LUCA) – the single organism from which all current life evolved. It is hypothesized by many, that the answer to that question is: a thermophile. Particularly, a chemolithoautotrophic hyperthermophilic prokaryote, that utilized the oxidation of inorganic molecules, such as hydrogen or sulphur, to synthetize organic compounds (Farmer, 1998). The studies on origins of life can be approached by researching geological records, that provide insight into Earth's history, as well as via phylogenetic approach, by constructing a tree of life, based on the genetic differences and similarities among present-day organisms (Farmer, 1998). One of the arguments for the hyperthermophilic origin of life is the position, that many thermophiles hold on the phylogenetic tree of life. Today's hyperthermophilic bacteria are very early-branching organisms, clustered at the base of the phylogenic tree, which suggests that they are closely related to the LUCA (Fig. 8). Based on that, it is suggested that our universal ancestor might have been a hyperthermophile as well (Farmer, 1998). In line with this theory, it is also speculated, that life on early Earth might have emerged in hydrothermal environments, much like today's deep-sea hydrothermal vents that provide a continuous source of inorganic compounds necessary for the formation of biomolecules and an energy source (Farmer, 1998). An even more compelling argument supporting the theory of a thermophilic LUCA, was presented by Akanuma *et al.* (2013). Via modelling methods, these researchers recreated the probable amino acid sequence of ancestorial nucleoside-diphosphate kinase (NDK) enzyme. They were then able to synthesize it and have discovered for it to be thermostable, presenting compelling evidence for the thermophilic nature of the common ancestor. The counterargument to these theories, however, is that organic molecules, such as ribose, amino acids and nucleobases, which are thought to have had to emerge for life to first originate, are highly unstable and quickly degrade under high temperatures, which makes it unlikely for them to accumulate in sufficient quantities, in a hot habitat (Islas *et al.*, 2003). Other theories suggest that the common ancestor was a mesophile, and hyperthermophily is an example of a very early adaptation (Islas et al., 2003). It is also known that Earth experienced numerous impacts during its early days, that could be lethal to its life, if at the time it was already formed. Because of that, it is possible that thermophiles may have been the sort of lifeforms that thanks to their adaptations were able to survive such impacts, that wiped their, and therefore also our, ancestors (Farmer, 1998).

