BIOSURFACTANTS
Research Trends and Applications

Edited by
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Ackmez Mudhoo
INTRODUCTION

Marine microbes are known for their many novel extra- and intracellular products such as antibiotics, enzymes, biopolymers, pigments, and toxins. Reports suggest that so far more than 10,000 metabolites with broad-spectrum biological activities and interesting medicinal properties have been isolated from marine microbes (Kelecom, 2002). However, due to the enormity of the marine biosphere, most of the marine microbial worlds remain unexplored. It has been estimated that <0.1% of marine microbial world has been explored or investigated (Ramaiah, 2005). Among various marine bioactive compounds, microbial biosurfactants (BSs) are of great importance due to their structural and functional diversity and industrial applications (Banat et al., 1991; Banat, 1995a,b; Rodrigues et al., 2006a). Marine microbial BSs are such metabolites with many interesting properties. BSs are basically amphiphilic surface active agents produced by bacteria, fungi, and actinomycetes. They belong to various classes including glycolipids, glycolipoproteins, glycopeptides, lipopeptides, lipoproteins, fatty acids, phospholipids, neutral lipids, lipopolysaccharides (Banat et al., 2010), and glyco-glycerolipids (Wicke et al., 2000). The properties/applications of BSs include detergency, emulsification, foaming, dispersion, wetting, penetrating, thickening, microbial growth enhancement (e.g., oil-degrading bacteria), antimicrobial agents, metal sequestering, and resource recovering (oil recovery). These interesting properties allow BSs to have the ability to replace some of the most versatile chemical surfactants that are now in practice. In addition, BSs are promising natural surfactants that offer several advantages over chemically synthesized surfactants, such as in situ production using
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renewable substrates, lower toxicity, biodegradability, and ecological compatibility (Marchant and Banat, 2012a,b). Interest in BS research has been on the increase during the past two decades due to their interesting properties, yet the reason behind the production of BSs by many microorganisms remains mostly unknown. Several proposed physiological roles of BSs have been put forward including (1) increasing the surface area and bioavailability of hydrophobic water-insoluble substrates (e.g., oil-degrading microbes) (Ron and Rosenberg, 1999), (2) bacterial pathogenesis and quorum sensing and biofilm formation (e.g., Pseudomonas aeruginosa) (Davey et al., 2003), (3) antimicrobial for self-defense (e.g., antimicrobial activity of rhamnolipids) (Stanghellini and Miller, 1997), and (4) cell proliferation in the producing bacteria (e.g., viscosinamide production by P. fluorescens) (Nielsen et al., 1999). To isolate BS-producing microbes, combination of various screening methodologies has been studied (Maneerat and Phetrong, 2007; Satpute et al., 2008; Thavasi et al., 2011c) and extensively reviewed (Nerurkar et al., 2009; Satpute et al., 2010). Microbial communities like Acinetobacter, Arthrobacter, Pseudomonas, Halomonas, Bacillus, Rhodococcus, Enterobacter, Azotobacter, Corynebacterium, Lactobacillus, and yeast have been reported to produce BSs (Schulz et al., 1991; Passeri et al., 1992; Banat, 1993; Abraham et al., 1998; Meenar et al., 2006; Thavasi et al., 2007, 2009, 2011a; Das et al., 2008a,b; Perfumo et al., 2010a). This chapter collates and highlights data search on isolation, culture methods, and potential applications for BSs from marine microbes.

MARINE BIOSURFACHTANTS

Biosurfactants from marine microbes: A detailed list of BSs from marine microbes is described (Table 5.1) and a graphic representation of the number of publications and their percentages are illustrated in Figures 5.1 through 5.4. Earlier reports on BSs of marine origin mainly focused on environmental remediation applications of BSs such as emulsifiers and dispersants or BSs from oil-degrading microbes (Rosenberg et al., 1979; Schulz et al., 1991; Yakimov et al., 1998; Thavasi and Jayalakshmi, 2003, Thavasi et al., 2006, 2009, 2008, 2011a; Peng et al., 2007, 2008) and other potential applications such as medical and industrial sectors have not been studied extensively (Rodrigues et al., 2006b; Marchant and Banat, 2012a,b). Recently the trend has changed, and scientists started focusing on other potential application/properties of marine BSs such as antimicrobial (Mukherjee et al., 2009), biofilm disruption (Kiran et al., 2010a), and nanoparticle synthesis (Kiran et al., 2010b). A detailed description of marine microbial surfactants, their composition, and producing organism are described in the following sections.

Glycolipids and glycolipids: Glycolipids are the most studied surfactants among all other marine microbial BSs, that is, 48% of the publications on marine BSs are about glycolipid BSs (Figure 5.1). Glycolipid BSs include glycolipids, glucose lipid, trehalose lipids, trehalose tetraester, trehalose corynomycolates, rhamnolipids, mannosylerythritol lipids, sophorolipids, and extracellular polysaccharide-lipids (ESLs). Glycolipids are composed of a hydrophobic fatty acid moiety esterified to a hydrophilic carbohydrate moiety. The sugar components of the glycolipids may be one or two molecules of glucose, trehalose, mannose, sophorose, or rhamnose.
### TABLE 5.1
Types of Biosurfactants and Microbial Strains

