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REVIEW ARTICLE

Haloalkaliphilic *Bacillus* species from solar salterns: an ideal prokaryote for bioprospecting studies

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Abstract Bioprospecting is an umbrella term describing the process of search and discovery of commercially valuable new products from biological sources in plants, animals, and microorganisms. In a way, bioprospecting includes the exploitative appropriation of indigenous forms of knowledge by commercial actors, as well as the search for previously unknown compounds in organisms that have never been used in traditional ways. These resources may be used in industrial applications, environmental, biomedical, and biotechnological aspects. *Bacillus* species are one of the most studied organisms from different perspectives and diverse environments, namely for industrial and environmental applications owing to the adaptations and versatile molecules they produce. The ability of different species to ferment in the acid, neutral, and alkaline pH ranges, combined with the presence of thermophiles in the genus, has lead to the development of a variety of new commercial enzyme products with the desired temperature, pH activity, and stability properties to address a variety of specific applications. Unlike other microbial species *Bacillus* species have been isolated from different sources both natural and artificial sources some being extreme in nature, for bioprospecting studies to exploit them to fabricate novel biomolecules or functions. Solar salterns are among the least documented environments as a source of *Bacillus* species due to their unique nature comprising multiple extremities of varying degrees, namely temperature, pH, and minimal nutrients along with saturating salinity. Haloalkaliphilic *Bacillus* species are the group specifically adapted to grow optimally under moderate halophilic and alkaline conditions. Artificial solar salterns are not evenly established as a habitat because they are created and maintained by humans. Hence, the present paper makes an attempt to review the potential of haloalkaliphilic *Bacillus* species from manmade solar salterns for bioprospecting studies.

Keywords Haloalkaliphilic *Bacillus* species · Artificial Solar salterns and Bioprospecting

Introduction

The seas that cover nearly 70 % of the surface of planet Earth contain about 35 g/L^{-1} dissolved salt. Hypersaline environments are easily formed when seawater dries up in coastal lagoons and salt marshes, as well as in manmade evaporation ponds of saltern systems built to produce common salt by evaporation of seawater. There are also inland saline lakes in which the salt concentrations can reach close to saturation. Well-known examples are the Great Salt Lake, UT, USA, a lake in which the ionic composition of the salts resembles that of seawater, and the Dead Sea on the border between Israel and Jordan, a lake dominated by magnesium rather than by sodium as the most abundant cation. Furthermore, there are extensive underground deposits of rock salt that originated by the drying of closed marine basins. All of these environments, as well as others such as saline soils, provide a habitat for salt-adapted microorganisms, obligate halophiles, as well as halotolerant organisms that can adjust to life over a wide range of salt concentrations.

Solar salterns are hypersaline water bodies located along the sea-coast and are the main source of salt generated through the evaporation of seawater. They are generally composed of a system of shallow ponds with salinities ranging from of

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seawater to supersaturated brines. These elevated saline concentrations represent extreme environmental conditions leading to the growth of only a few specialized groups of microorganisms: the halophiles. These halophilic microbial communities (Oren 2006; Pedrós-Alió 2006) are adapted to life at high salt concentrations and to the high osmotic pressure of their environment resulting from the high salinity. In addition, other factors such as temperature, pH, oxygen, nutrient availability, and solar radiation prevailing in these environments also limit the growth of microorganisms. Most of the solar salterns tend to be alkaline in nature due to carbonates, and only a negligible number are acidic in nature (those are near acidic or sulphur mines). Artificial solar salterns are unique polyextremophilic environments characterized by saturating salinities (15–35 %), moderate alkalinity pH (9.0), and mesophilic temperatures (45–50 °C), which are the conditions most prevalent in industrial processes. Another reason that artificial solar salterns are a source of potential prokaryotes is they are the dominant population when compared with eukaryotic groups such as fungi or algae (Syed et al. 2012).

Apart from Haloarchaea, *Bacillus* species are prominently found in the less saline zones of solar salterns, particularly in saturation ponds, which have 15–25 % salinity. *Bacillus* species continue to be dominant bacterial workhorses in microbial fermentations. *Bacillus subtilis* is the key microbial participant in the ongoing production of large-scale hydrolytic enzyme production, and some *Bacillus* species are on the Food and Drug Administration's GRAS (generally regarded as safe) list. The capacity of selected Bacillus strains to produce and secrete large quantities (20–25 g/L) of extracellular enzymes has placed them among the most important industrial enzyme producers. The *Bacillus* strains isolated from solar salterns have properties such as temperature and alkalinity tolerance of considerable level. Thus, the special natural adaptations of the Bacillus species from solar salterns render them ideal candidates for multiple application bioprospecting studies. This review attempts to consolidate the recent applications of haloalkaliphilic *Bacillus* species to inspire extensive study of the same to the fullest.