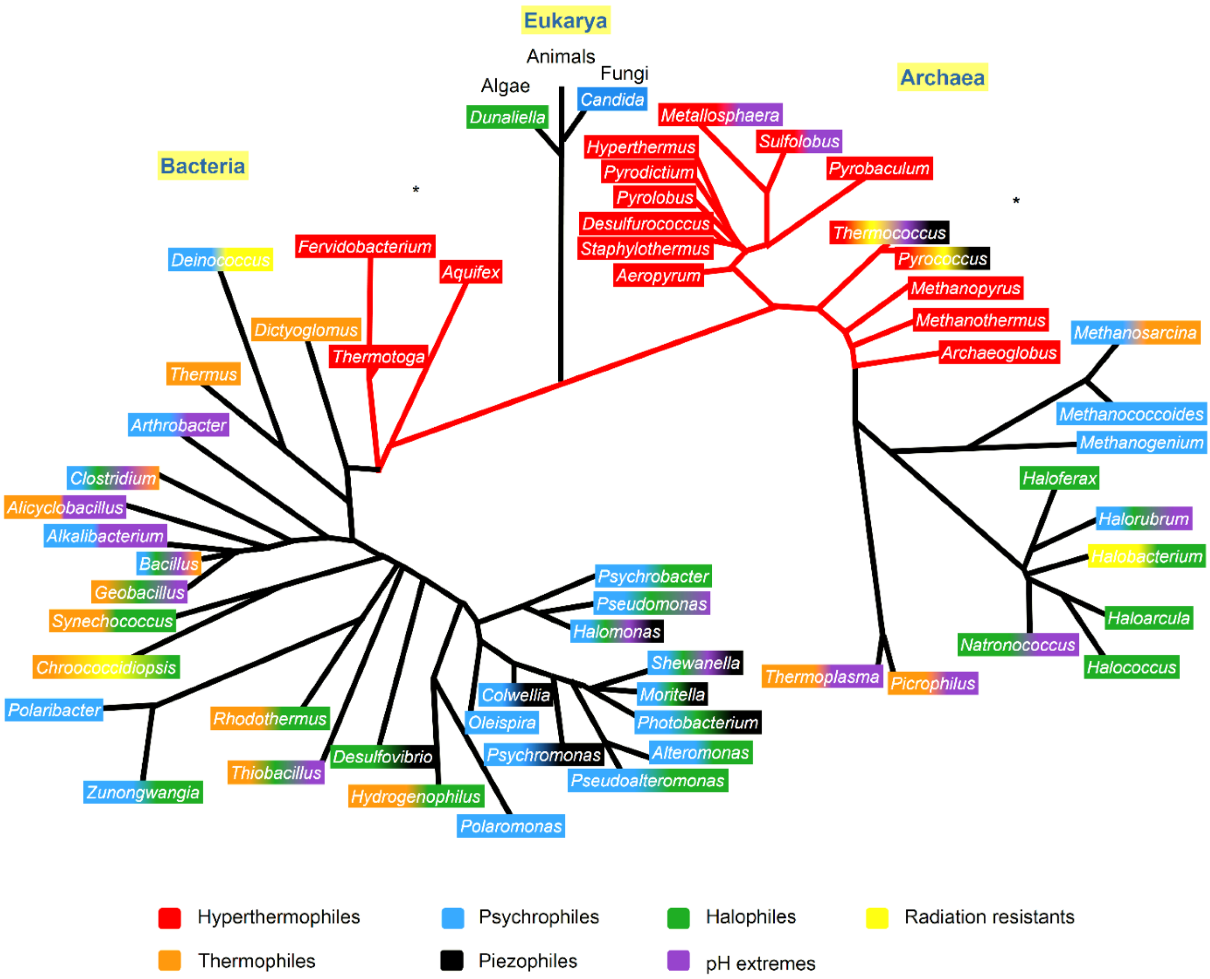

Fig. 8. Tree of life, showcasing the hypertherophilic nature of many early-branching organisms (*adapted from: Dalmaso et al., 2015*)

Whether or not the last common ancestor was a thermophile, these organisms provide a very important foundation for researching this topic, as the basal groups on the tree of life. This also raises a compelling question regarding the thermophilic adaptations – if the LUCA truly was a hyperthermophile, it was the rest of lifeforms that needed to adapt to environments that weren't hot. It is fascinating to think, that while thermophiles seem so extreme and specialized, it is possible that they are the closest thing to our ancestors, and life actually began in warmth.

Thermophiles for humanity

Throughout the course of my studies, I have mainly learned about thermophiles in the context of their biotechnological applications. While it is interesting, during my preparation for this essay, I have found it to be the least captivating thing about them. It is not surprising that this is what the emphasis is put on in the topic of thermophiles – both in education and in research. These applications contribute to the progress in various industries and often offer sustainable solutions or alternatives, which overall improve our quality of life and generate profits. These days, it is often the case that organisms are very intensively researched in regard to their possible applications, while other aspects of their being are largely ignored. It is understandable, but ultimately saddening, as there is so much more to thermophiles than their applicability, which I hope this essay has demonstrated thus far.

Thermophiles have been of intertest of researchers regarding their possible applications ever since their heat-loving nature has been more closely discovered and described. There are scientific articles exploring their potential that have been published in the 1970s, showcasing that thermophiles have inspired scientists for over 50 years now. Probably the most known and groundbreaking discovery regarding thermophiles came in 1988, when the first thermostable polymerase – Taq polymerase from Thermus aquaticus, revolutionized the PCR technology. Use of Taq polymerase for PCR, instead of mesophile-originating enzyme, makes the process much more efficient and less laborious. Since then, many other types of thermostable polymerases were introduced, all originating from thermophiles (Terpe, 2013). PCR is however only one of many processes that can be streamlined by using thermostable enzymes.