<table>
<thead>
<tr>
<th>Biosurfactant Type</th>
<th>Microorganism</th>
<th>Reference</th>
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<tbody>
<tr>
<td>Glycolipid</td>
<td>Bacterial strain MM1</td>
<td>Passeri et al. (1992)</td>
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<tr>
<td></td>
<td>Nocardioides sp.</td>
<td>Vasileva-Tonkawa and Gesheva (2005)</td>
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<td></td>
<td>Aeromonas sp.</td>
<td>Ilori et al. (2005)</td>
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<td>Halomonas sp. ANT-3b</td>
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<td></td>
<td>Azotobacter chroococcum</td>
<td>Thavasi et al. (2006)</td>
</tr>
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<td></td>
<td>Pseudomonas aeruginosa</td>
<td>Thaniyavarn et al. (2006)</td>
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<td>Pantoea sp.</td>
<td>Vasileva-Tonkawa and Gesheva (2007)</td>
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<td>Rhodococcus erythropolis</td>
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<tr>
<td></td>
<td>Bacillus megaterium</td>
<td>Thavasi et al. (2008)</td>
</tr>
<tr>
<td></td>
<td>Brevibacterium casei</td>
<td>Krian et al. (2010a)</td>
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<td>Nocardiopsis lutecentis MSA04</td>
<td>Kiran et al. (2010d)</td>
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<td></td>
<td>Bacillus pumilus</td>
<td>Dusane et al. (2011)</td>
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<td>Lactobacillus delbrueckii</td>
<td>Thavasi et al. (2011a)</td>
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<td>Streptomyces sp. B3</td>
<td>Khopade et al. (2012)</td>
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<tr>
<td>Glycolipid and phospholipids</td>
<td>Alcanivorax borkumensis</td>
<td>Abraham et al. (1998)</td>
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<td>Trehalose lipids</td>
<td>Rhodococcus fascians DSM 20669</td>
<td>Yakimov et al. (1999)</td>
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<td>Trehalose tetraester</td>
<td>Arthrobacter sp. EK 1</td>
<td>Schulz et al. (1991)</td>
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<td>Arthrobacter sp. SI 1</td>
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<td>Trehalose corynomycolates</td>
<td>Alcaligenes sp. MM 1</td>
<td>Schulz et al. (1991)</td>
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<td>Glucose lipid</td>
<td>Unidentified bacterial strain MM 1</td>
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<td>Alcanivorax borkumensis gen. nov., sp. nov.</td>
<td>Yakimov et al. (1998)</td>
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<td>Rhamnolipids</td>
<td>Aspergillus sp. MSF1</td>
<td>Kiran et al. (2010c)</td>
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<td>Mannosylerythritol lipids</td>
<td>Pseudoyzyma hubeiensis</td>
<td>Konishi (2010)</td>
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<td>Glucoglycerolipids</td>
<td>Microbacterium sp. DSM 12583</td>
<td>Wicke et al. (2000)</td>
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<td>Bacillus pumilus strain AAS3</td>
<td>Ramm et al. (2004)</td>
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<td>Micrococcus luteus</td>
<td>Palme et al. (2010)</td>
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<td>Emulsan</td>
<td>Acinetobacter calcoaceticus RAG-1</td>
<td>Reisfeld et al. (1972)</td>
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<td>Extracellular polysaccharide-lipid</td>
<td>Alcaligenes sp. PHY 9L-86</td>
<td>Goutx et al. (1987)</td>
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<td>Sulfated heteropolysaccharide</td>
<td>Halomonas euritihalina</td>
<td>Calvo et al. (1998)</td>
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<td>Extracellular polysaccharide</td>
<td>Pseudomonas putida ML2</td>
<td>Bonilla et al. (2005)</td>
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<td>Glycolipopeptide</td>
<td>Planococcus matriensis Anita I</td>
<td>Kumar et al. (2007)</td>
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<td></td>
<td>Yarrowia lipolytica NCIM3589</td>
<td>Zinjarde et al. (1997)</td>
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<td>Yarrowia lipolytica</td>
<td>Amaral et al. (2006)</td>
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<td></td>
<td>Corynebacterium kutscheri</td>
<td>Thavasi et al. (2007)</td>
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<td>Glycolipoprotein</td>
<td>Pseudomonas nautica</td>
<td>Husain et al. (1997)</td>
</tr>
<tr>
<td></td>
<td>Aspergillus ustus MSF3</td>
<td>Kiran et al. (2009)</td>
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</table>

(continued)
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<thead>
<tr>
<th>Biosurfactant Type</th>
<th>Microorganism</th>
<th>Reference</th>
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<tr>
<td>Trehalose lipid-o-dialkyl monoglycerides–protein</td>
<td><em>Pseudomonas fluorescence</em></td>
<td>Desai et al. (1988)</td>
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<td>Alasan</td>
<td><em>Acinetobacter radioresistens</em></td>
<td>Navon-Venezia et al. (1995)</td>
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<tr>
<td>Biodispersion</td>
<td><em>Acinetobacter calcoaceticus</em></td>
<td>Rosenberg and Ron (1998)</td>
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<tr>
<td>Carbohydrate–protein complex</td>
<td><em>Rhodotorula glutinis</em></td>
<td>Oloke and Glick (2005)</td>
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<td>Glycoprotein</td>
<td><em>Antarctobacter</em> sp. TG22</td>
<td>Gutiérrez et al. (2007a)</td>
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<td><em>Halomonas</em> sp. TG39 and 67</td>
<td>Gutiérrez et al. (2007b)</td>
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<td>Lipopeptide</td>
<td><em>Bacillus licheniformis</em> BAS50</td>
<td>Yakimov et al. (1995)</td>
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<td><em>Bacillus pumilus</em> KMM150</td>
<td>Kalinovskaya et al. (1995)</td>
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<td><em>Pseudomonas</em> sp. MK90e85 and MK91CC8</td>
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<td><em>Bacillus pumilus</em>1364</td>
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<td><em>Rhodococcus</em> sp. TW53</td>
<td>Peng et al. (2008)</td>
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<td></td>
<td><em>Nocardiopsis alba</em> MSA10</td>
<td>Gandhimathi et al. (2009)</td>
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<td></td>
<td><em>Azotobacter chroococcum</em></td>
<td>Thavasi et al. (2009)</td>
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<td><em>Brevibacterium aureum</em> MSA13</td>
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<td><em>Pseudomonas aeruginosa</em></td>
<td>Thavasi et al. (2011d)</td>
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<td><em>Bacillus circulans</em> DMS-2</td>
<td>Sivapathasekaran et al. (2011)</td>
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<td>Ornithine lipids</td>
<td><em>Myroides</em> sp. SM1</td>
<td>Maneerat et al. (2006)</td>
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<tr>
<td>Surfactin</td>
<td><em>Bacillus velezensis</em> H3</td>
<td>Liu et al. (2010)</td>
</tr>
<tr>
<td>Proline lipid</td>
<td><em>Alcanivorax</em> dieselolei B-5</td>
<td>Qiao and Shao (2010)</td>
</tr>
</tbody>
</table>