Halophiles

Halophiles are able to survive in salty conditions through cellular and molecular adaptations, including adjusting the cell turgor to different external salinities by controlling the concentration of protective molecules such as ectoine, betaine, and amino acids (glutamine, glutamate, proline, and glycine) by producing them intracellularly or taken up from the environment, and by concentration regulation of compatible solutes such as chloride and sodium/potassium in intracellular environments, depending on external salinity (Müller and Köcher 2011) (Fig. 1) (Marco and Erhard 2011). Because water tends to flow from areas of high solute concentration to areas of lower concentration, a cell suspended in a very salty solution will lose water and become dehydrated unless its cytoplasm contains a higher concentration of salts than its environment. Halophiles contend with this problem by producing large amounts of an internal solute or by recollecting a solute extracted from outside (Garabito et al. 1998). Halophily refers to the ionic requirements for life at high salt concentrations. Although these phenomena are physiologically distinct, they are environmentally associated with other physiological parameters. Thus, a halophile must cope with osmotic stress (Oren 2006). Halophiles include a range of microbes, but some Archaea, cyanobacteria, and the green alga *Dunaliella salina* can withstand periods in saturated NaCl. For instance, an Archaean known as *Halobacterium salinarum* concentrates potassium chloride in its interior. As might be expected, the enzymes in its cytoplasm will function only if a high concentration of potassium chloride is present, but proteins in *Halobacterium salinarum* cell structures that are in contact with the environment require a high concentration of NaCl.

Haloalkaliphiles

Alkaliphiles consist of two main physiological groups of microorganisms, alkaliphiles and haloalkaliphiles. Alkaliphiles require an alkaline pH of 9 or more for their growth and have an optimal growth pH of around 10, whereas haloalkaliphiles require both an alkaline pH (>pH 9) and high salinity (up to 33 % (w/v) NaCl) (Horikoshi 1996). The environments or sources for this group of microorganisms are both natural and artificial in nature (Oren 2002a).

Adaptation strategies for haloalkaliphiles

Haloalkaliphiles possess adaptation mechanisms, which include production of high density lipids with branched chains and increased content of cell wall components (glutamic acid, diaminopimelic acid, muramic acid, and glucosamine) along with the presence of poly-γ-L-glutamic acid along with Na^+/H^+ antiporters as internal pH homeostasis for survival in highly saline and alkaline pH (Horikoshi 2011; Krulwich et al. 2011). These properties make them interesting not only for fundamental research, but also for industrial application (Margesin and Schinner 2001; Purohit et al. 2014). So far, moderately haloalkaliphilic bacteria have been isolated from the different saline and alkaline environments (Ventosa et al. 1998; Patel et al. 2005; Xu et al. 2007).

Extremophiles adopt two distinct approaches to living within extreme environments; they adapt to function within

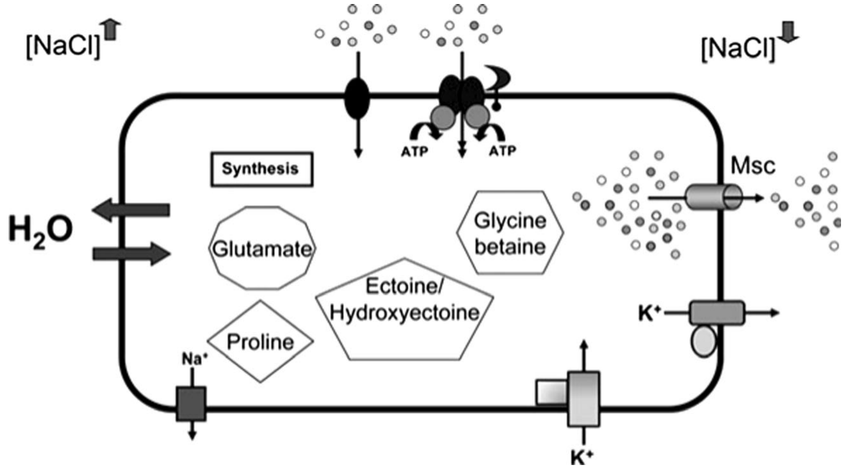

Fig 1 The core of osmostress response of Bacilli. Schematic overview of the initial and sustained cellular stress responses to high salinity through the uptake of K^+, synthesis and import of various compatible solutes and the active export of K^+ and Na^+ ions. Non-selective expulsion of ions and organic solutes occur in response to sudden osmotic downshifts via mechanosensitive channels (Msc)

the physical and chemical bounds of their environment or they maintain mesophilic conditions intracellularly, guarding against the external pressures. Among them, halophiles are an interesting class of extremophilic organisms that have adapted to harsh, hypersaline environments (Oren 2002b).

Applications of haloalkaliphiles

Stable alkaline conditions are caused by an unusual combination of climatic, geological, and topological conditions. Soda lakes represent the most stable high-pH environments on earth and commonly have pH values above 11.5. These environments are associated with a low Mg^{2+}, Ca^{2+} geology together with rates of evaporation that exceed any inflow. Transient alkalinity in microhabitats arising through biological activity such as ammonification or sulphate reduction is a widespread feature of heterogeneous environments such as soils. This is presumably the reason for the widespread presence of alkaliphiles in such environments that would be considered neutral or even acidic on the basis of bulk pH measurements (Imhoff et al. 1979).

