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Review

Extremozymes: A Potential Source for Industrial Applications

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Extremophilic microorganisms have established a diversity of molecular strategies in order to survive in extreme conditions. Biocatalysts isolated by these organisms are termed extremozymes, and possess extraordinary properties of salt allowance, thermostability, and cold adaptivity. Extremozymes are very resistant to extreme conditions owing to their great solidity, and they pose new opportunities for biocatalysis and biotransformations, as well as for the development of the economy and new line of research, through their application. Thermophilic proteins, piezophilic proteins, acidophilic proteins, and halophilic proteins have been studied during the last few years. Amylases, proteases, lipases, pullulanases, cellulases, chitinases, xylanases, pectinases, isomerases, esterases, and dehydrogenases have great potential application for biotechnology, such as in agricultural, chemical, biomedical, and biotechnological processes. The study of extremozymes and their main applications have emerged during recent years.

Keywords: Extremozymes, thermophiles, acidophiles, halophiles, biotechnology

Introduction

The extremophilic microorganisms live in extreme conditions and also adapt in ranges of environmental variables, such as temperature (55°C to 121°C and −2°C to 20°C), pressure (>500 atmospheres), alkalinity or acidity pH ($pH > 8$, $pH < 4$), salinity (2–5 M NaCl or KCl), geological scale/barriers, radiation (UVR resistance > 600 J/m), chemical extremes of heavy metals (arsenic, cadmium, copper, and zinc), lack of nutrients (*e.g.*, water, ice, air, rock, or soil), osmotic barriers, or polyextremity [1–4]. In the last decades, studies about the extremophilic microorganisms have increased; however, thermophilic proteins, piezophilic proteins, acidophilic proteins, and halophilic proteins have been receiving more attention for their biotechnological and industrial applications [5–7]. They can be classified as acidophile, alkaliphile, endolith, hyperthermophile, hypolith, metalotolerant, oligotroph, piezophile, psychrophile, radioresistant, thermophile, toxitolerant, and xerophile [8, 9]. The importance of enzymes and their roles in many processes have been investigated during the last years, especially enzymes from extremophiles [10–12]. Numerous enzymes have been identified (more than 3,000), where the majority has been used for biotechnological and industrial applications, but the enzymes market is still insufficient to respond to industry demands [13, 14]. The main reason for the insufficient demands of the enzymes is the fact that many do not resist the industrial conditions [15]. Additionally, the enzymes are used in technologies employing ecological processes [16]. The industrial process needs biocatalysts that can withstand conditions different in pH, temperature, and aerification, with high reproducibility, and other parameters [17–19]. With the growth and development of biotechnology, the interest for enzymes has increased considerably as a strategy towards attaining a biobased economy [20].

According to Dewan [21], the market of industrial enzymes is estimated to reach US$ 7,100 million by 2018, with a compound yearly progression rate of 8% during the 5-year period. Currently, microorganisms that produce new enzymes such as hydrolases, amylases, cellulases, peptidases, and lipases with potential for biotechnology to submit good activity at low temperatures are being sought [22]. Extremophilic microorganisms are a source of extremozymes with a great variety of industrial applications due to their biodegradability and extreme stability [23, 24]. The extremozymes as biocatalysts are solid and active under extreme environmental conditions that were previously regarded as incompatible with the biology. The application of extremozymes has made available a wide range of resistant biomolecules for industrial applications, such as cold-tolerant extremozymes, acid-tolerant extremozymes, alkali-tolerant extremozymes, and salt-tolerant extremozymes [25]. The exploration of enzymes with novel extreme activities and improved stability continues to be a priority objective in enzyme research [20]. This review focuses on the industrial applications of some enzymes from extremophilic microorganisms.

Thermophilic Proteins

Thermophilic microorganisms are among the most studied extremophiles during the last four decades [26, 27]. They have the capability to develop at great temperatures between 41°C and 122°C [28]. A wide number of enzymes from thermophilic microorganisms have been characterized, such as cellulases, amylases, pullulanases, xylanases, mannanase, pectinases, chitinases, proteases, lipases, esterases, and phytases [29]. Enzymes from thermophilic microorganisms are capable of accepting proteolysis and extreme situations like the presence of denaturing agents and organic solvents and high salinity. The use of these enzymes includes the possibility to reduce the risk of contamination, keeping a low adhesiveness, and greater solubility of substrates [20].

The thermozymes possess the physical property and electrostatic interactions to keep activity at great temperatures. They possess different adaptations, such as the capacity to keep their configuration and function in extremes of temperature. They also have the capacity to increase the quantity of hydrophobic deposits, forming bisulfide liaison between two ions with opposite charges [30, 31]. Biotechnological and industrial processes require thermostable enzymes like lipases that are used in different procedures such as grease hydrolysis, esterification, interesterification, transesterification, and organic biosynthesis. Additionally, thermozymes have been used in the creation of optical nanosensors and analytes [32]. Moreover, lipase has been used in the paper industry, milk industry, in processing of dyed products, leather industry, and in pharmaceuticals [17, 19]. Thermozymes include proteases that have been used in the synthesis of dipeptides and starch-processing and DNA [33, 34]. Cellulase, hemicellulases, and xylanases have had an important application in the bleaching of paper, and in environmental contamination [35, 36]. Today, biodetergents possess enzymes such as amylase, protease, cellulase, and lipase that are resistant to extreme conditions. Thermozymes such as amylase from *Pyrococcus furiosus* has had application in mutational studies. The mutation in pancreatic fistula amylase produced an augmentation in the fabrication of maltoheptaose from β-cycloamyloses. Maltoheptaose is used as a carrier in the food, cosmetic, and pharmaceutical industries [37]. At high temperatures, thermophilic enzymes exploit not only their activity, but they also lack to prove the catalytic activity at ambient temperatures [38]. Thermozymes have a great potential for biotechnological application and are energetic at great temperatures.