Number of publications (28, 48%) on marine glycolipid biosurfactants

FIGURE 5.1 (See color insert.) Breakdown compilation of publication on marine glycolipid biosurfactants.
Number of publications (6, 10%) on marine extracellular polysaccharide and polysaccharide lipid biosurfactants

FIGURE 5.2 (See color insert.) Breakdown compilation of publication on marine extracellular polysaccharide and polysaccharide lipid biosurfactants.

Number of publications (11, 19%) on marine glycolipopeptide and glycolipoprotein biosurfactants

FIGURE 5.3 (See color insert.) Breakdown compilation of publication on marine glycolipopeptide, glycolipoprotein, and glycoprotein biosurfactants.

Number of publications on (13, 22%) marine lipopeptide and lipoprotein biosurfactants

FIGURE 5.4 (See color insert.) Breakdown compilation of publication on marine lipopeptide and lipoprotein biosurfactants.
The fatty acid moiety comprises one or two fatty acids with a chain length of C₆–C₂₀ with or without unsaturation depending on the source of the fatty acid and the microbial enzyme involved in processing the fatty acid part of the BS. Glycolipid-producing microbes were isolated from different marine sources such as *Halomonas* sp. ANT-3b isolated from Ross Sea, Antarctica (Pepi et al., 2005), which produced a glycolipid BS with a molecular weight of 18 kDa using *n*-hexadecane as the sole carbon source. *P. aeruginosa* A41 isolated from the gulf of Thailand was capable of utilizing wide range of carbon sources (oil, lauric acid, myristic acid, palmitic acid, stearic acid, oleic acid, and linoleic acid) and produced 6.58 g/L rhamnolipids with olive oil as the carbon substrate (Thaniyavarn et al., 2006). *Azotobacter chroococcum*, *Bacillus megaterium*, and *Lactobacillus delbrueckii* isolated from Tuticorin coastal waters (Tamil Nadu, India) using crude oil as the carbon source produced glycolipid BSs on crude oil, waste motor oil, and peanut oil cake carbon sources (Thavasi et al., 2006, 2008, 2011a). The highest BS production was observed with peanut oil cake as 4.6, 1.4, and 5.3 g/L, respectively, and was able to emulsify a wide range of hydrocarbons and vegetable oil in the order of waste motor lubricant oil > crude oil > peanut oil > kerosene > diesel > xylene > anthracene > naphthalene.

Among the glycolipid BSs, trehalose lipids, trehalose corynomycolates, and trehalose tetraester are the second largest group reported (9%). Trehalose lipid production by an Antarctic *Rhodococcus fascians* DSM 20669 strain was reported by Yakimov et al. (1999), and the surfactant reduced the surface tension of water from 72 to 32 mN/m. Trehalose tetraester production was found with *n*-alkanes utilizing marine bacterium, *Arthrobacter* sp. EK1 (Passeri et al., 1991). The main fraction of the purified surfactant is an anionic 2,3,4,2′-trehalose tetraester. The chain lengths of fatty acids ranged from 8 to 14. Trehalose corynomycolates producing marine *Arthrobacter* sp. SII was isolated from North Sea, and it produced 2 g/L of BS. The isolated BSs showed significant interfacial and emulsifying properties (Schulz et al., 1991).

A marine sponge associated *Aspergillus* sp. MSF1 strain producing rhamnolipids was also isolated from the Bay of Bengal coast of India (Kirani et al., 2010c). Rhamnolipid BS isolated from *Aspergillus* sp. MSF1 showed potential activity against pathogenic yeast, *Candida albicans* and bacteria, *Streptococcus* sp., *Micrococcus luteus*, and *Enterococcus faecalis*. Konishi et al. (2010) recently isolated a mannosyl-erythritol lipid-producing *Pseudozyma hubeiensis* from a deep sea clam *Calyptogena soyae* at 1156 m in Sagami Bay. The major component of the BS was MEL-C (4-o-[4′-0-acetyl-2′,3′-di-o-alka(e)noil-β-d-mannopyranosyl]-d-erythritol). Analysis of the lipid part of the BS revealed that major fatty acids of MEL-C were saturated fatty acids with chain lengths of C₆, C₁₀, and C₁₂. The surface tension determination of the MEL-C showed a critical micelle concentration (CMC) of 1.1 × 10⁻⁵ M.