These hypersaline alkaline brines provide the most extreme environment with a pH of around 12 and are relatively high in organic content, presumably due to evaporative concentration. Originally assigned to two genera, *Natronobacterium* and *Natronococcus*, these organisms turn out to have just as much diversity as their counterparts in pH-neutral hypersaline environments, and there are currently six genera, *Natronococcus, Natronobacterium, Natrialba, Halorubrum, Natronorubrum,* and *Natronomonas* that harbour haloalkaliphilic representatives living in these environments. The only other aerobes to have been cultivated from these environments are haloalkaliphilic ***Bacillus* sp.**, which was distinct in having a minimum requirement of at least 15 % NaCl for growth. As might be expected from the nutrient-rich environments that they inhabit, the majority of the soda lake isolates are biochemically reactive with an arsenal of extracellular hydrolytic enzymes including proteinases, cellulases, xylanases, and lipases (Asha et al. 2012). Two different cellulases from Gram-positive soda lake isolates are currently marketed for use in laundry and textile processes (Jones et al. 1994; Grant 2006).

Haloalkaliphilic *Bacillus* sp.

Halophilic microorganisms require very high salt (2 to 5 M NaCl) concentrations for growth and are found in salterns and hypersaline lakes. Many extreme and moderate halophiles have been isolated and investigated for possible biotechnological applications. Early literature on organisms from salted foods and solar salt interjects a running debate on the nature of adaptation to hypersaline environments. Smith (1938) reviewed the arguments, which center on whether halophilism is an evolutionary consequence or simply the adaptation of a single generation. A group of media used for enrichments of moderately halophilic and halotolerant bacteria (*Bacillus, Halobacillus, Halomonas, Salibacillus, Salinibacter*) has approximately 10 % salinity (Quesada et al. 1983; Caton et al. 2004; Sass et al. 2008).

A large body of evidence suggests that *Bacillus* species were isolated from various haloalkaline environments such as soda lake Van in Turkey and Inner Mongolian Bear soda lake (Ma et al. 2004). Recently, Tambekar and Dhundale (2012) reported the phenotypic analysis of *B. flexus, B. cellulosilyticus, B. pseudofirmus, B. clausii , B. krulwichiae, B. pumilus, B. lehensis, B. halodurans, B. circulans, B. cereus, B. agaradhaerens, B. sphaericus, B. fusiformis, B. asahii, B. pseudalcalophilus, B. okuhidensis*, and *B. gibsonii*.

Potential applications of Haloalkaliphilic *Bacillus* sp.

The biological diversity of the marine environment, in particular, offers enormous scope for the discovery of novel natural products, several of which are potential targets for biomedical developments. Extremophiles have been recognized as valuable sources of novel bioproducts and this may well include antimicrobials (Horikoshi 1999; Das et al. 2014; Wu et al. 2014). These groups of prokaryotes have received considerable interest because of their potential applications in various biotechnological and industrial aspects, such as biomedical and chemical sciences, food, leather, laundry detergent, and pharmaceutical industries (Rothschild and Mancinelli 2001). Moreover, some bacterial metabolites, such as proteins, extracellular enzymes, osmotically active substances, exopolysaccharides, and special lipids have potential industrial applications (Schiraldi and De Rosa 2002; Ara et al. 2014). They appear to be a very good source of various biomolecules and can open the dimensions for the development of novel value based products because of unique properties, which can withstand at harsh environment (Saju et al. 2011; Prakash and Gopal 2014) Fig. 2.

Enzymes/biocatalysts

Haloalkaliphilic *Bacillus* sp., have the capability to produce multiple enzymes applied in multifaceted industries from food and related sectors to bioremediation of polluted environments (Fergus 1977; Adams et al. 1995). The biocatalysts from the haloalkaliphilic *Bacillus* sp. have optimal activity at moderately extreme conditions requiring presence of Na^+-Cl^- for ion induced stability of the enzymes, where normal enzymes would deactivate and cease to function (Bajaj et al. 2014). The enzymes from this genus include both α and β amylases, proteases both alkali and acidic, nucleases and phosphatase, and bacteriolytic enzymes, which are able to function optimally at higher temperatures (40–60 °C), salinity (0.5–1.5 M), and alkalinity (7.0–8.5) compared with those from normal organisms (Oren 2002a; Ibrahim and El-diwany 2007; Syed et al. 2013a, b; Singh and Bajaj 2014; Annamalai et al. 2014) (Table 1).