Piezophilic Proteins

Piezophiles are organisms that adapt optimally at hydrostatic high pressures in deep-sea environments such as deep-sea and volcano areas, for example *Pyrococcus abyssi* [39−43]. Study realized with the Sso7d protein (small with 7 kDa and 63 amino acids) from *Sulfolobus solfataricus* showed its piezophilic adaptation [44, 45]. Piezophilic protein, such as peptidase from *Pyrococcus horikoshii,* demonstrates stability at high pressure. Cavicchioli [46] and Georlette *et al*. [47] have reviewed the potential of piezophilic and piezophilic enzymes. Piezophilic microorganisms do not possess saline channels for stability, compared with thermopiezophiles that adapt to low temperature and great pressure [48, 49]. Piezophilic enzymes have a great potential for industrial applications, but nevertheless few research on enzymes from Piezophilic microorganisms exist. Abe and Horikoshi [50] demonstrated that α-amylase from piezophilic proteins produces trisaccharide in place of maltobiose and tetrasaccharide, with maltooligosaccharide as substrate, at great pressure and little energy. This reaction offers great industrial and biotechnological potential, particularly in the food industry [51, 52]. Piezophilic proteins have shown high efficiency in the detergent and food industries and chemical products [1].

Acidophilic Proteins

Acidophiles are organisms that grow at an optimum pH below 3−4 [53]. The adaptation of acidophilic proteins has not been investigated. For example, the endo-β-glucanase from *Sulfolobus solfataricus* demonstrated stability at optimum pH of 1.8 [54]. Nevertheless, at pH < 2, endo-β-glucanase cannot stabilize in the acidic environments [55]. The α-glucosidase from *Ferroplasma acidiphilum* has demonstrated stability at low pH. This enzyme also showed a preferrence for pH of 3 in place of 5.6, which is the internal pH of *Ferroplasma acidiphilum* [56]. Pikuta *et al.* [57] demonstrated that carboxylesterase in *Ferroplasma acidiphilum* has a pH optimum of approximately 2. With similar pH optima, other cytoplasmic enzymes also presented significantly lower activity at pH > 5. Acidophilic enzymes form multienzyme complexes at pH optima near that of the cytoplasm [58−60]. Enzymes from acidophilic microorganisms possess a great potential for biotechnological and industrial applications in biofuel and ethanol production. Cellulolytic and xylanolytic enzymes are used in an acid milieu at great temperature and acidity to help hydrolyze cellulolytic materials, making them more manageable [55, 61].

Halophilic Proteins

Halophilic microorganisms are capable of living in high salt concentrations (at least 1 M NaCl) and they have established different chemical, structural, and physiological modifications that allow the selectivity and stability of proteins with physicochemical properties [62, 63]. Halophilic microorganisms can be classified into three categories according to the optimal salt concentration: (i) extreme halophiles, capable of developing at 2,500−5,200 mM NaCl; (ii) moderate halophiles developing at 500−2,500 mM NaCl; and (iii) the slightly halophilic capable of developing at 200−500 mM NaCl [57]. Enzymes from halophiles employ different adaptation mechanisms and are very stable at low water activity and in the presence of organic solvents [64−66]. Halophilic enzymes show a great percentage of acid amino residues such as serine and threonine, in comparison with non-halophilic microorganisms; these include polysaccharide-hydrolyzing enzymes for xylan and starch [66−69]. Extremozymes from halophiles, such as xylanases, amylases, proteases, and lipases, produced by *Acinetobacter, Haloferax, Halobacterium, Halorhabdus, Marinococcus, Micrococcus, Natronococcus, Bacillus, Halobacillus,* and *Halothermothrix,* have been reported [70−72]. Lipases and esterases have great potential industrial applications, especially in the production of polyunsaturated fatty acids, food, and biodiesel [73, 74].

In the case of ligase N from *Haloferax volcanii*, KCl is needed to increase their enzymatic activity; otherwise, in the presence of NaCl their activities are very low [75]. As properties, halophilic enzymes have low solubility in aqueous/organic and non-aqueous media [76, 77]. So far, published research on the enzymatic behavior of halophilic enzymes in non-aqueous media are limited, such as proteases from *Halobacterium halobium* [78], *Saliniovibrio* sp. strain AF-2004 [79], and *Natrialba magadii* [80]; organic solvent-tolerant amylases from *Haloarcula* sp. strain S-1 [81], *Nesterenkonia* sp. strain F [82], and *Salimicrobium halophilum* strain LY20 [83]; and glutamate dehydrogenase from *Halobacterium salinarum* strain NRC-36014 [84]. Various investigations have reported that these conditions change according to enzymes. For example, enzyme protease from *Halogeometricum* sp. TSS101 showed varied production between 10% and 15% NaCl, whereas the optimal concentration for maximum biomass production was 20% NaCl [85]. Extremozymes from halophilic microorganisms present great opportunities for the industries of food, bioremediation, and biosynthetic processes. The biotechnological usages of halophilic enzymes are not restricted to their stability at high salt concentrations, as they are tolerant to high temperatures and stable in the presence of organic solvents [86]. They are active and stable in media with low water activity, as they have sufficient water to keep suitable charge distribution at the active site, maintaining the conformation of the enzyme [87]. Halophilic enzymes are involved in different stability and solubility mechanisms against high sodium chloride and potassium chloride concentrations, such interactions with organic solvents and in the three-dimensional enzyme structure [88, 89]. The activities of halophilic enzymes are very important, principally in optimal culture conditions for enzymatic activity, according to their salt requirement so as not to generate enzyme inhibition [62].

Potential Biotechnology Applications of Extremozymes

Extremophiles have a great potential for future expansions in biotechnological applications [90]. The cold-active enzymes allow an augmentation in connection with the solvent and an augmentation in structural flexibility that contribute to keep catalytic action at low temperatures [91,

Table 1. Classification of extremophiles and industrial application of some enzymes.

