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Extremophiles and their Potentials in the Food Industries: A Review

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Review Article

ABSTRACT

Extremophiles are microorganisms that thrive in extreme environments, such as high temperatures, high pressures, and acidic or alkaline conditions. These organisms have unique adaptations that allow them to survive in these harsh conditions, and they are of great interest to the food industry for a variety of applications. Extremophilic microorganisms produce a broad range of bioactive compounds, secondary metabolites, and value-added products such as flavors, food ingredients, and vitamins, therefore, making them widely applicable in the food and food processing industries. In food industries, one of the extremophiles, *Rhodothermus marinus*, which has been an excellent biocatalyst producing lipase as an enzyme, could be utilized to improve the aroma of food and add natural flavor to food. Others have emerged as a valuable resource for the food industry, offering solutions to food safety and preservation challenges, as well as opportunities for sustainable food processing. By harnessing the unique characteristics and enzymes of extremophiles, the food industry can improve product quality, develop novel fermentation processes, and enhance food

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safety. Extremophiles hold significant potential for use in the food industry; however, translating this potential into practical applications is fraught with several challenges. These challenges include specialized growth conditions, slow growth rate, and contamination risks. Advancing genetic, biotechnological, and engineering research will be pivotal in realizing the full potential of extremophiles. Ongoing exploration of these organisms is crucial not only for improving food production processes but also for fostering sustainability and driving innovation within the food industry.

Keywords: Extremophiles; extremozymes; metabolites; food industries.

1. INTRODUCTION

Extremophiles are remarkable microorganisms that thrive in environments once considered uninhabitable for life. These resilient organisms have adapted to survive and even thrive in extreme conditions, such as high temperatures, acidic or alkaline environments, high salinity, and pressure. These environments can include extreme temperatures, high levels of radiation, acidic or alkaline conditions, high pressures, and even environments with low nutrient availability. The discovery of extremophiles has revolutionized our understanding of the diversity and adaptability of life on Earth. In recent years, their unique characteristics and versatile enzymes have found promising applications in various industries, including the food sector (Bajpai and Bajpai, 2019; Zhu *et. al.*, 2020). Extremophiles are organisms capable of thriving in extreme environmental conditions such as extreme temperatures, pH levels, salinity, and pressure. They have evolved specialized strategies and mechanisms to adapt and survive in these harsh environments. Prominent extremophilic genera include *Acidithiobacillus*, *Arthrobacter*, *Bacillus*, *Caldicellulosiruptor*, *Clostridium*, *Coprothermobacter*, *Enterobacter*, *Geobacillus*, *Micrococcus*, *Paenibacillus*, *Penicillium*, *Picrophilus*, *Pseudoalteromonas*, and *Thermobifida* (Zhu et al*.,* 2020).

The food industry faces numerous challenges, including food spoilage, safety concerns, and the need for sustainable processes. Extremophiles offer potential solutions to these challenges due to their robust nature and the enzymes they produce. Their applications in the food industry range from enhancing food safety and quality to developing eco-friendly processes (Bhalla et al*.,* 2017). Extremophiles produce antimicrobial peptides and enzymes that can be used as natural preservatives. These bioactive compounds have the potential to inhibit the growth of spoilage microorganisms and foodborne pathogens, extending the shelf life of perishable food products and making food safe for consumption. Enzymes from extremophiles, especially those with unique thermal stability and activity, have gained significant attention in food processing. Thermostable enzymes can improve the efficiency of processes like starch hydrolysis, protein modification, and the production of sweeteners and other food additives (García-López and Cid, 2016). These compounds enhance the potential, add a positive health benefit to the food products and mitigate certain long-term diseases **(**Raddadi et al*.,* 2015).

The study of extremophiles has provided valuable insights into the limits of life on Earth and the potential for life in extreme environments elsewhere in the universe. Extremophiles can be found in various habitats, including deep-sea hydrothermal vents, acidic hot springs, polar ice caps, salt flats, and even within the human body. They belong to diverse taxonomic groups, including bacteria, archaea, and some eukaryotic organisms such as fungi and algae.

One of the most well-known types of extremophiles is thermophiles, which thrive in high-temperature environments. These organisms can survive and reproduce at temperatures exceeding 60 degrees Celsius (140 degrees Fahrenheit) and can be found in geothermal areas such as hot springs and deep-sea hydrothermal vents. Some thermophiles, like the bacterium *Thermus aquaticus*, have provided valuable enzymes for applications in biotechnology, such as the heat-stable DNA polymerase used in the polymerase chain reaction (PCR) technique.