Organic acids

During the cultivation of alkaliphiles, the pH values of culture media often decrease sharply due to the production of organic acids, which are produced by growth on carbohydrates. Paavilainen et al. (1994) reported comparative studies of organic acids produced by alkaliphilic bacilli. Four bacilli, *Bacillus* sp. strain 38–2 (ATCC 21783), *B. alkalophilus* sub sp. *Halodurans* (ATCC 27557), *B. alcalophilus* (ATCC 27648), and *Bacillus* sp. strain 17–1 (ATCC 31007), were cultured in the presence of various concentrations of sugars (1 % w/v) and related compounds such as sugar alcohols. All these alkaliphiles produced acetic acid (4.5 to 5.0 g/L at the maximum), while formic acid was produced by only one of the strains. In contrast, among neutrophilic *Bacilli*, acetoin, butanediol, and ethanol were not detected and are essentially produced as an adaptive response for fluctuating salinity gradients (Oren 2002a). Moderate amounts of isobutyric, isovaleric, α-oxo-isovaleric, α-oxo-β-methylvaleric, α-oxo-

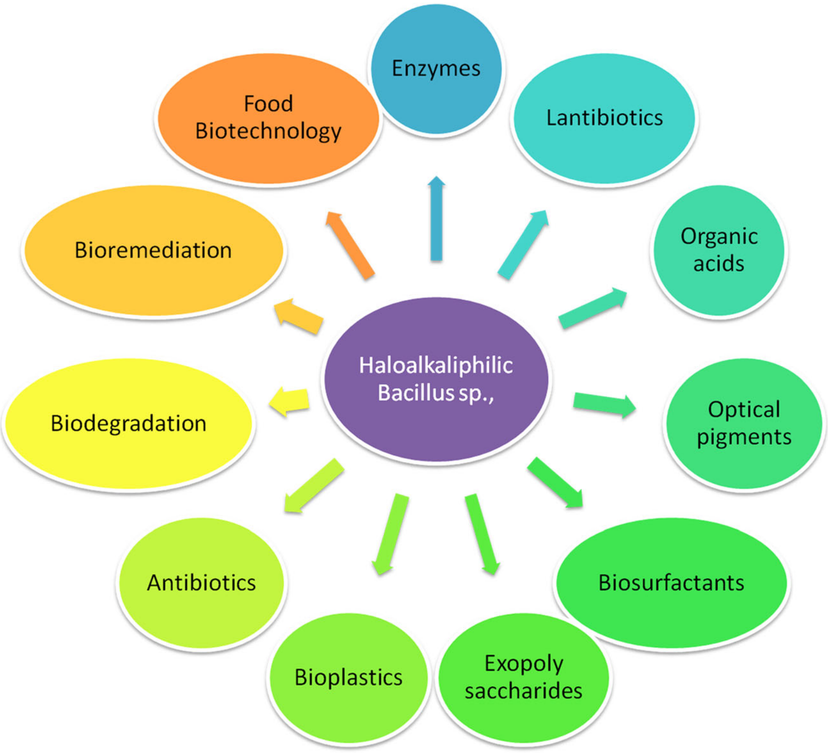

Fig 2 Potential applications of Haloalkaliphilic Bacillus sp.

Table 1 Different Enzymes from the genus *Bacillus*[*]

Enzyme	Species	Comments
Agarase	*Bacillus* sp.	Hydrolyzes the (β-1,4 linkage of agarose
α-Amylase	*B. amyloliquefaciens* *B. caldolyticus, B. coagulans* *B. licheniformis, B. macerans* *B. stearothermophilus* *B. subtilis, B. subtilis* var. *amylosaccharitcus*	Endohydrolysis of the α-1,4-glucosidic linkages in polysaccharides; different species produce enzymes with different properties
β-Amylase	*B. cereus, B. megaterium* *B. polymyxa* Alkalophilic *Bacillus* spp.	Exohydrolysis of the α-1,4-glucosidic linkages in polysaccharides yielding β-maltose
Cellulase	*B. brevis, B. firmus,B. polymyxa* *B. pumilus, B. subtilis*	Hydrolysis of carboxymethyl cellulose to cellobiose
Chitinase	*B. circulans*	Four enzymes induced by growth on crab-shell chitin
β-1,3-glucanase	*B. circulans, B. polymyxa* *B. subtilis,* Alkalophilic *Bacillus* sp.	Endohydrolysis of the β-1,3-glycosidic linkages in laminarin and related glucans
Isoamylase	*B. amyloliquefaciens* *B. polymyxa*	Hydrolysis of the α-1,6-glycosidic branch linkages in glycogen, amylopectin, etc.
Pectate lyase	*B. circulans, B. polymyxa* *B. pumilus, B. sphaericus* *B. stearothermophilus* *B. subtilis,* Alkalophilic *Bacillus* sp.	Endocleavage of polygalacturonic acid by an eliminative reaction
Pullulanase	Alkalophilic *Bacillus* sp.	Endohydrolysis of the α-1,6 linkage of pullulan
Xylanase	*B. amyloliquefaciens* *B. firmus, B. polymyxa* *B. subtilis, B. subtilis* var. *amylosaccharitcus*	Hydrolysis of xylans; specificity of the enzymes has not been studied in detail
Proteases		
Alkalophilic protease	Alkalophilic *Bacillus* sp.	Serine enzymes from alkalophilic species with very high pH optima
Aminopeptidase	*B. licheniformis, B. subtilis*	
Esterase	*B. subtilis*	Serine enzyme with high esterolytic and low proteolytic activity
Halophilic protease	*Bacillus* sp.	Produced optimally in media containing 1.0 M NaCl
Metal protease	*B. amyloliquefaciens* *B. cereus, B. licheniformis* *B. megaterium, B. polymyxa* *B. subtili, B. subtilis* var. *amylosaccharitcus* *B. thermoproteolyticus* *B. thuringiensis*	Enzymes require Ca+ for stability and Zn^{2}+ for activity; pH optimum at or near neutral
Serine protease	*B. amyloliquefaciens* *B. licheniformis, B. pumilus* *B. subtilis, B. subtilis* var. *amylosaccharitcus*	The subtilisins; alkaline pH optima, serine residue at or near the active site
Penicillinases		
β-Lactamase	*B. anthracis, B. cereus* *B. licheniformis, B. megaterium* *B. subtilis*	Hydrolysis of the amide bond in the β-lactam ring of penicillins and cephalosporins