Types	Growth characteristics	Environment/source/ geographical location	Enzymes	Applications	Reference
Acidophile	Organism with a pH optimum for growth at or below 3-4	Acid mine drainage, volcanic springs, USA	Amylase, glucoamylase	Starch processing. Single-cell protein from shellfish waste	[80, 95]
			Proteases	Animal feed for the improvement of digestibility	[124–126]
			Cellulases	Removal of hemicellulosic material from feed Feed component	[127]
			Oxidases	Desulfurization of coal	[14]
Alkaliphile	Organism with optimal growth at pH values above 10	Soda Lakes, Utah USA.	Proteases, cellulases	Detergents, food, and feed Fermentation of beer and wine, breadmaking, and fruit juice processing	[14, 124, 128]
Halophile	Organism requiring at least 1 M salt for growth	Salt Lakes, Utah USA	Proteases	Peptides synthesis	[127, 129]
			Dehydrogenases	Biocatalysis in organic media Asymmetric chemical synthesis	[14, 46]
Neolith	Organism that lives inside rocks	Upper subsurface to deep subterranean, Mediterranean and Japan Seas	[a]NI	[a]NI	[130]
Hyperthermophile	Organism having a growth temperature optimum of 80°C or higher	Submarine Hydrothermal vents, East Pacific, Porto di Levante, Vulcano, Italy	[a]NI	[a]NI	[83]
Hypolith	Organism that lives inside rocks in cold deserts	Desert, rock, Cornwallis Island and Devon Island in the Canadian high Arctic	[a]NI	[a]NI	[106]
Metallophile	Organism capable of tolerating high levels of heavy metals, such as copper, cadmium, arsenic, and zinc	Heavy metals, Latin America, and Europe	[a]NI	[a]NI	[131]
Oligotroph	Organism capable of growth in nutritionally deplete habitats	Carbon source, or carbon concentration, Antarctic	[a]NI	[a]NI	[71]
Piezophile	Organism that lives optimally at hydrostatic pressures of 40 MPa or higher	Deep ocean, Mariana Trench, Antarctic ice	To be defined	Food processing and antibiotic production	[14, 121]
Psychrophile	Organism having a growth temperature optimum of 10°C or lower, and a maximum temperature of 20°C	Ice, snow, Antarctic ice and Arctic Ocean	Proteases	Detergents, food applications	[14, 38, 132]
			Amylase	Detergents and bakery	
			Cellulases	Detergents feed and textiles	
			Dehydrogenases	Biosensors	

Table 1. Continued.

Types	Growth characteristics	Envrionment/source/ geographical location	Enzymes	Applications	Reference
Radioresistant	Organisms resistant to high levels of ionizing radiation	Sunlight, high UV radiation, Brazil	[a]NI	[a]NI	[105]
Thermophile	Organism that can thrive at temperatures between 60°C and 85°C humidity	Hot Spring, Grand Prismatic Spring, Yellowstone National Park, USA	Lipase, protease	Additive to detergents for washing at room temperature Breaking down of lipid stains Breaking down of protein stains Detergents in food and feed, brewing, baking Biodiesel production by trans-esterification of oils and alcohols Flavor modification, optically active esters	[14, 127, 132–134]
			Amylases, pullulanase, glucoamylases, cellulases, xylanases	Starch, cellulose, chitin, and pectin processing, textiles Breakdown starch-based stains Wash of cotton fabrics Starch hydrolysis Clarification of fruit, vegetable juices, and wine Cheese ripening Dough fermentation, bakery products	[14, 133, 135]
			Chitanases	Conversion of cellulose to ethanol	[1126]
			Xynalases	Chitin modifications for food and health products Starch hydrolysis Cheese ripening	[119]
			Esterases	Paper bleaching Bioremediation, degradation and removal of xenobiotics and toxic compounds	[127]
			DNA polymerases	Detergents, stereospecific reactions	[14]
			Dehydrogenases	Molecular biology Oxydation reaction	[14]
			Mannanase	Degradation of mannan or gum	[133]
Toxitolerant	Organisms able to withstand high levels of damaging agents, such as organic solvents	Water saturated with benzene or water-core of a nuclear reactor, Yellowstone National Park, USA	[a]NI	[a]NI	[135]
Xerophile	Organism capable of growth at low water activity and resistant to high desiccation	Desert, rock, surfaces, Atacama Desert in Chile	[a]NI	[a]NI	[103]

[a] NI: No Information.

92]. These enzymes are capable of keeping more compactly to water, parallel to salt-adapted enzymes [10]. Enzymes such as lipase, protease, chitanase, glucanase, xylanase, α-amylase, glucoamylase, pectinase, oxidase, pullulanase, esterase, cellulase, mannanase, and peroxidase have great potential for industrial application (Table 1). During the last years, many efforts have been realized to search for enzymes that can be developed in industrial process conditions, due to the increasing industrial demands for biocatalysts, enzymes, and metabolites [93]. In some parts of the world, the utilization of high temperatures is restricted for energetic motives. Amylases and proteases are cold-adapted and able to eliminate starch stains and are already available from Novozymes and from Genencor [94]. The lipases are also very important but show to be more difficult to produce in heterologous microorganisms. In the food industry, cold-adapted enzymes are very important owing to their high activity and their low structural stability [46, 47, 95]. Cold-active enzymes have great potential applications for biotransformations, including volatile substrates, cosmetic industry, and pharmaceutical industry, such as for production of enantiomer peptides, lipids, and sugars. Their flexibility can offer a significant benefit in terms of activity over mesophilic enzymes [96]. In agriculture, they can be used to improve the management of water by plants under deficiency stress [97, 98]. The properties of cold-active enzymes allow them to have a great variety of applications in biotechnology and industry [1]. One of the main biotechnological applications of extremophiles is due to their ability to produce enzymes that can be useful in the composition of commercial products, in industrial processes such as bioremediation of toxic contaminants from water and sediments, and in the production of biomolecules for medical and industrial purposes [99–102]. Enzymes from extremophilic microorganisms provide different biotechnological opportunities for biocatalysis and biotransformations, due to their stability at high and low temperatures, range of pH, ionic strengths, salinities, and the ability to function in organic solvents that would denature most other enzymes [103, 104]. The enzymes are used in many commercial products and many industrial processes [103]. More than 3,000 enzymes are identified, and nearly 65% are used in the detergent, textile, pulp, paper, and starch industries and 25% are used for food processing [105]. Amylase is being incorporated into biochemical reactions that produce at high temperatures, and could be substituted for high-cost reactants [94, 106]. In addition, extremozymes often have higher reaction rates, the capability of destroying and/or eliminating xenobiotics (chemical compounds foreign to a given biological system), and the ability to modulate the hyperaccumulation of substances such as heavy metals, pollutants, and radionuclides. The use of extremozymes allows industrial processes to closely approach the gentle, efficient processes that take place in nature. As an example, the protease from alkalophilic bacteria could be used in the detergent industry with a range of pH 8–11 for this enzyme, and also supports a temperature of 70ºC, and a salt concentration of 10%, representing an advantage to the current market of mesophilic enzymes [107]. Cellulolytic enzymes have established great biotechnological potential in industries related to food, brewing and wine, agriculture, biomass refining, pulp and paper, textile, and laundry, whereas cellulases protease, and lipase are used in the detergents industry, and also are capable of modifying cellulose to increase the color intensity, feel, and dirt elimination from cotton blend garments [90, 108, 109]. Xylanases have offered great applications in biotechnology and industry in the bio-bleaching of pulp and paper, thus lowering the environmental pollution by halogens [110, 111]. Extremozymes such as proteases, lipases, cellulases, and amylases are commercial enzymes that have been used in industry, especially in detergents [112–115]. The production of detergents from enzymes is an enormous market that constitutes about 40% of the total enzymes produced globally, ranging from large-scale processing to smaller-scale high-value-added products [116–118]. Cellulases and amylases are used for desizing processes, such as biofinishing, in removing the surface fibrils and pills, and in stone washing processes [119]. The diversity and exceptional properties of extremozymes such as their reproducibility, high performance, and economic viability, among others, have increased their biotechnological application to different industrial processes [120].