Another class of BSs that are not in the spotlight of general research is glycoglycerolipids. There are three reports available on glycoglycerolipids from marine bacterial strains. The marine bacterium *Microbacterium* sp. DSM 12583, isolated from the Mediterranean sponge *Halichondria panicea*, was able to form a glucosylmannosyl-glycerolipid (GGL 2), 1-o-acyl-3-[α-glucopyranosyl-(1–3)- (6-o-acyl-α-mannopyranosyl)]glycerol, when grown on a complex medium with glycerol (Wicke et al., 2000). Another marine strain, *M. luteus* was isolated from the North sea and reported to produce a dimannosyl-glycerolipid (GGL 5),
mannopyranosyl(1α-3)-6-acylmanopyranosyl(1α-1)-3-acylglycerol on artificial seawater supplemented with glucose, yeast extract, peptone, and nitrogen/phosphate sources (Palme et al., 2010). The third marine bacterium, *B. pumilus* strain AAS3 isolated from the Mediterranean sponge *Acanthella acuta* and synthesized a diglucosyl-glycerolipid (GGL 11), 1,2-o-diacyl-3-[β-glucopyranosyl-(1–6)-β-glucopyranosyl])glycerol, when grown on artificial medium provided with glucose, yeast extract, peptone, and nitrogen/phosphate sources (Ramm et al., 2004).

**Extracellular polysaccharide-lipids (ESL) and polysaccharides (PS):** ESLs and PSs are another class of BSs produced by marine microbes, and reports on ESLs and PSs contribute 10% of total publications on marine BSs (Figure 5.2). *Acinetobacter calcoaceticus* RAG-1 strain (formally known as *Arthrobacter* RAG-1) was isolated from tar balls collected in beach soil (Rosenberg et al., 1979). RAG-1 strain produced an emulsifier called emulsan, an extracellular polyanionic amphipathic heteropolysaccharide. Its amphipathic and polymeric characteristics provide it with emulsifying as well as stabilizing activity of oil/water systems. The bioemulsifier exhibits specificity toward its hydrocarbon emulsifiable substrates. It tends to concentrate at the oil/water interface of the hydrocarbon droplets preventing their coalescence and allowing the formation of concentrated emulsanosols, which were found to be useful in enhancing oil degradation, binding heavy metal cations or constituting a low-viscosity stable oil-in-water emulsion suitable for oil pipeline transportation or direct combustion. Emulsan was also found to protect its producing cells against the toxic cationic detergent cetyltrimethylammonium bromide (Shabtai and Gutnick, 1986).

Another marine bacterium *Alcaligenes* sp. PHY 9 L-86 was isolated from hydrocarbon-polluted sea-surface waters that produced surface active exopolysaccharides (extracellular carbohydrates) and lipids on a medium containing 0.1% tetradecane. Chemical analysis revealed the composition of the extracellular lipids as phospholipids, free fatty acids, triglycerides, monoglycerides, esters, and free fatty acids (73%) as the major constituent (Goutx et al., 1987). A PS BS-producing *P. putida* ML2 strain was also isolated from hydrocarbon-polluted sediment collected at the Montevideo bay (Uruguay). Chemical composition of the PS BS revealed its sugar composition as rhamnose, glucose, and glucosamine in a 3:2:1 molar ratio with a molecular weight of 10–80 kDa. Another PS surfactant-producing marine *Planococcus* strain called *P. maitriensis Anita I* was isolated from coastal area of Gujarat, India (Kumar et al., 2007). The extracellular polymeric substance produced had a chemical composition of carbohydrate (12.06%), protein (24.44%), uronic acid (11%), and sulfate (3.03%) and effectively emulsified xylene and formed stable emulsions with jatropha, paraffin, and silicone oils. Its cell-free supernatant reduced the surface tension of water from 72 to 46.07 mN/m.

**Glycolipopeptides, Glycolipoproteins, and Glycoproteins (GLPs):** Glycolipopeptide and glycolipoprotein BSs are made of sugar–lipid–peptides or amino acids. GLPs are the third most studied surfactants among marine BSs, and reports on GLPs contribute 19% of total publications (Figure 5.3). *Corynebacterium kutscheri*, a marine bacterium isolated by Thavasi et al. (2007) from Tuticorin harbor, India, produced a glycolipopeptide BS. The BS was composed of carbohydrate (40%), lipid (27%), and protein (29%) and was able to emulsify waste motor lubricant oil, crude oil,
peanut oil, kerosene, diesel, xylene, naphthalene, and anthracene. Its emulsification activity was comparatively higher than the activity found with Triton X-100.

Amaral et al. (2006) isolated a yeast strain, *Yarrowia lipolytica*, from Guanabara Bay in Brazil, which produced a glycolipopeptide BS called Yansan in glucose-based medium. It was reported to contain 15% protein and 1% lipid. The fatty acid composition of the lipid was palmitic acid (35.8%), stearic acid (21.4%), lauric acid (8.8%), and oleic acid (6.9%). However, there was no quantitative information available on its sugar content, but its monosaccharide composition was reported as arabinose, galactose, glucose, and mannose in a ratio of 1:6:17:31. The molecular weight of the BS was approximately 20 kDa with a CMC value of 0.5 g/L. Another marine yeast strains called *Yarrowia lipolytica* NCIM 3589 isolated by Zinjarde et al. (1997) produced an emulsifier with a chemical composition of 75% lipid, 20% carbohydrate, and 5% protein. The lipid and carbohydrate part of the emulsifier comprised palmitic acid, mannose, and galactose, respectively, while the main amino acid components were aspartic acid, alanine, and threonine.