Table 1 (continued)

Enzyme	Species	Comments
Nucleases and phosphatases		
Alkaline phosphatase	*B. amyloliquefaciens* *B. cereus, B. subtilis* Alkalophilic *Bacillus* sp.	Often cell-bound, the enzyme is extracellular in these species
Deoxyribonucleaseribonuclease	*B. amyloliquefaciens,* *B. cereus* *B. pumilus, B. subtilis*	A large number of DNases, RNases, and phosphodiesterases with individual properties have been purified
3-Nucleotidase	*B. subtilis*	Active on both ribonucleotides and deoxyribonucleotides
5-Nucleotidase		Cell-bound enzyme in these species
Bacteriolytic enzymes		
Endo-N-acetylglucosaminidase	*B. licheniformis, B. subtilis*	
Exo-N-acetylglucosaminidase	*B. subtilis*	
Endo-N-acetylmuramidase	*B. subtilis*	True lysozyme
Exo-N-acetylmuramidase	*B. subtilis*	
N-acetyl-muramylL-alanine amidase	*B. licheniformis B. subtilis*	A cell-bound enzyme; the major autolysin
Lipase	*B. licheniformis*	Hydrolysis of triacylglycerol to diacylglycerol and a fatty acid anion
Phospholipase C	*B. anthracis B. cereus B. thuringiensis*	Responsible for the "egg-yolk" reaction
Thiaminase	*B. thiaminolyticus*	

[*] Source-Priest (1977)

isocaproic, and phenylacetic acids were generated by three of the alkaliphiles (Meyer et al. 2014).

Bacteriorhodopsin

Certain extremely halophilic and haloalkaliphilic bacteria contain membrane bound retinal pigments called **Bacteriorhodopsin** (BR) and **Halorhodopsin** (HR) (Lanyi 1993). The applications comprise holography, special light modulators, artificial retinas, neural networks, optical computing, and volumetric and associative memories. Recently, cloning and functional expression of the archea rhodopsin gene from *Halorubrum xinjiangense* was successfully achieved in *E. coli*, where the purple membrane was fabricated into films and photoelectric responses depending on light-on and light-off stimuli were observed (Mosin and Ignatov 2014). The presence of extreme halotolerant *Bacillus* sp. creates a great opportunity to use them as cell factories for the production of these optical pigments with less economic burden (Garabito et al. 1998).

Lantibiotics/lipopeptides

Lantibiotics or lipopeptides are small lipid molecules associated with linear or cyclic oligopeptides and other compounds and used in medicines and cosmetics for the transport of compounds to specific target sites in the body. Lipopeptides have received considerable attention for their antimicrobial, cytotoxic, anti-tumour, immunosuppressant, and surfactant properties (Pirri et al. 2009; Raaijmakers et al. 2010; Fuchs et al. 2011; Yuan et al. 2012). The lipopeptides from *Bacillus* sp. have broad spectrum anti-microbial activity (Ongena and Jacques 2008). The ability of the *Bacillus* sp. to use different carbon sources (including cheaper ones such as paddy straw and potato peels) makes them potent candidates for lipopeptide production (Das and Mukherjee 2007; Zhu et al. 2012). Production of lipopeptides such as iturins is limited to a few species such as *B. subtilis* and *B. amyloliquefaciens*, but that of surfactin and fengycin is widespread among many *Bacillus* sp., and in that too diversity of lipopeptides and related compounds is tremendous (Mukherjee, and Das 2005; Price et al. 2007).