Conclusions and Prospects

Extremozymes have been used as a source of novel enzymes owing to their stability and ability to live under extreme conditions. Notwithstanding their potentials, the extremozymes are very few. In particular, thermophilic enzymes have large potential biotechnological applications, due to their high resistance under extreme temperature, chemicals, organic solvents, and pH. The extremozymes have an economic potential application in agriculture, food beverages, pharmaceutical, detergent, textile, leather, pulp and paper, and biomining industries. The expansion of new industrial processes based on extremozymes and the increasing demand of biotech industries for novel biocatalysts are of great interest for extremophile research [121, 122]. In some cases, extremozymes have been identified in metagenomes as overcoming bottlenecks related to the non-cultivable extremophiles [6, 122]. The extremophilic microorganisms are sustainable sources that might be better exploited in numerous biotechnological areas towards the expansion of a bio-based economy. Enzymes from extremophiles have had a large impact so far from a commercial and biotechnological perspective [123].

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References

1. Cavicchioli R, Amils D, McGenity T. 2011. Life and applications of extremophiles. *Environ. Microbiol.* **13:** 1903-1907.
2. Deppe U, Richnow HH, Michaelis W, Antranikian G. 2005. Degradation of crude oil by an arctic microbial consortium. *Extremophiles* **9:** 461-470.
3. Navarro-González R, Iniguez E, de la Rosa J, McKay CR. 2009. Characterization of organics, microorganisms, desert soil, and Mars-like soils by thermal volatilization coupled to mass spectrometry and their implications for the search for organics on Mars by Phoenix and future space missions. *Astrobiology* **9:** 703-711.
4. Seitz KH, Studdert C, Sanchez J, de Castro R. 1997. Intracellular proteolytic activity of the haloalkaliphilic archaeon *Natronococcus occultus*. Effect of starvation. *J. Basic Microbiol.* **7:** 313-322.
5. Cárdenas JP, Valdés J, Quatrini R, Duarte F, Holmes DS. 2010. Lessons from the genomes of extremely acidophilic bacteria and archaea with special emphasis on bioleaching microorganisms. *Appl. Microbiol. Biotechnol*. **88:** 605-620.
6. López-López O, Cerdán ME, González-Siso MI. 2014. New extremophilic lipases and esterases from metagenomics. *Curr. Protein Pept. Sci*. **15:** 445-455.
7. Yildiz SY, Radchenkova N, Arga KY, Kambourova M, Toksoy OE. 2015. Genomic analysis of *Brevibacillus thermoruber* 423 reveals its biotechnological and industrial potential. *Appl. Microbiol. Biotechnol*. **99:** 2277-2289.
8. Cowan DA, Ramond JB, Makhalanyane TP, De Maayer P. 2015. Metagenomics of extreme environments. *Curr. Opin. Microbiol*. **25:** 97-102.
9. Qin J, Zhao B, Wang X. 2009. Non-sterilized fermentative production of polymer-grade L-lactic acid by a newly isolated thermophilic strain *Bacillus* sp. *PLoS One* **4:** 43-59.
10. Karan R, Capes MD, DasSarma S. 2012. Function and biotechnology of extremophilic enzymes in low water activity. *Aquat. Biosyst.* **8:** 3-15.
11. Nigam SP. 2013. Microbial enzymes with special characteristics for biotechnological applications. *Biomolecules* **3:** 597-611.
12. Singh OV, Gabani P. 2011. Extremophiles: radiation resistance microbial reserves and therapeutic implications. *J. Appl. Microbiol*. **110:** 851-861.
13. Demirjian DC, Morís-Varas F, Cassidy CS. 2001. Enzymes from extremophiles. *Curr. Opin. Chem. Biol*. **5:** 144-151.
14. Van den Burg B. 2003. Extremophiles as a source for novel enzymes. *Curr. Opin. Microbiol.* **6:** 213-218.
15. Irwin JA, Baird AW. 2004. Extremophiles and their application to veterinary medicine. *Ir. Vet. J.* **57:** 348-354.
16. Díaz-Tenaa E, Rodríguez-Ezquerroa A, López de Lacalle Marcaide LN, Bustinduyb LG, Sáenzb AE. 2013. Use of extremophiles microorganisms for metal removal. *Procedia Eng*. **63:** 67-74.
17. Eichler J. 2001. Biotechnological uses of archaeal extremozymes. *Biotechnol. Adv*. **19:** 261-278.
18. Fujiwara S. 2002. Extremophiles: developments of their special functions and potential resources. *J. Biosci. Bioeng*. **94:** 518-525.
19. Haki GD, Rakshit SK. 2003. Developments in industrially important thermostable enzymes: a review. *Bioresour. Technol*. **89:** 7-34.
20. Raddadi N, Cherif A, Daffonchio D, Mohamed N, Fava F. 2015. Biotechnological applications of extremophiles, extremozymes and extremolytes. *Appl. Microbiol. Biotechnol.* **99:** 7907-7913.
21. Dewan S. 2014. *Global Markets for Enzymes in Industrial Applications*. BCC Research, Wellesley, MA. USA.
22. Marhuenda-Egea FC, Piere-Velazquez S, Cadenas C, Cadenas E. 2002. An extreme halophilic enzyme active at low salt in reversed micelles. *J. Biotechnol*. **93:** 159-164.
23. Jaenicke R, Schuring H, Beaucamp N, Ostendorp R. 1996. Structure and stability of hyperstable proteins: glycolytic enzymes from hyperthermophilic bacterium *Thermotoga maritima*. *Adv. Protein Chem.* **48:** 181-269.
24. Sthal S. 1993. *In* Gupta MN (ed.). *Thermostability of Enzymes,* pp. 45-74. Springer, Berlin, Germany.
25. Cavicchioli R, Siddiqui KS, Andrews D, Sowers KR. 2002. Low-temperature extremophiles and their applications. *Curr. Opin. Biotechnol.* **13:** 253-261.
26. Bertoldo C, Antranikian G. 2002. Starch-hydrolyzing enzymes from thermophilic archaea and bacteria. *Curr. Opin. Chem. Biol*. **6:** 151-60.
27. Van der Maarel MJ, van der Veen B, Uitdehaag JC, Leemhuis H, Dijkhuizen L. 2002. Properties and application of starch-converting enzymes of the α-amylase family. *J. Biotechnol*. **94:** 137-155.
28. Madigan MT, Marrs BL. 1997. Gli estremofili. *Le Scienze* **346:** 78-85.
29. Sunna A, Bergquist PL. 2003. A gene encoding a novel extremely thermostable 1,4-beta-xylanase isolated directly

from an environmental DNA sample. *Extremophiles* **7:** 63-70.