In the era of climate change, finding new ways to produce and obtain goods is a crucial part of the fight against it. One promising approach is biocatalysis, the use of enzymes to catalyze chemical reactions, which offers a greener and more environmentally friendly alternative to the traditional use of chemical catalysis in countless industries. One of the problems arising from using enzymes is their instability in harsh conditions, such as high pressure or temperatures, that often accompany the processes that are catalyzed. Thermozymes, in contrast, have the numbers of adaptations to heat, and are overall far more stable than mesophilic enzymes. They are already utilized in number of industrial processes, such as production of detergents, textiles, food and feed, biofuels and pharmaceuticals (Atalah *et al.*, 2019).

Thermophiles, besides possibly carrying answers to the origins of life on Earth, are also used in the studies of astrobiology – extraterrestrial life. It is important to note, that extremophiles as a whole, are widely used in that field. Astrobiology explores the possibilities of extraterrestrial life – whether it could exist at all, where it might emerge and how could it look like. Another important aspect of astrobiology is the study of terraforming: the potential to transform planets that are currently hostile to human life into habitable environments (Akanuma *et al.*, 2013). Celestial bodies that are investigated in terms of astrobiology are Mars, Venus, as well as some moons of gas giants within the Solar System, such as Europa or Titan (Thombre *et al.*, 2020). Extremophiles can help predict if, life as we know it, could emerge on these planets and moons. Firstly, the natural environments within which extremophiles reside often exhibit similar conditions to the ones found on other planets, one of which often is high temperature. These environments are referred to as flied analogue sites, and studying the microbes inhabiting them provides insight into possibilities of extraterrestrial life

(Thombre *et al.*, 2020; Fig. 9). Another approach is the recreation of these conditions in the laboratory, or even in space. While Bacteria and Archaea are more conventionally used as model organisms in astrobiology, some eukaryotic thermophiles are also researched in that area. Alongside many prokaryotes, fungi from the phylum Ascomycota are models for researching life under Martian conditions. Similarly, extremophilic red algae are utilized regarding environments found on Venus (Akanuma *et al.*, 2013). In line with the themes of astrobiology and biotechnology is the recent Polish space mission to the International Space Station (ISS), during which several innovations were tested. Among them was the Space Volcanic Algae project, led by Extremo Technologies, co-founded by Ewa Borkowska, an Oceanography graduate from our university (Axiom Space Research | Space Volcanic Algae). The project explores the potential of extremophilic – probably thermophilic, since they were isolated from volcanic environments – microalgae, as possible renewable oxygen and nutrient source abord space missions. The experiments carried out on the ISS was designed to determine how the algae adapt to and grow in the microgravity conditions and under the exposure to cosmic radiation (Axiom Space Research | Space Volcanic Algae). It is great to think that thermophiles may not only help us understand the life in space, but in the future could also possibly sustain our own lives there.

Fig. 9. An aerial view of Death Valley National Park (California, USA), a popular filed analogue site (*National Park Service*)

Overall, thermophiles carry an outstanding biotechnological potential, however I believe that as climate change unravels and the temperatures around the globe are rising, thermophiles might have something to offer not only to humans, but all kinds of lifeforms. The holobiont concept describes an organism and its associated microbial community. These microbes are necessary for the proper functioning of their host, forming very close and dependent symbiotic relationships (Sánchez-Cañizares *et al.*, 2017). The aforementioned Pompeii worms can live in the environment of hydrothermal vents only due to their symbiosis with thermophilic bacteria, which is of course an extreme case. It is possible that thermophilic or mildly thermophilic microbes acting as symbionts of temperature-sensitive organisms could similarly expand their environmental niches, enhancing their resistance to heat and, therefore, to climate change. It is the ultimate way in which thermophiles could impact humanity – by integrating more within the biosphere, maybe even humans, and by that helping tackle our mistakes. It is of course a very hopeful perspective, not backed by any data, however as thermophiles show us best, life adapts and persists even under the harshest of circumstances.

Final thoughts

Thermophiles are a fascinating group of organisms, that not only provide a unique insight into ecology, evolution and the boundaries of life, but also present important solutions and possibilities for some of humanities biggest problems and questions. I hope that this essay offers an insight into thermophilic life and an invitation to further investigate these masters of heat.

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