Extremophiles have attracted significant scientific interest due to their ability to survive in conditions that were previously thought to be uninhabitable. The study of extremophiles has not only expanded our understanding of the diversity of life on Earth but also has implications for astrobiology and the search for life beyond our planet. The discovery of extremophiles has led to the concept of the "habitable zone" being broadened, as it suggests that life may exist in environments previously considered inhospitable.

2. ECOLOGY AND CLASSIFICATION OF EXTREMOPHILES

2.1 Ecology and Distribution of Extremophiles

The ecology of extremophiles encompasses their distribution, diversity, metabolic strategies, and interactions with the environment. Understanding their ecological roles is crucial for exploring their potential applications and shedding light on the limits of life on Earth.

Extremophiles are ubiquitous and can be found in a wide range of extreme habitats across the globe. For example, thermophiles (organisms thriving at high temperatures) are commonly found in hot springs, geothermal areas, and hydrothermal vents (Giovannelli et al*.,* 2016). Acidophiles (organisms thriving in acidic conditions) are prevalent in acidic lakes, acid mine drainage sites, and volcanic soils (Liao et al*.,* 2016). Halophiles (organisms thriving in high salt concentrations) inhabit hypersaline environments such as salt flats, salt pans, and saline soils (Oren, 2013). The diversity of extremophiles in various extreme habitats showcases their adaptability to challenging conditions.

2.2 Metabolic Strategies of Extremophiles

Extremophiles have evolved unique metabolic strategies to cope with extreme conditions. Thermophiles, for instance, produce thermostable enzymes that function optimally at high temperatures (Bornscheuer et al*.,* 2012). Acidophiles employ acid-resistant proteins and cell membranes to maintain stability in low-pH environments (Justice et al*.,* 2014). Halophiles accumulate compatible solutes, such as potassium ions and osmolytes to balance internal osmotic pressure with the surrounding high salinity (Sleator and Hill, 2001). These metabolic adaptations allow extremophiles to efficiently utilize available resources and outcompete other organisms in extreme habitats.

2.3 Classification of Extremophiles

2.3.1 Osmophililes

One important group of extremophiles are osmophilic organisms, which have adapted to live in environments with high osmotic pressures. These environments can include sugary or salty conditions that are inhospitable to many other organisms. Osmophilic organisms possess unique physiological and biochemical adaptations that enable them to tolerate these extreme conditions. Osmophiles are microorganisms that have evolved to thrive in high osmotic environments, where solute concentrations are considerably higher than in the surrounding environment. To survive in such conditions, osmophilic organisms have developed specialized mechanisms to counteract the detrimental effects of osmotic stress. These adaptations can include synthesizing osmoprotectants, altering membrane composition, and controlling intracellular water balance (Querol et al*.,* 2010).

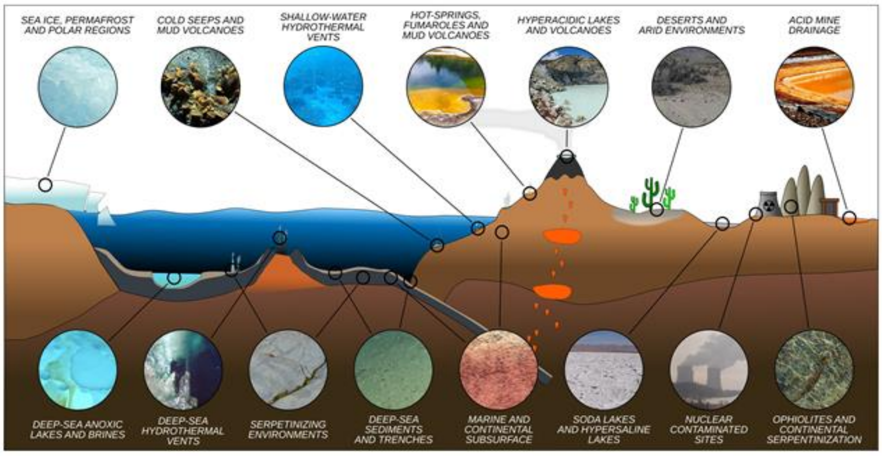

Fig. 1. Earth’s crust showing the diversity of extreme environments and their approximate location (Merino et al., 2019)