Biosurfactants

Biosurfactants enhance the remediation of oil-contaminated soil & water and have potential for pollution treatment in marine and coastal region (Al-Wahaibi et al. 2014; Martinez et al. 2014). *Bacillus* sp. from a variety of environments ranging from halophilic to haloalkaline are able to produce biosurfactants of multiple applications including antimicrobial, anti-adhesive agents, and enhanced oil recovery agents (Jenneman et al. 1983; Simpson et al. 2011; Joshi et al. 2012; Donio et al. 2013; Sarafin et al. 2014). Biosurfactants from *Bacillus* species are also used for in situ Microbial Enhanced Oil Recovery (MEOR), but the production cost is a limiting factor for exploitation of these biosurfactants (Souayeh et al. 2014). To further the applications of biosurfactants, the substrates, which are cheaper, abundant, and easily available, have to be used along with statistical modelling of optimal conditions (Joshi et al. 2007; Barros et al. 2008).

Exopolysaccharides

Exopolysaccharides (EPS) are biopolymers resulting from active bacterial secretion, shedding of cell surface material, cell lysis materials, and from adsorption of organics from the environment (Wingender et al. 1999). They are composed of a variety of organic substances: carbohydrates and proteins being major constituents, with humic substances, uronic acids, and nucleic acids in smaller quantities (Liu and Fang 2002). Halophilic exopolysaccharide (EPS) producers could be interesting source for MEOR, where polymers with appropriate properties act as emulsifiers, biosorbents for metal removal or recovery, and mobility controllers (Salehizadeh and Shojaosadati 2003; Comte et al. 2006). The exopolymer poly D-glutamic acid (PGA) can be used as a biodegradable thickener, sustained release material (Zhang et al. 2014), or drug carrier in the food or pharmaceutical industries (Raliya et al. 2014). Hezayen et al. (2000) first described a PGA-producing extremely halophilic archaeon related to the genus *Natrialba. Bacillus* sp., in particular *B. subtilis*, *B. cereus*, *B. pumilis, B. coagulans,* and *B. lincheniformis,* are potent producers of EPS materials as they are widely known to cope with fluctuating physiological conditions including temperature and salinity outside their cell membranes (Maugeri et al. 2002; Morikawa 2006; Marvasi et al. 2010).

Food biotechnology

Halotolerant microorganisms play an important role in various fermentation processes, occurring in the presence of salt and producing compounds that give characteristic taste, flavour, and aroma to the resulting products. In the production of pickles (fermented cucumbers), brine strength is increased by gradual increase of NaCl from 5 to 15.9 % (w/v). Certain species of halophiles; *Halobacterium salinarum*, *Halococcus* sp., *Bacillus* sp., *Pseudomonads,* and *Coryneform* bacteria are used in the production of an Asian (Thai) fish sauce, in which fish is fermented in concentrated brine (Esteban-Torres et al. 2015; Cui et al. 2015). Also related to the food industry is the commercial production of the flavoring agents 5′-guanylic acid (5′-GMP) and 5′-inosinic acid from RNA, using the halophilic nuclease H of Micrococcus varians subsp. halophilus (Kamekura and Onishi 1974). *Canthaxanthin* is used in cosmetics to decrease the necessary exposure time in sunlight to acquire a tan and to intensify the tan as the compound attaches to the subcutaneous layer of fat (Margesin and Schinner 2001).

Metabolites produced by alkaliphilic Bacillus

Hamasaki et al. (1993) found that a large amount of 2-phenylethylamine was synthesized by cells of the alkaliphilic *Bacillus* sp. strain YN-2000. Most of this amine was secreted in the medium during cell growth as extracellularly released compounds where they can be extracted easily. Aono and Horikoshi (1991) reported that alkaliphilic *Bacillus* sp. strains A-40-2, 2B-2 and 57–1 produce yellow pigments in the cells and that these are triterpenoid carotenoids. Gascoyne et al. (1991) isolated a siderophore-producing alkaliphilic bacterium that accumulated iron, gallium, and aluminium. Enrichment cultures initiated with samples from a number of alkaline environmental sources yielded carotenoids (Shindo and Misawa 2014).

Bioplastics

Polyhydroxyalkanoates (PHA) is intracellularly accumulated bacterial storage molecules. Because of the unique characteristics of polyhydroxybutyrate (PHB), such as biodegradable thermo-polyester that can be produced from renewable resources and has properties similar to those of petroleum-derived plastics, they are used to replace the conventional plastics. Many Bacillus sp., including *B. thuringiensis*, *B. cereus B. brevis*, *B. sphaericus*, *B. circulans*, *B. subtilis*, *B. licheniformis,* and *B. coagulans* are well known PHB producers (Yilmaz et al. 2005; Kumar et al. 2009). The production of PHB is essentially driven by the carbohydrate content in the medium leading to the expensive nature of its production (Yilmaz et al. 2005). Bacillus sp. are able to survive on a variety of carbon sources such as industrial waste, bio-wastes, and agri-wastes and are potential candidates for PHB production (Santimano et al. 2009; Quillaguamán et al. 2010). Currently, cheaper carbon and nitrogen sources, such as used vegetable oil, and low sugar carbohydrates, such as molasses and fruit peels, are employed to design novel cost effective models for production of these bioplastics (Koller et al. 2005; Verlinden et al. 2007).