GLPs are another set of BSs produced by marine microbes composed of sugar and protein complexes. Gutiérrez et al. (2007a) reported the GLP bioemulsifier production by a marine bacterium, *Antarctobacter* sp. TG22, in a low-nutrient seawater medium supplemented with glucose. Chemical, chromatographic, and nuclear magnetic resonance spectroscopic analysis confirmed that the bioemulsifier has a high-molecular-weight (>2000 kDa) GLP with high uronic acid contents. The carbohydrate content of this emulsifier was reported as 15.4% ± 0.2%; further analysis of the carbohydrate component revealed the presence of hexoses (rhamnose, fructose, galactose, glucose, and mannose), amino sugars (galactosamine, glucosamine, and muramic acid), and uronic acids (galacturonic and glucuronic acids). The amino acid component was 5.0% ± 0.2% and mainly contained the three major amino acids, aspartic acid, glycine, and alanine.

Gutiérrez et al. (2007b) reported GLP BS production by two *Halomonas* species, TG39 and TG67. These strains produced two different GLP emulsifiers, called HE39 (strain TG39) and HE67 (strain TG67). The total carbohydrate content of HE39 and HE67 was 17.3% ± 1.0% and 22.7% ± 0.8%, respectively. The major monosaccharides identified in HE39 were rhamnose (31.7% ± 2.1%), glucuronic acid (27.9% ± 1.9%), and galactose (15.3% ± 0.5%). Carbohydrate content of HE67 showed that the main monosaccharides detected were glucuronic acid (58.8% ± 0.4%), glucosamine (10.9% ± 0.1%), and mannose (11.5% ± 0.5%), while rhamnose, galactose, galactosamine, glucose, muramic acid, and galacturonic acid, each of them present at less than 10% of the total monosaccharide composition and together they contributed only 18% to the total carbohydrate content. The total amino acid content of HE39 and HE67 was 26.6% ± 1.0% and 40.5% ± 1.6%, respectively. Amino acid analysis of hydrolyzed surfactant identified the presence of four major amino acids in both emulsifiers as aspartic acid, glutamic acid, glycine, and alanine, which in total contributed 45.1% and 50.7% to the total amino acid content of HE39 and HE67, respectively.

**Lipopeptides**: Lipopeptides are the second well-studied BS group from marine microorganisms that accounts for 22% of the total publications on marine BSs of which the genus *Bacillus* alone contributes 38% (Figure 5.4). Lipopeptide BSs are made of hydrophilic peptide head group and a hydrophobic lipid tail. A marine
bacterium, *Azotobacter chroococcum* (Thavasi et al., 2009) isolated from seawater, grew and produced a lipopeptide BS in a medium provided with crude oil, waste motor lubricant oil, and peanut oil cake. Peanut oil cake gave the highest BS production (4.6 mg/mL). The BS product emulsified waste motor lubricant oil, crude oil, diesel, kerosene, naphthalene, anthracene, and xylene. Preliminary characterization using biochemical, Fourier transform infrared spectroscopy, and LC-MS analysis indicated that the BS was a lipopeptide with percentage lipid and protein proportion of 31.3:68.7. Sivapathasekaran et al. (2011) isolated a marine lipopeptide BS-producing *B. circulans* strain from seawater sample from Andaman and Nicobar Islands, India. Similar marine *Bacillus* strains, *B. pumilus* KMM150 isolated from an Australian marine sponge *Ircinia* sp. (Kalinovskaya et al., 1995) and *B. pumilus* KMM1364 isolated from the surface of the ascidian *Halocynthia aurantium* (Kalinovskaya et al., 2002), were also reported to produce lipopeptide BSs. Strain KMM150 produced a mixture of cyclic depsipeptides known as bacircines (1–5 fractions with different molecular weights). Bacircines 1, 2, and 3 had molecular masses of 1007, 1021, and 1021, respectively, and bacircines 4 and 5 had a molecular mass of 1035. The amino acid composition of the bacircines 1, 2, 3, 4, and 5 were similar with a combination of Leu:Val:Asp:Glu with a ratio of 4:1:1:1. Bacircines 1, 2, and 3 has C\textsubscript{13}–C\textsubscript{14}–hydroxyacids in their lipid part whereas bacircines 4 and 5 had 3\(\beta\)-hydroxypentadecanoic acid (C15-\(\beta\)-hydroxyacid). *B. pumilus* KMM1364 also produced a mixture of lipopeptide analogs with major components with molecular masses of 1035, 1049, 1063, and 1077. The variation in molecular weight represents changes in the number of methylene groups in the lipid and/or peptide portions of the surfactant. Structurally, these lipopeptides differ from surfactin in the substitution of the valine residue in position 4 by leucine and have been isolated as two carboxy-terminal variants, with valine or isoleucine in position 7. The lipid part of the surfactant is composed of \(\beta\)-hydroxy-C15-, \(\beta\)-hydroxy-C16-, and a high amount of \(\beta\)-hydroxy-C17 fatty acids. Liu et al. (2010) reported a marine *B. velezensis* strain producing \(n\)C\textsubscript{14}-surfactin and \(anteiso\)C\textsubscript{15}-surfactin. These compounds can reduce the surface tension of phosphate-buffered saline (PBS) from 71.8 to 24.8 mN/m. The CMCs of C\textsubscript{14}-surfactin and C\textsubscript{15}-surfactin in 0.1 M PBS (pH 8.0) were determined to be 3.06 \times 10^{-5} and 2.03 \times 10^{-5} M, respectively. The surface tension values at CMCs for C\textsubscript{14}-surfactin and C\textsubscript{15}-surfactin were 25.7 and 27.0 mM/m, respectively.