One of the key adaptations of osmophilic organisms is the synthesis and accumulation of osmoprotectants. Osmoprotectants are small molecules that protect cells from osmotic stress by balancing the intracellular osmotic pressure with the external environment. Examples of osmoprotectants include sugars (e.g., trehalose), polyols (e.g., glycerol), and amino acids (e.g., proline) (Rainey et al*.,* 2015). The yeast *Saccharomyces cerevisiae* is a well-known example of an osmophilic organism. It is widely used in various food and beverage fermentations, such as wine and beer production, where high sugar concentrations are present. *S. cerevisiae* has developed efficient osmoregulation mechanisms, including the synthesis of trehalose, to tolerate the high sugar environments (Blomberg, 2017)

Osmophilic microorganisms play a crucial role in food preservation, particularly in sugary or salty foods. Their ability to thrive in high osmotic environments can help extend the shelf life of certain products by preventing the growth of spoilage or pathogenic microorganisms. However, they can also lead to food spoilage if not properly controlled (Franco-Duarte et al*.,* 2018). Osmophilic microorganisms have several biotechnological applications. Their ability to tolerate high osmotic stress makes them valuable for processes involving concentrated solutions, such as bioethanol production, bioremediation, and the production of osmolytes for various industries (Panesar et al*.,* 2017). Osmophilic organisms are fascinating examples of extremophiles that have successfully adapted to high osmotic environments. Their ability to thrive in these extreme conditions relies on unique physiological and biochemical adaptations, including the synthesis of osmoprotectants and alterations in membrane composition. Understanding osmophilic organisms not only contributes to our knowledge of extremophiles but also has practical applications in food preservation, biotechnology, and other industries. Among the most osmophilic organisms are: *Saccharomyces rouxii* (0.62), *Saccharomyces bailii* (0.80), *Debaryomyces* spp*.* (0.83), *Wallemia sebi* (0.87), *Saccharomyces cerevisiae* (0.90)

2.3.2 Alkaliphiles

Extremophiles are remarkable organisms that thrive in extreme environments that were once considered inhospitable to life. Among them, alkaliphiles are a group of extremophiles that have adapted to highly alkaline conditions, with pH values typically above 9. These organisms are found in various alkaline habitats, including soda lakes, alkaline soils, and alkaline hydrothermal vents. Their ability to survive and thrive in extreme alkaline conditions make them fascinating subjects for scientific research and potential applications in biotechnology (Querol et al*.,* 2010).

To survive in high pH environments, alkaliphiles have developed unique adaptations that allow them to maintain cellular integrity and function. Alkaliphiles possess specialized ion transport systems that help maintain the intracellular pH within a suitable range. These mechanisms involve the transport of protons and other ions across the cell membrane to prevent intracellular alkalinization. Alkaliphiles often have proteins that are structurally stable and functional at high pH levels. These proteins have evolved to resist denaturation and maintain their biological activity under alkaline conditions. The lipid composition of the cell membrane in alkaliphiles is different from that of organisms living in neutral pH environments. The membrane lipids in alkaliphiles are typically more rigid and contain specific fatty acids that contribute to the stability of the membrane at high pH. Alkaliphiles regulate their internal pH by producing and utilizing buffering molecules and enzymes that counteract the effects of alkaline conditions (Baker and Banfield, 2003).

The unique adaptations of alkaliphiles have attracted significant attention from researchers and industries due to their potential applications in biotechnology. Alkaliphiles are known to produce enzymes that remain stable and functional at high pH levels. These enzymes have various industrial applications, such as in detergent formulation, food processing, and biofuel production. The ability of alkaliphiles to thrive in alkaline conditions makes them potentially useful in wastewater treatment processes where the pH is elevated. They may play a role in breaking down certain organic compounds and contaminants in such environments (Justice et al*.,* 2014).

2.3.3 Thermophiles

Thermophiles are a fascinating group of extremophiles that thrive in high-temperature environments, often well above the boiling point of water. These remarkable organisms have adapted to live in extreme heat, such as hot springs, hydrothermal vents, geothermal areas, and even deep-sea hydrothermal vents. Studying thermophiles provides valuable insights into the limits of life on Earth and has significant implications for understanding the potential for life on other planets or celestial bodies with extreme conditions (Schiraldi and Cannio, 2012).