30. Brasen C, Urbanke C, Schonheit P. 2005. A novel octameric AMP-forming acetyl-CoA synthetase from the hyperthermophilic crenarchaeon *Pyrobaculum aerophilum. FEBS Lett*. **579:** 477-482.
31. Mayer F, Küper U, Meyer C, Daxer S, Müller V, Rachel R, Huber H. 2012. AMP-forming acetyl coenzyme A synthetase in the outermost membrane of the hyperthermophilic crenarchaeon *Ignicoccus hospitalis*. *J. Bacteriol*. **194:** 1572-1581.
32. Staiano M, Bazzicalupo P, Rossi M, D'Auria S. 2005. Glucose biosensors as models for the development of advanced protein-based biosensors. *Mol. Biosyst*. **1:** 354-362.
33. Bruins ME, Janssen AE, Boom RM. 2001. Thermozymes and their applications: a review of recent literature and patents. *Appl. Biochem. Biotechnol*. **90:** 155-186.
34. Jayakumar R, Jayashree S, Annapurna B, Seshadri S. 2012. Characterization of thermostable serine alkaline protease from an alkaliphilic strain *Bacillus pumilus* MCAS8 and its applications. *Appl. Biochem. Biotechnol*. **168:** 1849-1866.
35. De Pascale D, Cusano AM, Author F, Parrilli E, di Prisco G, Marino G, Tutino ML. 2008. The cold-active Lip1 lipase from the Antarctic bacterium *Pseudoalteromonas haloplanktis* TAC125 is a member of a new bacterial lipolytic enzyme family. *Extremophiles* **12:** 311-323.
36. Unsworth LD, Van Der OJ, Koutsopoulos S. 2007. Hyperthermophilic enzymes − stability, activity and implementation strategies for high temperature applications. *FEBS J*. **274:** 4044-4056.
37. Rosenbaum E, Gabel F, Durá MA, Finet S, Cléry-Barraud C, Masson P, Franzetti B. 2012. Effects of hydrostatic pressure on the quaternary structure and enzymatic activity of a large peptidase complex from *Pyrococcus horikoshii*. *Arch. Biochem. Biophys*. **517:** 104-110.
38. De Champdoré M, Staiano M, D'Auria S. 2007. Proteins from extremophiles as stable tools for advanced biotechnological applications of high social interest. *J. R. Soc. Interface* **4:** 183-191.
39. Boonyaratanakornkit BB, Park CB, Clark DS. 2002. Pressure effects on intra- and intermolecular interactions within proteins. *Biochim. Biophys. Acta* **1595:** 235-249.
40. Fang J, Zhang L, Bazylinski DA. 2010. Deep-sea piezosphere and piezophiles: geomicrobiology and biogeochemistry. *Trends Microbiol*. **18:** 413-422.
41. Reed CJ, Lewis H, Trejo E, Winston V, Evilia C. 2013. Protein adaptations in archaeal extremophiles. *Archaea* **2013:** 373275.
42. Simonato F, Campanaro S, Lauro FM, Vezzi A, D'Angelo M, Vitulo N. 2006. Piezophilic adaptation: a genomic point of view. *J. Biotechnol*. **126:** 11-25.
43. Takai K, Miyazaki M, Hirayama H, Nakagawa S, Querellou J, Godfroy A. 2009. Isolation and physiological characterization of two novel piezophilic, thermophilic chemolithoautotrophs from a deep-sea hydrothermal vent chimney. *Environ. Micriobiol*. **11:** 1983-1997.
44. Fusi P, Grisa M, Mombelli E, Consonni R, Tortora P, Vanoni M. 1995. Expression of a synthetic gene encoding P2 ribonuclease from the extreme thermoacidophilic archaebacterium *Sulfolobus solfataricus* in mesophylic hosts. *Gene* **154:** 99-103
45. Mombelli E, Shehi E, Fusi P, Tortora P. 2002. Exploring hyperthermophilic proteins under pressure: theoretical aspects and experimental findings. *Biochim. Biophys. Acta* **1595:** 392-396.
46. Cavicchioli R. 2002. Extremophiles and the search for extraterrestrial life. *Astrobiology* **2:** 281-292.
47. Georlette D, Blaise V, Collins T, D'Amico S, Gratia E, Hoyoux A, *et al*. 2004. Some like it cold: biocatalysis at low temperatures. *FEMS Microbiol. Rev*. **28:** 25-42.
48. Gomes J, Steiner W. 1998. Production of a high activity of an extremely thermostable β-mannanase by the thermophilic eubacterium *Rhodothermus marinus. Biotechnol. Lett*. **20:** 729-733.
49. Gomes J, Gomes I, Terler K, Gubala N, Ditzelmuller G, Steiner W. 2000. Optimisation of culture medium and conditions for α-L-arabinofuranosidase production by the extreme thermophilic eubacterium *Rhodothermus marinus*. *Enzyme Microb. Technol*. **27:** 414-422.
50. Abe F, Horikoshi K. 2001. The biotechnological potential of piezophiles. *Trends Biotechnol.* **19:** 102-108.
51. Cannio R, Di Prizito N, Rossi M, Morana A. 2004. A xylan-degrading strain of *Sulfolobus solfataricus*: isolation and characterization of the xylanase activity. *Extremophiles* **8:** 117-124.
52. Giuliano M, Schiraldi C, Marotta MR, Hugenholtz J, De Rosa M. 2004. Expression of *Sulfolobus solfataricus* α-glucosidase in *Lactococcus lactis*. *Appl. Microbiol. Biotechnol*. **64:** 829-832.
53. Jaenicke R. 1981. Enzymes under extreme of physical conditions. *Annu. Rev. Biophys. Bioeng*. **10:** 1-67.
54. Huang Y, Krauss G, Cottaz H, Driguez H, Lipps G. 2005. A highly acid-stable and thermostable endo-β-glucanase from the thermoacidophilic archaeon *Sulfolobus solfataricus*. *Biochem. J*. **385:** 581-588.
55. Golyshina O, Timmis KN. 2005. *Ferroplasma* and relatives, recently discovered cell wall-lacking archaea making a living in extremely acid, heavy metal-rich environments. *Environ. Microbiol*. **7:** 1277-1288.
56. Sharma A, Kawarabayasi Y, Satyanarayana T. 2012. Acidophilic bacteria and archaea: acid stable biocatalysts and their potential applications. *Extremophiles* **16:** 1-19.
57. Pikuta EV, Hoover RB, Tang J. 2007. Microbial extremophiles at the limits of life. *Crit. Rev. Microbiol*. **33:** 183-209.
58. Hauenstein S, Zhang CM, Hou YM, Perona JJ. 2004. Shape-selective RNA recognition by cysteinyl-tRNA synthetase. *Nat. Struct. Mol. Biol*. **11:** 1134-1141.
59. Szilágyi A, Závodszky P. 2000. Structural differences between