Kiran et al. (2010e) isolated a marine sponge (*Dendrilla nigra*)-associated *Brevibacterium aureum* MSA13 strain producing lipopeptide BS. The peptide part of the surfactant was made of short sequence of four amino acids including pro–leu–gly–gly coupled with a lipid moiety composed of octadecanoic acid methylester. Oil-degrading lipopeptide BS-producing *Rhodococcus* sp. was isolated from Pacific Ocean deep-sea sediments (Peng et al., 2008). The hydrophobic lipid part of the surfactant contained five types of fatty acids with chain lengths of C\textsubscript{14}–C\textsubscript{19} and C\textsubscript{16}H\textsubscript{32}O\textsubscript{2} as a major component making up 59.18\% of the total. The hydrophilic fraction was composed of five kinds of amino acids with a sequence of Ala–Ile–Asp–Met–Pro.

Two strains of marine *Pseudomonas*, namely, MK90e85 and MK91CC8, produced antimycobacterial cyclic depsipeptides and viscosin (Gerard et al., 1997). The MK90e85 strain isolated from a red alga produced massetolides A, B, C, and D and the other strain MK91CC8 isolated from a marine tubeworm produced massetolides
E, F, G, H, and viscosin. Massetolide A is an optically active molecule, with a mass of 1141 Da and a molecular formula of C_{55}H_{97}N_{9}O_{16}. Another marine *Pseudomonas* strain called *P. aeruginosa* producing lipopeptide BS was also isolated from coastal waters of Tamil Nadu, India (Thavasi et al., 2011d). The BS is composed of protein (50.2%) and lipid (49.8%), and at 1 mg/mL concentration, the BS was able to emulsify waste motor lubricant oil, crude oil, peanut oil, kerosene, diesel, xylene, naphthalene, and anthracene, and the emulsification activity was higher than that achieved by Triton X-100 at similar concentration. A marine bacterium, *Myroides* sp. SM1 capable of producing ornithine lipid bioemulsifier was isolated from seawater (Maneerat et al., 2006; Maneerat and Dikit, 2007). l-Ornithine lipids were composed of l-ornithine and two different iso-3-hydroxyfatty acid (C_{15}–C_{17}) and iso-fatty acid (C_{15} or C_{16}) in a ratio of 1:1:1. Ornithine lipids exhibited emulsifying activity with crude oil in a broad range of pH, temperature, and salinity and showed high oil displacement activity.

### AREAS OF POTENTIAL APPLICATIONS OF MARINE BIOSURFACTANTS

**Biosurfactants and hydrocarbon degradation/remediation:** Oil pollution in terrestrial and aquatic environments is a common phenomenon that causes significant ecological and social problems. The recent British Petroleum deepwater horizon oil spill at the Gulf of Mexico during the summer of 2010 is a poignant example. The traditional available treatment processes used to decontaminate polluted areas have on the main been limited in their application (Perfumo et al., 2010b). Physical collection methods such as booms, skimmers, and adsorbents typically recover no more than 10%–15% of the spilled oil, and the use of chemical surfactants as remediating agents is not favored due to their toxic effects on the existing biota in the polluted area. Therefore, despite decades of research, successful bioremediation of oil contaminated environment remains a challenge (Perfumo et al., 2010a).

Oil pollution in marine environments stimulates the indigenous community of obligate hydrocarbonoclastic bacteria to flourish, becoming the majority of the total microbial population (Yakimov et al., 2007). Microorganisms involved in oil degradation have adopted different strategies to enhance the bioavailability and gain access to hydrophobic compounds, such as hydrocarbons, including (1) BS-mediated solubilization, (2) direct access of oil drops, and (3) biofilm-mediated access (Hommel, 1990). The production of BSs and bioemulsifiers is generally involved in varying degrees, in all the strategies provided earlier. BS structural uniqueness resides in the coexistence of the hydrophilic (a sugar or peptide) and the hydrophobic (fatty acid chain) domains in the same molecule, allowing them to occupy the interfaces of mixed-phase systems (e.g., oil/water, air/water, and oil/solid/water) and consequently altering the forces governing the equilibrium conditions, which is a prerequisite for the occurrence of a broad range of surface activities including emulsification, dispersion, dissolution, solubilization, wetting, and foaming (Desai and Banat, 1997; Banat et al., 2000). Such advantage was reported by Thavasi et al. (2011a,b) investigating the effect of BS and fertilizer on biodegradation of crude oil by four marine oil-degrading bacteria, *B. megaterium*, *Corynebacterium kutscheri*, *P. aeruginosa*, and *Lactobacillus delbrueckii*. It was reported that the addition of BS and fertilizer into the lab-scale
biodegradation system increased the degradation process from 19% to 37.7% as compared to the experiments where no BS and fertilizer was added. The BSs used in the earlier experiments were able to emulsify a range of different hydrocarbons.

Another example is the high-molecular exopolysaccharide-producing marine bacterium Alcaligenes sp. PHY 9L-86, which was able to use 0.1% tetradecane as the sole carbon and energy source and degrade 98% of the substrate within 48 h (Goutx et al., 1987). In the same way, emulsifiers from Halomonas sp. TG39 and TG67 showed significant emulsification activity with different edible oils as well as with hexadecane, and these emulsions remained stable for several months (Gutiérrez et al., 2007b). Low-molecular-weight BSs such as glycolipids produced by marine bacterium, Halomonas sp. ANT-3b, was able to degrade n-hexadecane and use it as the sole source of carbon to produce BSs (Pepi et al., 2005). In addition to the broad-spectrum emulsification ability to promote the biodegradation process, marine microbial BSs also exhibited higher stability at various conditions as reported by Thaniyavarn et al. (2006); the researchers isolated a P. aeruginosa A41 strain producing rhamnolipid BS that had good stability and activity at a wide range of temperatures (40°C–121°C), pH (2–12), and NaCl concentrations (0%–5%). Higher stability at various conditions and broad-spectrum emulsification activities found with marine BSs indicated their potential broad-spectrum application against various hydrocarbons and in different environments.