Thermophiles have evolved several unique adaptations that enable them to survive and function in extremely high-temperature environments. One of the key adaptations of thermophiles is the production of thermostable proteins. These proteins can maintain their structure and function even at temperatures that would denature typical proteins. The increased stability is often due to more extensive hydrogen bonding and other non-covalent interactions within the protein structure. Thermophiles produce a class of proteins known as heat shock proteins (HSPs). These proteins play a vital role in protecting cellular components from heat-induced damage and aiding in the refolding of denatured proteins. The cell membranes of thermophiles are composed of lipids that have a higher heat tolerance compared to those of mesophilic organisms (organisms that thrive at moderate temperatures). These lipid structures help maintain the integrity of the cell membrane under extreme heat. Thermophiles have developed mechanisms to protect their DNA from heat-induced damage. Enzymes called DNA-stabilizing proteins, along with specific DNA repair mechanisms, help ensure the preservation of genetic material even at high temperatures (Gudbergsdottir et al*.,* 2016).

The unique properties of thermophiles and their enzymes have significant biotechnological applications. Thermophiles produce enzymes that are stable and active at high temperatures. These thermostable enzymes have various industrial uses, including in DNA amplification (e.g., PCR), food processing, and biofuel production. Thermophiles can be used in bioprocessing applications, particularly in bioconversion processes that require elevated temperatures, such as the breakdown of lignocellulosic biomass for biofuel production. Thermophiles have been explored for their potential in the bioremediation of certain contaminants present in high-temperature environments, such as certain heavy metals and organic pollutants (Gudbergsdottir et al*.,* 2016).

2.3.4 Psychrophiles

Psychrophiles are a fascinating group of extremophiles that have adapted to thrive in cold environments, including polar regions, glaciers, and deep ocean waters. These remarkable organisms have developed unique molecular and physiological adaptations to withstand the challenges posed by low temperatures. Understanding the mechanisms behind their cold-adapted lifestyles has implications for astrobiology, biotechnology, and our understanding of the limits of life on Earth. This review highlights the adaptations of psychrophiles, their biotechnological relevance, and current research trends in this field.

Psychrophiles produce enzymes that remain active and functional at low temperatures. These enzymes have evolved to be flexible and catalyze reactions efficiently, even in cold conditions, making them valuable for various biotechnological applications. The cell membranes of psychrophiles are rich in unsaturated fatty acids, which contribute to membrane fluidity at low temperatures. Additionally, some psychrophiles produce antifreeze proteins that prevent the formation of ice crystals within the cells. They synthesize cold shock proteins, which help protect cellular components and maintain cellular integrity in response to sudden temperature drops. To preserve genetic information, psychrophiles have evolved efficient DNA repair mechanisms that counteract the damage caused by cold-induced stresses. Cold-active enzymes from psychrophiles have diverse industrial uses, including in the detergent, food, and pharmaceutical industries. The demand for eco-friendly enzymes has increased interest in exploring psychrophile-derived enzymes. Psychrophiles play a potential role in bioremediation efforts in cold environments, assisting in the breakdown of contaminants in polar regions and cold marine environments.

Psychrophiles, therefore represent an extraordinary group of extremophiles that have evolved to thrive in harsh, icy environments. Their unique adaptations have broad implications for biotechnology, bioremediation, and astrobiology. Continued research on these cold-adapted microorganisms promises to expand our understanding of life's resilience and diversity on Earth and beyond.

2.3.5 Acidophiles

Acidophiles are a fascinating group that has adapted to survive and flourish in highly acidic conditions. These remarkable organisms are found in various acidic environments, such as acid mine drainage, acidic soils, and acidic hot springs. Studying acidophiles provides valuable insights into the adaptations that enable life to persist in seemingly inhospitable environments.

Acidophiles have evolved several unique adaptations that allow them to withstand the extreme acidity of their habitats. Acidophiles possess specialized ion transport systems that actively pump out protons to maintain the intracellular pH close to neutral. These mechanisms are crucial for preventing intracellular acidification, which can be detrimental to cellular processes (Valdes et al*.,* 2008).

Acidophiles produce proteins that are highly stable at low pH values. These proteins have adapted to resist denaturation and maintain their functional structure in acidic conditions. The lipid composition of the cell membrane in acidophiles differs from that of neutralophilic organisms. Acidophiles often have higher proportions of branched-chain fatty acids, which contribute to membrane stability in acidic environments. Acidophiles produce acid-resistance genes and proteins, such as chaperones and proteases, which protect cellular components from acid-induced damage (Valdes et al*.,* 2008).

3. APPLICATION OF EXTREMOPHILES IN FOOD INDUSTRIES

These unique organisms have garnered significant interest in various industries, including the food industry, due to their remarkable adaptations and potential applications. In this article, we will explore in detail the diverse applications of extremophiles in food industries, supported by relevant citations.