mesophilic, moderately thermophilic and extremely thermophilic protein subunits: results of a comprehensive survey. *Structure* **8:** 493-504.

60. Wright DB, Banks DD, Lohman JR, Hilsenbeck JL, Gloss LM. 2002. The effect of salts on the activity and stability of *Escherichia coli* and *Haloferax volcanii* dihydrofolate reductases. *J. Mol. Biol.* **323:** 327-344.
61. Jackson BR, Noble C, Lavesa-Curto M, Bond PL, Bowater RP. 2007. Characterization of an ATP-dependent DNA ligase from the acidophilic archaeon "*Ferroplasma acidarmanus*" Fer1. *Extremophiles* **11:** 315-327.
62. Delgado-García M, Valdivia-Urdiales B, Aguilar-González CN, Contreras-Esquivel JC, Rodríguez-Herrera R. 2012. Halophilic hydrolases as a new tool for the biotechnological industries. *J. Sci. Food Agric.* **92:** 2575-2580.
63. Jackson CR, Langner HW, Donahoe-Christiansen J, Inskeep WP, McDermott TR. 2001. Molecular analysis of microbial community structure in an arsenite-oxidizing acidic thermal spring. *Environ. Microbiol.* **3:** 532-542.
64. Datta S, Holmes B, Park J, Chen Z, Dibble DC, Hadi M, *et al*. 2010. Ionic liquid tolerant hyperthermophilic cellulases for biomass pretreatment and hydrolysis. *Green Chem.* **12:** 338-345.
65. Madern D, Pfister C, Zaccai G. 1995. Mutation at a single acidic amino acid enhances the halophilic behaviour of malate dehydrogenase from *Haloarcula marismortui* in physiological salts. *Eur. J. Biochem.* **3:** 1088-1095.
66. Raddadi N, Cherif A, Daffonchio D, Fava F. 2013. Halo-alkalitolerant and thermostable cellulases with improved tolerance to ionic liquids and organic solvents from *Paenibacillus tarimensis* isolated from the Chott El Fejej, Sahara desert, Tunisia. *Bioresour. Technol.* **150:** 121-128.
67. Bhalla A, Bansal N, Kumar S, Bischoff KM, Sani RK. 2013. Improved lignocellulose conversion to biofuels with thermophilic bacteria and thermostable enzymes. *Bioresour. Technol.* **128:** 751-759.
68. Elleuche S, Schröder C, Sahm K, Antranikian G. 2014. Extremozymes – biocatalysts with unique properties from extremophilic microorganisms. *Curr. Opin. Biotechnol.* **29:** 116-123.
69. Madern D, Ebel C, Zaccai G. 2000. Halophilic adaptation of enzymes. *Extremophiles* **4:** 91-98.
70. Sutrisno A, Ueda M, Abe Y, Nakazawa M, Miyatake K. 2004. A chitinase with high activity toward partially N-acetylated chitosan from a new, moderately thermophilic, chitin-degrading bacterium, *Ralstonia* sp. A-471. *Appl. Microbiol. Biotechnol.* **63:** 398-406.
71. Taylor INR, Brown C, Rycroft M, King G, Littlechild JA, Lloyd MC, *et al*. 2004. Application of thermophilic enzymes in commercial biotransformation processes. *Biochem. Soc. Trans.* **32:** 290-292.
72. Woosowska S, Synowiecki J. 2004. Thermostable glucosidase with broad substrate specificity suitable for processing of lactose-containing products. *Food Chem.* **85:** 181-187.
73. Litchfield CD. 2011. Potential for industrial products from the halophilic Archaea. *J. Ind. Microbiol. Biotechnol.* **38:** 1635-1647.
74. Schreck SD, Grunden AM. 2014. Biotechnological applications of halophilic lipases and thioesterases. *Appl. Microbiol. Biotechnol.* **98:** 1011-1021.
75. Ortega G, Laín A, Tadeo X, López-Méndez B, Castaño D, Milleta O. 2011. Halophilic enzyme activation induced by salts. *Sci. Rep.* **1:** 6.
76. Serour E, Antranikian G. 2002. Novel thermoactive glucoamylases from the thermoacidophilic Archaea *Thermoplasma acidophilum, Picrophilus torridus* and *Picrophilus oshimae*. *Antonie Van Leeuwenhoek* **81:** 73-83.
77. Suzuki T, Nakayama T, Kurihara T, Nishino T, Esaki N. 2001. Cold-active lipolytic activity of psychrotrophic *Acinetobacter* sp. strain no. 6. *J. Biosci. Bioeng.* **92:** 144-148.
78. Kim J, Dordick S. 1997. Unusual salt and solvent dependence of a protease from an extreme halophile. *Biotechnol. Bioeng.* **55:** 471-479.
79. Karbalaei-Heidari HR, Ziaee AA, Amoozegar MA. 2007. Purification and biochemical characterization of a protease secreted by the *Salinivibrio* sp. strain AF-2004 and its behavior in organic solvents. *Extremophiles* **11:** 237-243.
80. Ruiz DM, De Castro RE. 2007. Effect of organic solvents on the activity and stability of an extracellular protease secreted by the haloalkaliphilic archaeon *Natrialba magadii*. *J. Ind. Microbiol. Biotechnol.* **34:** 111-115.
81. Fukushima T, Mizuki T, Echigo A, Inoue A, Usami R. 2005. Organic solvent tolerance of halophilic a-amylase from a haloarchaeon, *Haloarcula* sp. strain S-1. *Extremophiles* **9:** 85-89.
82. Shafiei M, Ziaee AA, Amoozegar MA. 2011. Purification and characterization of an organic-solvent-tolerant halophilic a-amylase from the moderately halophilic *Nesterenkonia* sp. strain F. *J. Ind. Microbiol. Biotechnol.* **38:** 275-281.
83. Yu HY, Li X. 2012. Purification and characterization of novel organic-solvent-tolerant b-amylase and serine protease from a newly isolated *Salimicrobium halophilum* strain LY20. *FEMS Microbiol. Lett* **329:** 204-211.
84. Munawar N, Engel PC. 2012. Overexpression in a non-native halophilic host and biotechnological potential of NAD$^+$-dependent glutamate dehydrogenase from *Halobacterium salinarum* strain NRC-36014. *Extremophiles* **16:** 463-476.
85. Vidyasagar M, Prakash S, Sreeramulu K. 2006. Optimization of culture conditions for the production of haloalkaliphilic thermostable protease from an extremely halophilic archaeon *Halogeometricum borinquense* sp. TSS 101. *Lett. Appl. Microbiol.* **43:** 385-391.
86. Zaccai G. 2004. The effect of water on protein dynamics. *Philos. Trans. R. Soc. Lond. B Biol. Sci.* **359:** 1269-1275.
87. Sellek GA, Chaudhuri JB. 1999. Biocatalysis in organic media using enzymes from extremophiles. *Enzyme Microb. Technol.* **l25:** 471-482.