Degradation of aromatic (phenols and phenolics) compounds

Hypersaline environments have both surface extension and ecological significance. As with all other ecosystems, they are impacted by pollution. However, less information is available on the biodegradation of organic pollutants by halophilic microorganisms in such environments. In addition, it is estimated that 5 % of industrial effluents are saline and hypersaline. Environmental pollution due to anthropogenic activity has affected all types of ecosystems. Phenols and phenolic compounds are major pollutants of industrial wastes since they are commonly used in many industries such as oil refining, coke conversion, pharmaceuticals, and resin manufacturing plants. Contamination and biodegradation in extreme environments has received little attention, although many contaminated ecosystems present high or low temperatures, extreme acidic or alkaline pH, high pressure, or high salinity (Margesin and Schinner 2001). Biodegradation of phenol in hypersaline wastewaters was described by Woolard and Irvine (1994), who used a halophilic bacterial biofilm isolated from a saltern at the Great Salt Lake. More than 99 % of the phenol was removed from synthetic waste water containing 0.1 to 0.13 g/L of phenol and 15 % (w/v) NaCl in a batch-sequenced reactor. The bacteria present in the biofilm and responsible for biodegradation were not identified. Hinteregger and Streischsberg (1997) studied the biodegradation capacity of a new phenol-degrading *Halomonas* sp. strain isolated from the Great Salt Lake. Several studies have demonstrated bacterial degradation of aromatic compounds in saline conditions (Peyton et al. 2002). Bacillus sp., such as *B. subtilis, B. stearothermophilus, Bacillus brevis*, and *Bacillus* sp., have shown to possess the ability to degrade phenol by using it as a carbon source (Gurujeyalakshmi and Oriel 1989; Arutchelvan et al. 2006). The ability of halophiles/halotolerants to oxidize hydrocarbons in the presence of salt is useful for the biological treatment of saline ecosystems, which are contaminated with petroleum products (Margesin and Schinner 2001). However, the ecological studies concerning the ability of these microorganisms to degrade different aromatic compounds are still in their infancy.

Degradation of petroleum hydrocarbons

Petroleum hydrocarbons and their products are the origin of important pollution in almost all types of ecosystems. Atmosphere, soils, superficial and underground waters, and marine environments have been continuously affected by pollution produced during the extraction, combustion, refining, transport, and use of petroleum. There is a significant amount of literature regarding hydrocarbon biodegradation by marine microorganisms, starting with the classical reviews, such as Atlas (1981) and Colwell (1977), or more recent reviews (Swannell 1999; Harayama et al. 2004; Head et al. 2006; Chandankere et al. 2014). However, information on hydrocarbon degradation in the presence of high salt concentrations is scarce. As mentioned above, hydrocarbon biodegradation in the presence of high salt concentrations is important for the bioremediation of oil-polluted salt marshes and treatment of industrial wastewater (Fathepure 2014; Sabina et al. 2014).

Few studies of hydrocarbon degradation at high salt concentration have been carried out using axenic cultures. Bacteria as *Rhodococcus*, *Micrococcus*, and *Arthrobacter* were able to grow in a wide salinity range of 0.5 to 25 % NaCl, but hydrocarbon metabolisation was observed only up to 15 % of NaCl (Kulichevskaya et al. 1992; Zvyagintseva et al. 2001). Extreme halophilic archaea have been reported as able to metabolize hydrocarbons. *Halobacterium* sp. shows a high capacity to degrade C_{10} - C_{30} n-alkanes in a medium containing 30 % NaCl. Hydrocarbon co-metabolization has been reported for *H. salinarium*, *H. volcanii*, and *H. distributum* (Kulichevskaya et al. 1992).

Biosorption of heavy metals

Contamination of the environment by heavy metals is a consequence of technological and industrial processes (Volesky and Holan 1995; Abbas et al. 2010). This has led to increasing concern about the effects of toxic metals as environmental contaminants. Thus, heavy metal pollution represents an important environmental problem due to the toxic effects of metals, and their accumulation throughout the food chain leads to serious ecological and health problems (Goyer and Chisholm 1972; Nriagu 1988; Fang et al. 2014; Liu et al. 2014). Biosorption of heavy metals by microorganisms is an attractive and economical alternative method that consists of removing toxic metals from aqueous solutions based on the property of certain types of biomasses to bind and accumulate these pollutants by different mechanisms such as physical adsorption, complexation, ion exchange, and surface microprecipitation (Kratochvil and Volesky 1998; Gutnick and Bach 2000; Ahluwalia and Goyal 2007; Mansour 2014). Halophilic and halotolerant microorganisms are suitable candidates for bioremediation processes, since they are able to grow on a wide range of salt concentrations (Hassen et al. 1998; Kratochvil and Volesky 1998; Wongsasuluk et al. 2014). The haloalkaliphiles and their products including exopolymers are used for heavy metal biosorption as they comprise charged molecules (Rudd et al. 1984; Nieto et al. 1989; Mullen et al. 1989; Rani et al. 2000; Bai et al. 2014). Syed and Paramageetham (2015) reported that the *Bacillus* sp. from solar salterns were able to remove 90 % of lead from aqueous solution.