One of the most significant applications of extremophiles in the food industry is the production of extremozymes. Extremozymes are enzymes produced by extremophiles that exhibit remarkable stability and activity under extreme conditions. These enzymes play a crucial role in various food processing applications. For example, thermophilic amylases, proteases, and lipases are used in starch hydrolysis, protein modification, and fat degradation, respectively, under high-temperature conditions (Bornscheuer et al*.,* 2012). They offer improved efficiency and reduced processing time compared to conventional enzymes, leading to cost savings and enhanced food quality.

Extremophiles have been explored for their potential in food preservation and fermentation processes. Certain extremophiles, like halophiles, have the ability to grow and produce antimicrobial compounds in high-salt environments. These properties can be harnessed for the preservation of high-salt food products (DasSarma et al*.,* 2008). Additionally, some extremophiles, such as thermophilic lactic acid bacteria, can carry out fermentation at elevated temperatures, resulting in the production of heat-stable and unique fermented foods (Fiala-Médioni et al*.,* 2008).

Extremophiles have the capacity to synthesize high-value compounds under extreme conditions, which can be advantageous for the food industry. For instance, some thermophiles produce carotenoids, antioxidants, and bioactive peptides at elevated temperatures (Martínez-Espinosa et al*.,* 2017). These compounds can be utilized as natural food additives and functional ingredients to enhance the nutritional profile and health benefits of food products.

Extremophiles have shown potential in bioremediation processes, where they can utilize food-processing waste materials as substrates. For example, thermophilic bacteria can be used to degrade organic waste from food processing industries, such as starch, protein, and lipid residues (Mancuso et al*.,* 2008). This approach not only reduces environmental pollution but also generates value-added products during the waste treatment process.

The application of extremophiles in the food industry holds tremendous promise for improving food processing, preservation, and the production of high-value compounds. Extremozymes enable efficient and sustainable processes, while extremophiles' unique properties offer solutions to challenging food production conditions. As research and technological advancements continue, the integration of extremophiles in the food industry is expected to open new opportunities for innovation and the development of high-quality and functional food products.

3.1 Extremozymes in Food Industries: Applications and Examples

Extremozymes, enzymes produced by extremophilic microorganisms have emerged as valuable biocatalysts in various industrial applications, including the food industry. Their unique properties, such as thermostability, pH resistance, and solvent tolerance, make them well-suited for challenging food processing conditions. In this article, we will delve into the applications of extremozymes in the food industry, along with examples and relevant citations.

3.2 Starch Hydrolysis and Baking Applications

Amylases are a crucial class of extremozymes used in the food industry for starch hydrolysis and baking applications. Thermostable amylases can efficiently break down starch into fermentable sugars at elevated temperatures, improving the efficiency of the process and enhancing the quality of baked goods. The most well-known example of a thermostable amylase is the α-amylase from *Thermococcus kodakarensis* (Zhang et al., 2014).

3.3 Protease for Meat Tenderization

Proteases are enzymes that hydrolyze proteins, and they are used in the food industry for meat tenderization. Thermophilic proteases offer advantages in meat processing due to their high activity and stability at elevated temperatures. They help break down muscle fibers and collagen in meat, resulting in more tender and palatable products. An example of a thermophilic protease is the one from *Thermococcus kodakarensis* (Jang et al., 2019).

3.4 Lipases for Fat Modification

Lipases are extremozymes used for fat modification in the food industry. Thermophilic lipases offer advantages in food processing applications due to their high activity and stability at elevated temperatures. They are employed in various processes, including the production of low-calorie fats, structured lipids, and fats. An example of a thermophilic lipase is the one from *Thermomyces lanuginosus* (Devi and Khandual, 2018).

3.5 Pectinases for Fruit Juice Clarification

Pectinases are enzymes used in the food industry for fruit juice clarification. Thermophilic pectinases can effectively degrade pectin, a polysaccharide responsible for cloudiness in fruit juices. These enzymes improve the clarity and stability of fruit juices. An example of a thermophilic pectinase is the one from *Bacillus* spp. (Liu et al., 2017).

3.6 Xylanases for Food Additives

Xylanases are enzymes used in the food industry for the degradation of xylan, a complex polysaccharide found in plant cell walls. Thermophilic xylanases have potential applications in food additives, improving the processing of cereal-based products and increasing the digestibility of dietary fibers. An example of a thermophilic xylanase is the one from *Thermotoga maritima* (Sriyapai et al., 2019).