88. Cordone L, Ferrand M, Vitrano E, Zaccai G. 1999. Harmonic behavior of trehalose-coated carbon-monoxy-myoglobin at high temperature. *Biophys. J*. **76:** 1043-1047.
89. Lehnert U, Réat V, Weik M, Zaccaï G, Pfister C. 1998. Thermal motions in bacteriorhodopsin at different hydration levels studied by neutron scattering: correlation with kinetics and light-induced conformational changes. *Biophys. J*. **75:** 1945-1952.
90. Singh A, Kuhad RC, Ward OP. 2007. Industrial application of microbial cellulases, pp. 345-358. *In* Kuhad RC, Singh A (eds.). *Lignocellulose Biotechnology: Future Prospects*. I.K. International Publishing House, New Delhi, India.
91. Merlino A, Russo KI, Castellano I, De VE, Rossi B, Conte M, *et al*. 2010. Structure and flexibility in cold-adapted iron superoxide dismutases: the case of the enzyme isolated from *Pseudoalteromonas haloplanktis*. *J. Struct. Biol*. **172:** 343-352.
92. Siddiqui KS, Cavicchioli R. 2006. Cold-adapted enzymes. *Annu. Rev. Biochem*. **75:** 403-433.
93. Sukumaran RK, Singhania RR, Pandey A. 2005. Microbial cellulases – production, applications and challenges. *J. Sci. Ind. Res*. **64:** 832-844.
94. Kumar L, Awasthi G, Singh B. 2011. Extremophiles: a novel source of industrially important enzymes. *Biotechnol. Appl. Biochem*. **10:** 1-15.
95. Gerday C, Aittaleb M, Bentahir M, Chessa JP, Claverie P, Collins T, *et al*. 2000. Cold-adapted enzymes: from fundamentals to biotechnology. *Trends Biotechnol*. **18:** 103-107.
96. Huston AL. 2008. Biotechnological aspects of cold-adapted enzymes, pp. 347-363. *In* Margesin R, Schinner F, Marx J-C, Gerday C (eds.). *Psychrophiles: From Biodiversity to Biotechnology*. Springer, Heidelberg. Germany.
97. Marasco R, Rolli E, Ettoumi B, Vigani G, Mapelli F, Borin S, *et al*. 2012. A drought resistance-promoting microbiome is selected by root system under desert farming. *PLoS One* **7:** e48479.
98. Rolli E, Marasco M, Vigani G, Ettoumi B, Mapelli F, Deangelis ML, *et al*. 2015. Improved plant resistance to drought is promoted by the root-associated microbiome as water stress-dependent trait. *Environ. Microbiol*. **17:** 316-331.
99. Hotta Y, Ezaki S, Atomi H, Imanaka T. 2002. Extremely stable and versatile carboxylesterase from a hyperthermophilic archaeon. *Appl. Environ. Microbiol*. **68:** 3925-3931.
100. Johnson DB. 2014. Biomining – biotechnologies for extracting and recovering metals from ores and waste materials. *Curr. Opin. Biotechnol*. **30:** 24-31.
101. Karasová-Lipovová P, Strnad H, Spiwok V, Malá S, Králová B, Russell NJ. 2003. The cloning, purification and characterisation of a cold-active β-galactosidase from the psychrotolerant Antarctic bacterium *Arthrobacter* sp. C2-2. *Enzyme Microb. Technol*. **33:** 836-844.
102. Navarro CA, von Bernath D, Jerez CA. 2013. Heavy metal resistance strategies of acidophilic bacteria and their acquisition: importance for biomining and bioremediation. *Biol. Res*. **46:** 363-371.
103. Adrio JL, Demain AL. 2014. Microbial enzymes: tools for biotechnological processes. *Biomolecules* **4:** 117-139.
104. Karmakar M, Ray RR. 2011. Current trends in research and application of microbial cellulases. *Res. J. Microbiol*. **6:** 41-53.
105. Birgisson H, Delgado O, Arroyo LG, Hatti-Kaul R, Mattiasson B. 2003. Cold-adapted yeasts as producers of cold-active polygalacturonases. *Extremophiles* **7:** 185-193.
106. Singh BK. 2010. Exploring microbial diversity for biotechnology: the way forward. *Trends Biotechnol.* **28:** 111-116.
107. Hess M, Katzer M, Antranikian G. 2008. Extremely thermostable esterases from the thermoacidophilic euryarchaeon *Picrophilus torridus*. *Extremophiles* **12:** 351-364.
108. Staley JT, Konopka A. 1985. Measurement of in situ activities of nonphotosynthetic microorganisms in aquatic and terrestrial habitats. *Annu. Rev. Microbiol*. **39:** 321-346.
109. Young P. 1997. Major microbial diversity initiative recommended. *ASM News* **63:** 417-421.
110. Mohammed K, Pramod WR. 2009. Cold-active extracellular alkaline protease from an alkaliphilic *Stenotrophomonas maltophilia*: production of enzyme and its industrial applications. *Can. J. Microbiol*. **55:** 1294-1301.
111. Yumoto I. 2002. Bioenergetics of alkaliphilic *Bacillus* spp. *J. Biosci. Bioeng*. **93:** 342-353.
112. Chang P, Tsai WS, Tsai CL, Tseng MJ. 2004. Cloning and characterization of two thermostable xylanases from an alkaliphilic *Bacillus firmus*. *Biochem. Biophys. Res. Commun.* **319:** 1017-1025.
113. Das H, Sing SK. 2004. Useful byproducts from cellulosic waste of agriculture and food industry – a critical appraisal. *Crit. Rev. Food Sci. Nutr.* **44:** 77-89.
114. Hashim SO, Delgado O, Hatti-Kaul R, Mulaa FJ, Mattiasson B. 2004. Starch hydrolysing *Bacillus halodurans* isolates from a Kenyan soda lake. *Biotechnol. Lett.* **26:** 823-828.
115. Von Solingen P, Meijer D, Kleij WA, Branett C, Bolle R, Power SD, Jones BE. 2001. Cloning and expression of an endocellulase gene from a novel streptomycete isolated from an East African soda lake. *Extremophiles* **5:** 333-341.
116. Ma Y, Xue Y, Grant WD, Collins NC, Duckworth AW, Van Steenbergen RP, Jones BE. 2004. *Alkalimonas amylolytica* gen. nov., sp. nov., and *Alkalimonas delamerensis* gen. nov., sp. nov., novel alkaliphilic bacteria from soda lakes in China and East Africa. *Extremophiles* **8:** 193-200.
117. Margesin R, Schinner F, Marx JC, Gerday C (eds.). 2008. *Psychrophiles: From Biodiversity to Biotechnology*. Springer-Verlag, Berlin–Heidelberg. Germany.
118. Zeng R, Zhang R, Zhao J, Lin N. 2003. Cold-active serine alkaline protease from the psychrophilic bacterium *Pseudomonas* strain DY-A: enzyme purification and characterization. *Extremophiles* **7:** 335-337.
119. Collins T, D'Amico S, Marx JC, Feller G, Gerday C. 2007.