Besides the reports on the application of marine microbes and their BSs, there are few reports on the application of microbes, and their BSs isolated from nonmarine origin support the concept of the application of microbial BSs in oil bioremediation. Bioremediation of gasoline contaminated soil by bacterial consortium with poultry litter (PL), coir pith (CP), and rhamnolipid BS in an ex situ bioremediation system was reported by Rahman et al. (2002). In this study, the authors treated red soil (RS) with gasoline-spilled soil (GS) from a gasoline station, and different combinations of amendments were prepared using (1) mixed bacterial consortium (MC), (2) PL, (3) CP, and (4) rhamnolipid BS produced by Pseudomonas sp. DS10–129. The study was conducted for a period of 90 days during which bacterial growth, hydrocarbon degradation, and growth parameters of Phaseolus aureus RoxB (mung bean planted on the oil-polluted soil) including seed germination, chlorophyll content, and shoot and root length were measured. Results from the biodegradation experiments revealed that 67% and 78% of the hydrocarbons were effectively degraded within 60 days in soil samples amended with RS + GS + MC + PL + CP + BS at 0.1% and 1%. Maximum seed germination, shoot length, root length, and chlorophyll content of the P. aureus were recorded after 60 days in the earlier amendments. This study suggests that using BSs or BS-producing microbes, oil-polluted agriculture soil can be restored to its original state, and the application of BS as a growth enhancer in agriculture lands polluted with hydrocarbons. Another examples is enhanced bioremediation of n-alkane in petroleum sludge using bacterial consortium amended with rhamnolipid and micronutrients (Rahman et al., 2003). Results reported in this study showed that maximum hydrocarbon degradation was observed after the 56 days of treatment. Degradation of hydrocarbons with different carbon chain length showed that n-alkanes in the range of nC8–nC11 were degraded completely followed by nC12–nC21, nC22–nC31, and nC32–nC40 with percentage degradations of 100%,
Addition of rhamnolipids into the biodegradation system significantly increased the microbial growth by promoting the efficient utilization of hydrocarbons.

**Biosurfactants and microbially enhanced oil recovery (MEOR):** BSs have extensive potential application in the petroleum industry such as emulsifiers, demulsifiers, and oil recovery agents. MEOR is a technique that either uses a crude preparation of BS or sterilized BS containing culture broth to liberate crude oil from a binding substrate (Marchant and Banat, 2012b). For example, Banat et al. (1991) carried out a crude oil sludge tank cleanup and oil recovery process in which BS-containing sterilized culture broth was used to clean up oil sludge from an oil storage tank. After 5 days of treatment involving energy addition and circulation to enhance the process of emulsification followed by a deemulsification, 91% of crude oil present in the oil storage tank was recovered. Hydrocarbon analysis for the recovered crude showed a 100% hydrocarbon content. This result indicated that MEOR process doesn’t require live microorganisms or pure BSs and that sterilized BS-containing broth is sufficient to mobilize and recover significant amount of oil from oil sludge deposits.

**Biosurfactants and heavy metal remediation:** Microbial BSs are known for their metal-complexing activities that have been reported to be effective in the remediation of heavy metal-contaminated environments (Mulligan et al., 2001; Singh and Cameotra, 2004). The mechanisms behind metal binding are (1) anionic BSs create complexes with metals in a nonionic form by ionic bonds. These bonds are stronger than the metal’s bonds with the soil/sediment and metal–BS complexes are desorbed from the soil matrix to the solution due to the lowering of the interfacial tension and (2) the cationic BSs can replace the same charged metal ions by competition for some but not all negatively charged surfaces (ion exchange). Metal ions can be removed from soil surfaces by the BS micelles. The polar head groups of micelles bind metals that mobilize the metals in water (Mulligan and Gibbs, 2004).

Applications of marine BSs in heavy metal remediation have been reported by many researchers. Das et al. (2009b) studied the bacterial cells (*B. circulans*) and BS-mediated cadmium and lead metal binding and suggested that there was no cell-mediated metal binding, but that an increase in metal binding was observed with an increase in BS concentration from 0.5 × CMC to 5 × (CMC of the BS was 40 mg/L). The percentage removal at 0.5 × CMC was 76.6%, 53.18%, 56.63%, and 42.74%, 29.72%, 23.19% for lead and cadmium, respectively, while the percentage removal was increased to 100%, 95.75%, 87.69%, and 97.66%, 88.43%, 86.35% for lead and cadmium, respectively at 5.0 × CMC of BS. A complete removal of the metals was seen at 10 × CMC.

Gnanamani et al. (2010) reported the chromium reduction and trivalent chromium tolerance behavior of marine *Bacillus* sp. MTCC5514 through its extracellular enzyme reductase and BS production. The isolate reduces 10–2000 mg/L of hexavalent chromium to trivalent chromium within 24–96 h, and the release of extracellular chromium reductase was responsible for the metal reduction. The role of the BS in this metal reduction process is to entrap the trivalent chromium in the micelle of BSs, which prevents microbial cells from exposure toward trivalent chromium. It was concluded that extracellular chromium reductase and BS mediate the remediation.
process and keep the cells active and provide tolerance and resistance toward high concentration of hexavalent chromium and trivalent chromium. The earlier reports on the application of marine BSs in heavy metal binding and mobilization activities clearly indicated the potential application marine BSs in metal remediation.