Degradation of reactive dyes

Synthetic dyes are widely used in such industries as textile, cosmetic, printing, drug, and food processing units (Padamavathy et al. 2003). The release of coloured waste water is a problematic reality for a variety of industrial sectors. Among these are effluents released from textile and printing processes, dry cleaning, tanneries, food industries, manufacture of paints and varnishes, manufacture of plastics, and a variety of chemical processes. Insufficient treatment of wastes or effluents released from the production process of textiles can cause grave environmental pollution, sometimes to levels that can threaten human health, livestock, wildlife, aquatic life, and collapse the entire ecosystem (Pearce et al. 2003).

Conventional treatment methods such as activated sludge process, chemical coagulation, electro-chemical treatment, chemical oxidation, carbon absorption, photo decomposition, reverse osmosis, or hydrogen peroxide catalysis are difficult, ineffective, or economically disadvantageous methods for the decolourization of reactive dyes (Gong et al. 2005; Shah et al. 2013a, b, c). Hence, the treatment of dyes focus on the involvement of some microorganisms that are able to degrade and biosorb dye in waste water. *Bacillus* species particularly haloalkaliphilic in nature are rigorously employed in the decolourisation process (Wong and Yuen 1996; Vijayaraghavan and Yun 2008; Shyamala et al. 2014; Maulin et al. 2014). Different *bacillus* species applied in bioremediation and biodegradation of different environmental pollutants are presented in Table 2.

Future perspectives and concluding remarks

Haloalkaliphilic microorganisms, particularly *Bacillus* sp., offer a multitude of actual or potential applications in various fields of biotechnology. Not only do many of them produce compounds of industrial interest, but they also posses useful physiological properties; this can facilitate their exploitation for commercial purposes. Thus, microbial communities in natural haloalkaliphilic environments have attracted attention for

Table 2 Different Bacillus sp. in biodegradation and bioremediation studies of environmental pollutants

Bacillus species	Biodegradation and/or Bioremediation of	Effective conditions	Reference
B. subtilis ETL-221	Azo dye decolourisation (crystal violet)	pH 8.0, 40 ° C	Shah et al. (2013a, b, c)
Bacillus sp. VUS	Brilliant blue G	pH 9.0, 50 ° C	Jadhav et al. (2008)
Bacillus sp.	Razomol balck B		Shah et al. (2013a, b, c)
Bacillus sp.	Brown 3 REL		Dawkar et al. (2008)
Bacillus fusiformis	Disperse Blue 79 and Acid Orange 10		Kolekar et al. (2008)
Bacillus cereus	Cibacron black PSG and Cibacron red P4B		Ola et al. (2010)
B. stearothermophilus	Phenol		Gurujeyalakshmi and Oriel (1989)
Bacillus sp., *Bacillus brevis*	Phenol		Arutchelvan et al. (2006)
Bacillus sp.	polycyclic aromatic hydrocarbons (PAH)	pH 7.0, 60-70 ° C	Feitkenhauer et al. (2003)
B. subtilis, B. cereus, Bacillus cereus, *Bacillus sphaericus*, *B. fusiformis*, and *B. pumilus*	Diesel oil		Bento et al. (2005)
Bacillus sp.,	Hydrocarbons		Ghazali et al. (2004)
Bacillus species	Phenanthrene		Doddamani and Ninnekar (2000)
Bacillus species	Polycyclic aromatic hydrocarbons and long chain alkanes	60–70 ° C	Feitkenhauer et al. (2003)
B. subtilis, B. licheniformis, Bacillus sp,	Heavy Metals		Volesky and Holan (1995)
B. subtilis	Cadmium		Boyanov et al. (2003)
B. subtilis	Lead		Singh et al. (2012)
Bacillus licheniformis	Chromium		Zhou et al. (2007)
Bacillus sphaericus and *B. thuringiensis*	Cadmium		Allievi and Mariano (2011)
Bacillus marisflavi	Chromium		Mishra and Doble (2008)
Bacillus sp,	Manganese		Hasan et al. (2012)
Bacillus cereus	Arsenic		Giri et al. (2011)
Bacillus sp.	Mercury		Green-Ruiz (2006)
Bacillus subtilis	Mercury		Wang et al. (2010)
Bacillus sp,	Lead and Copper		Tunali et al. (2006)
Bacillus cereus	Arsenic		Giri et al. (2013)
Bacillus subtilis	Arsenic		Yang et al. (2012)

their possible biotechnological use of enzymes, metabolites, and metabolic processes.

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Compliance with ethical standards

Disclosure of potential conflicts of interest All the authors declared that there is no conflict of interest regarding this manuscript and we have not involved any Humans and Animal participants in this manuscript.

Informed consent "Informed consent was obtained from all individual participants included in the study."

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