Cold-adapted enzymes, pp. 165-179. *In* Gerday C, Glansdorff N (eds.). *Physiology and Biochemistry of Extremophiles*. ASM Press, Washington, DC. USA.

120. Gurung N, Ray S, Bose S, Rai V. 2013. A broader view: microbial enzymes and their relevance in industries, medicine, and beyond. *Biomed. Res. Int.* **2013:** 329121.
121. Egorova K, Antranikian G. 2005. Industrial relevance of thermophilic Archaea. *Curr. Opin. Microbiol*. **8:** 649-655.
122. Ferrer M, Golyshina O, Beloqui A, Golyshin PN. 2007. Mining enzymes from extreme environments. *Curr. Opin. Microbiol.* **10:** 207-214.
123. Secades P, Alvarez B, Guijarro JA. 2003. Purification and properties of a new psychrophilic metalloprotease (Fpp2) in the fish pathogen *Flavobacterium psychrophilum*. *FEMS Microbiol. Lett*. **226:** 273-279.
124. Huang H, Luo H, Wang Y, Fu D, Shao N, Yang P, *et al*. 2009. Novel low-temperature-active phytase from *Erwinia carotovora* var. *carotovota* ACCC 10276. *J. Microbiol. Biotechnol*. **19:** 1085-1091.
125. Tutino ML, di Prisco G, Marino G, de Pascale D. 2009. Cold-adapted esterases and lipases: from fundamentals to application. *Protein Pept. Lett*. **16:** 1172-1180.
126. Ueda M, Goto T, Nakazawa M, Miyatake K, Sakaguchi M, Inouye K. 2010. A novel cold-adapted cellulase complex from *Eisenia foetida*: characterization of a multienzyme complex with carboxymethylcellulase, beta-glucosidase, beta-1,3 glucanase, and beta-xylosidase. *Comp. Biochem. Physiol. B Biochem. Mol. Biol.* **157:** 26-32.
127. Wang F, Hao J, Yang C, Sun M. 2010. Cloning, expression, and identification of a novel extracellular cold-adapted alkaline protease gene of the marine bacterium strain YS-80-122. *Appl. Biochem. Biotechnol*. **162:** 1497-1505.
128. Parkes R, Cragg J, Banning BA, Brock N, Webster F, Fry G, *et al*. 2007. Biogeochemistry and biodiversity of methane cycling in subsurface marine sediments (Skagerrak, Denmark). *Environ. Microbiol*. **9:** 1146-1161.
129. Aurilia V, Parracino A, D'Auria S. 2008. Microbial carbohydrate esterases in cold adapted environments. *Gene* **410:** 234-240.
130. Toplin JA, Norris TB, Lehr CR, McDermott TR, Castenholz RW. 2008. Biogeographic and phylogenetic diversity of thermoacidophilic Cyanidiales in Yellowstone National Park, Japan, and New Zealand. *Appl. Environ. Microbiol*. **74:** 2822-2833.
131. Zeng X, Birrien JL, Fouquet Y, Cherkashov G, Jebbar M, Querellou J, *et al*. 2009. *Pyrococcus* CH1, an obligate piezophilic hyperthermophile: extending the upper pressure-temperature limits for life. *ISME J*. **3:** 873-876.
132. Joseph B, Ramteke PW, Thomas G. 2008. Cold active microbial lipases: some hot issues and recent developments. *Biotechnol. Adv*. **26:** 457-470.
133. Sarmiento F, Rocío P, Blamey JM. 2015. Cold and hot extremozymes: industrial relevance and current trends. *Front. Bioeng. Biotechnol*. **3:** 1-15.
134. Schmid AK, Reiss DJ, Pan M, Koide T, Baliga NS. 2009. A single transcription factor regulates evolutionarily diverse but functionally linked metabolic pathways in response to nutrient availability. *Mol. Syst. Biol*. **5:** 282-294.
135. Nicholas JR. 2006. Antarctic microorganism: coming in from the cold. *Culture* **27:** 965-989.