Extremozymes offer significant potential in the food industry, providing enhanced processing efficiency, improved product quality, and increased stability. From starch hydrolysis and meat tenderization to fat modification and fruit juice clarification, extremozymes play a vital role in various food processing applications. Their unique properties make them valuable

4. EXOPOLYSACCHARIDES FROM EXTREMOPHILES

Exopolysaccharides (EPS) from extremophiles are intriguing biopolymers produced by microorganisms that thrive in extreme environments, such as high temperatures, extreme pH levels, and high salinity. These unique polymers have drawn considerable attention due to their extraordinary properties and potential applications in various industries, including food, pharmaceuticals, and biotechnology. Extremophiles, being resilient microorganisms, secrete EPS as a protective mechanism to survive in their harsh surroundings. The EPS produced by extremophiles often exhibit exceptional stability and resistance to extreme conditions, making them valuable biomaterials for diverse applications. In the food industry, EPS from extremophiles is of interest for its potential as texturizing, gelling, and stabilizing agents. They can enhance the sensory attributes and shelf stability of food products (Lazaridou and Biliaderis, 2007). Furthermore, EPS from extremophiles has been investigated for its potential prebiotic effects, promoting gut health (Costa et al., 2021).

In biotechnology and pharmaceuticals, EPS from extremophiles has shown promise in various applications. They have been explored as stabilizers for enzymes and vaccines, delivery vehicles for drugs, and potential components in wound dressings (Costa et al., 2021). One well-known example of EPS from extremophiles is the xanthan gum, produced by the bacterium *Xanthomonas campestris*. Xanthan gum is widely used as a food thickener and stabilizer due to its high viscosity and pseudoplastic behavior (Moure et al., 2006). Another remarkable EPS is pullulan, produced by the fungus *Aureobasidium pullulans*. Pullulan has found applications as a food and pharmaceutical additive, offering properties such as film-forming, moisture-retention, and antioxidant activity (Devi and Khandual, 2018). Overall, the study of EPS from extremophiles presents exciting opportunities for the development of novel biomaterials with exceptional properties, opening new avenues for innovative applications in various industries.

4.1 Application of Exopolysaccharides in Food Industries

Exopolysaccharides (EPS) are complex polymers of sugars produced by microorganisms and have found diverse applications in the food industry due to their unique functional properties. EPS act as texturizing and stabilizing agent in various food products, improving their consistency and mouthfeel (Lazaridou and Biliaderis, 2007). They serve as emulsifiers and foaming agents, enhancing the stability and appearance of food formulations (Morais et al., 2013). Certain EPS exhibit gelling properties, making them valuable for producing gelled and encapsulated food items (Moure et al., 2006). EPSs are also used as fat replacers, providing a desirable sensory experience in low-fat or fat-free food products (Wijesundera et al., 2003). Moreover, some EPS possess prebiotic properties, promoting gut health and overall well-being (Costa et al., 2021). Additionally, EPS-based encapsulation systems are explored for the controlled release of bioactive compounds and functional ingredients in food products (Sanz et al., 2007). The application of exopolysaccharides in the food industry continues to grow, offering innovative solutions to improve food quality, texture, and consumer experience (Vandieken et al., 2018)

4.2 Environmental Impact and Sustainability Benefits of using Extremophiles in Food Processing

Microorganisms are among the most widespread and diverse living entities on Earth, occupying nearly every conceivable habitat (Hug et al., 2016). Despite their ubiquity, it is estimated that only about 1% of all microorganisms on the planet have been identified, leaving many unexplored habitats and species yet to be discovered (Cavicchioli et al., 2019). Extremophiles, a group of microorganisms thriving in extreme conditions, remain particularly underexplored. These organisms have evolved remarkable genetic and metabolic adaptations to survive hostile environments, such as high temperatures, extreme pressures, and acidic or saline conditions (Rothschild and Mancinelli, 2001). Notably, some extremophiles are considered ancient life forms, offering valuable insights into the evolution of life on Earth and the environmental conditions present during its early stages (Madigan et al., 2021).

Examples of extremophiles include both prokaryotes (bacteria and archaea) and some eukaryotes (algae, yeast, and fungi). Hyperthermophilic archaea such as *Pyrolobus fumarii* and *Geogemma barossii* can tolerate temperatures up to 121°C, with *Methanopyrus kandleri* strain 116 holding the record for surviving temperatures as high as 122°C (Kashefi and Lovley, 2003). Among psychrophiles, *Psychrobacter cryopegella* from Siberian permafrost can endure temperatures as low as −20°C (Moyer and Morita, 2007). Barophilic thermophilic methanogens, such as *Methanocaldococcus jannaschii* and *Methanothermococcus thermolithotrophicus*, have been isolated from the high-pressure niches of deep-sea beds (Parkes et al., 2014). Halophilic microbes, including *Halarsenatibacter silvermanii* from the Great Salt Lake and Dead Sea, have adapted to survive in salt concentrations of up to 35% (Oren, 2011). Acidophiles, such as *Thiobacillus*, *Sulfolobus*, and *Thermoplasma*, thrive in highly acidic environments. Recently, *Picrophilus oshimae* and *Picrophilus torridus* were identified as the most acidophilic archaea, capable of growth at a pH as low as 0.06 in the hot springs of Noboribetsu, Japan (Schleper et al., 1995). In contrast, the haloalkalophile *Halomonas campisalis* from Soap Lake, USA, can tolerate alkaline conditions with a pH of up to 12 (Duckworth et al., 1996). Metallophiles capable of resisting high concentrations of heavy metals such as cadmium, cobalt, and mercury have been isolated from volcanic regions, geothermal and hydrothermal vents, and industrially polluted sites (Gadd, 2010). Radiation-tolerant and xerotolerant archaea, like *Halobacterium salinarum NRC-1* from salt mines, are another notable example of extremophilic diversity (DasSarma et al*.,* 2012). These examples represent only a fraction of the fascinating extremophiles discovered so far, and the potential for identifying novel species from extreme environments remains vast.

Extremophilic microorganisms are not only ecologically significant but are also gaining prominence in biotechnological research and industrial applications. Thermophiles, for instance, produce thermostable proteins and possess robust cell membranes that resist denaturation at elevated temperatures. At the same time, psychrophiles and barophiles demonstrate stable membranes and cell walls adapted to low temperatures and high pressures (Elleuche et al*.,* 2014). Halophiles accumulate high concentrations of inorganic ions and compatible solutes, and acidophiles or alkaliphiles maintain intracellular pH neutrality by expelling excess ions through specialized mechanisms (Seckbach and Oren, 2010). These extremophiles also stabilize their membrane fluidity and protect their genetic material under hostile conditions, showcasing unique genetic adaptations that enable them to thrive and reproduce in extreme environments (Cavicchioli et al*.,* 2011).

These exceptional characteristics make extremophiles invaluable for the production of biomolecules that remain functional under extreme temperature, pH, pressure, and pollutant conditions. Extremophilic microbes and their metabolites hold immense industrial potential, as they can provide stable enzymes for extreme environments, facilitate biodegradation and bioremediation, and serve as sources of biofuels, bioenergy, and specialized pigments for solar cells (Ferrer et al*.,* 2007; Rampelotto, 2013). For example, cold-active enzymes derived from psychrophiles exhibit high catalytic activity at low temperatures, reducing energy costs and ensuring high reaction yields in industrial processes (D'Amico et al*.,* 2006). Similarly, pressure-adapted proteins from barophiles are used in food sterilization and production under varied pressure conditions (Bartlett, 2002).

Extremozymes—enzymes derived from extremophiles—are particularly noteworthy, with over 3,000 enzymes isolated from various microbes, many of which are being applied in industrial and biotechnological processes (Dalmaso et al*.,* 2015). The global industrial enzyme market is experiencing a compound annual growth rate (CAGR) of 8.2% and is expected to grow further with advancements in biotechnology (Market Research Future, 2023). Notable examples include thermostable DNA polymerases used in polymerase chain reactions (PCR), such as *Taq* polymerase from *Thermus aquaticus*, *Vent* polymerase from *Thermococcus litoralis*, and *Pfu* polymerase from *Pyrococcus furiosus*. Hydrolases like amylases, cellulases, esterases, lipases, peptidases, and xylanases from extremophiles have applications across diverse industries, including detergents, petroleum, pulp and paper, food and beverage processing, and bioremediation (Haki and Rakshit, 2003). The study of extremophiles also offers insights into the functioning of extreme ecological systems. Research on microbial life in such habitats provides valuable information about biogeochemical cycling and the ecological roles of these organisms, contributing to our understanding of global environmental changes (Rothschild and Mancinelli, 2001). These insights can be applied to restore polluted ecosystems and improve degraded habitats, supporting ecological sustainability (Cavicchioli et al*.,* 2019). Additionally, as vast microbial diversity remains unexplored, particularly in uncharted habitats, there is significant potential for discovering novel species and metabolites with industrial and ecological applications (Tchounwou et al*.,* 2012). Extreme ecosystems represent a rich biological resource and genetic diversity hotspot. Mining this wealth for green and sustainable purposes is critical in addressing global challenges. Advancing our understanding of extremophiles and their adaptations will play a pivotal role in fostering a bio-based economy, driving industrial innovation, and promoting ecological restoration in a rapidly changing world.

4.3 Challenges in the Bioprocessing and Application of Extremozymes in Food

Extremozymes, enzymes produced by extremophiles, have garnered significant attention in various industrial applications, including the food industry. Their unique properties, such as thermal stability, solvent tolerance, and pH resistance, make them valuable tools for food processing and production. However, there are several challenges in harnessing the full potential of extremozymes in the food sector. One of the primary challenges is the efficient production of extremozymes at a large scale. Many extremophiles are slow-growing, and their optimal growth conditions are often challenging to replicate in laboratory settings. Additionally, the isolation and cultivation of extremophiles can be time-consuming and expensive. Scaling up the production of extremozymes to meet industrial demand while maintaining their stability and activity is a significant challenge (Alquati et al*.,* 2018). Extremozymes are renowned for their stability under extreme conditions. However, when isolated and purified for commercial use, they may lose some of their unique properties. Maintaining the stability of extremozymes during purification, storage, and application is crucial for their successful integration into food processes. Factors like temperature, pH, and the presence of inhibitors can affect their stability (Amoozegar et al*.,* 2017).

Extremozymes are often highly specialized enzymes, optimized for specific tasks in their natural environments. In food processing, where multiple reactions may occur simultaneously, achieving precise control over extremozyme activity and specificity can be challenging. The risk of unwanted side reactions and potential interactions with other food components must be carefully considered (Bornscheuer et al*.,* 2012).

The use of extremozymes in food applications must be economically viable and competitive with conventional enzymes or chemical methods. Additionally, there may be regulatory hurdles to overcome, as extremozymes from extremophiles may not have an established history of safe use in food processing (Wang et al*.,* 2021). In certain food processing applications, such as in solid-state fermentation or in situ enzyme catalysis, the efficient delivery of extremozymes to the target substrate can be challenging due to mass transfer limitations. This can affect the overall efficiency of the bioprocess (Lindner et al*.,* 2020; Cassidy et al*.,* 2021).

The utilization of extremozymes in the food industry holds great promise for enhancing food processing, preservation, and production. However, overcoming the challenges in extremozyme production, stability, specificity, cost-effectiveness, and regulatory acceptance is critical for their successful integration into food processes. Continued research and innovation in extremozyme bioprocessing and application will undoubtedly lead to more sustainable, efficient, and advanced food technologies in the future.

5. CONCLUSION

Extremophiles, remarkable organisms capable of thriving in extreme environments, have opened new avenues for innovation and advancement in various industries, including the food industry. Their unique biochemical and physiological features have been harnessed to tackle challenges and enhance processes, ultimately benefiting food production and quality. Extremophiles play a significant role in food preservation, with their enzymes offering stable functionality under extreme conditions, such as high temperatures and acidic or alkaline environments. By using extremophilic enzymes, food industries can develop novel preservation techniques that extend the shelf life of perishable products and improve food safety.

Additionally, extremophiles have contributed to the production of valuable food additives and ingredients. These organisms produce specialized molecules, such as ectoine, trehalose, and xylanases, which have diverse applications as stabilizers, texturizers, and flavor enhancers. The use of extremophile-derived compounds in food formulations allows for more natural and sustainable alternatives to traditional additives. Moreover, the application of extremophiles in the food industry has led to advancements in food processing. Their enzymes have proven effective in various biotransformation processes, converting raw materials into high-value products with improved nutritional profiles. For example, lipases from extremophiles have been utilized in the production of healthier oils and fats, leading to the increasing demand for functional and nutritious foods.

Furthermore, the understanding of extremophile metabolic pathways has paved the way for innovative bioprocesses. By exploiting the unique properties of these microorganisms, food industries can develop efficient and eco-friendly methods for waste utilization and bioconversion of raw materials. While the potential of extremophiles in the food industry is vast, further research and development are essential to harness their full capabilities. Challenges in large-scale cultivation, enzyme purification, and process optimization need to be addressed to realize the full potential of extremophiles in food applications.

In summary, the utilization of extremophiles in the food industry holds great promise for revolutionizing food production, preservation, and processing. Their remarkable adaptations to extreme conditions offer a wealth of possibilities for creating innovative and sustainable solutions, contributing to a safer, healthier, and more diverse range of food products. As research in this field progresses, the full extent of extremophiles' contributions to the food industry is likely to continue expanding, opening up exciting opportunities for future advancements in food science and technology.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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