**Antimicrobial and antifouling agents:** Marine microbial surfactants have been recognized for their biological properties such as antimicrobial and antifouling/biofilm activities. Antimicrobial activity of lipopeptide BS produced by marine *B. circulans* was reported by Mukherjee et al. (2009). Significant inhibitory activity was seen against gram-positive bacteria like *M. flavus*, *B. pumilus*, and *Mycobacterium smegmatis*, and gram-negative bacteria like *Escherichia coli*, *Serratia marcescens*, *Proteus vulgaris*, *Pseudomonas* sp., and *Klebsiella aerogenes*. The BS also showed significant inhibitory action against fungal species such as *Aspergillus niger*, *Aspergillus flavus*, and *C. albicans*. The purified BS showed more antimicrobial activity, and its broad-spectrum activity against gram-positive and -negative and fungal cultures indicated its potential application as an antimicrobial agent in medical and household antimicrobial and disinfectant applications.

Gerard et al. (1997) reported the antimicrobial activity of cyclic depsipeptides (Massetolide A-H) and viscosin produced by *Pseudomonas* sp. MK90e85 and MK91CC8 strains. Massetolide A and viscosin showed antimicrobial action against *Mycobacterium tuberculosis* and *Mycobacterium avium-intracellulare*. Massetolide A showed a minimum inhibitory concentration (MIC) value of 5–10 μg/mL against *M. tuberculosis* and 2.5–5 μg/mL against *M. avium-intracellulare*. Viscosin had an MIC value of 10–20 μg/mL against *M. tuberculosis* and 10–20 μg/mL against *M. avium-intracellulare*. Even though these molecules are toxic to pathogenic microbial cells, massetolide A was nontoxic to mice at a dose of 10 mg/kg body weight. This nontoxic nature to mammalian cell property of the massetolide A indicates its potential application in treating infections caused by *Mycobacterium* sp. The proposed antimicrobial mechanism of BSs is membrane lipid order perturbation, which compromises the viability of microorganisms and their spores (Azim et al., 2006). Similar to antimicrobial activity, BSs play an important role in the formation of biofilm especially attachment and detachment of cells. Das et al. (2009a) reported the antiadhesive and biofilm dislodging activities of a lipopeptide surfactant isolated from marine *B. circulans* strain. The concentration of BS used in both the experiments was 0.1–10 mg/mL, and the results suggested that maximum antiadhesive and biofilm dislodging activity was observed at 10 mg/mL concentration at which percentage antiadhesion activity was 89%, 88%, 84%, 87%, 86%, 88%, 87%, and 83% against *E. coli*, *M. flavus*, *S. marcescens*, *Salmonella typhimurium*, *P. vulgaris*, *Citrobacter freundii*, *Alcaligenes faecalis*, and *K. aerogenes*, respectively. The biofilm dislodging activity of the BS against bacterial strains was as follows: *E. coli* (59%), *M. flavus* (72%), *S. marcescens* (94%), *S. typhimurium* (89%), *P. vulgaris* (82%), *Citrobacter freundii* (77%), *Alcaligenes faecalis* (79%), and *K. aerogenes* (80%). Biofilm disruption potential of a glycolipid BS isolated from marine *B. casei* was reported by Kiran et al. (2010a). The biofilm-forming bacterial cultures used in the assay system were *Vibrio parahaemolyticus* MTCC 451, *Vibrio harveyi* MTCC 3438, *Vibrio alginolyticus* MTCC 4439, *Vibrio alcaligenes* MTCC 4442,
Vibrio vulnificus MTCC 1145, P. aeruginosa MTCC 2453, and E. coli MTCC 2339. Biofilm disruption results revealed that biofilm-forming capacity of both mixed culture and individual strains were significantly inhibited at 30 mg/mL concentration. Dusane et al. (2011) reported the antibiofilm activity of a glycolipid BS produced by a tropical marine bacterium S. marcescens isolated from the hard coral, Symphyllia sp. The reported antibiofilm activity of the glycolipid BS was 89% and 90%, 75% and 88%, 76% and 82% at 50 and 100 μg/mL concentrations against B. pumilus, P. aeruginosa, and C. albicans, respectively.

Biosurfactants in medical/therapeutic applications: Antimicrobial activities of marine BSs reviewed in the previous section of this chapter make them relevant molecules for applications in combating many diseases and as therapeutic agents. In addition, their role as antiadhesive agents against several pathogens indicates their utility as suitable antiadhesive coating agents for medical insertional materials leading to a reduction in a large number of hospital infections without the use of synthetic drugs and chemicals. Recent reports suggest that microbial surfactants also have other important medicinal and therapeutic applications. The use and potential commercial application of BSs in the medical field have increased during the past decade. There are few reports available on therapeutic applications of BSs of nonmarine origin. Example, Rodrigues et al. (2006a) reported the inhibition of microbial adhesion to silicone rubber treated with BS from Streptococcus thermophilus A. Pathogens used in this study were Rothia dentocariosa GBJ 52/2B and Staphylococcus aureus G2/1 (bacterial strains) and C. albicans GBJ 13/4A and C. tropicalis GB 9/9 (yeast strains). After 4 h of treatment of the silicon rubber with BS, a decrease in the initial cell deposition rate was observed for Rothia dentocariosa GBJ 52/2B and S. aureus G2/1 from 1937 ± 194 to 179 ± 21 microorganisms/cm²/s and from 1255 ± 54 to 233 ± 26 microorganisms/cm²/s, respectively, which was an 86% reduction of the initial deposition rate for both strains. The number of bacterial cells adhering to the silicone rubber with preadsorbed BS after 4 h was further reduced by 89% and 97% for the two strains, respectively. Antiadhesion activity observed against the two yeast strains showed 67% and 70% reduction, respectively, for C. albicans GBJ 13/4A and C. tropicalis GB 9/9.

Another example was reported by Rodrigues et al. (2006c) on antimicrobial cell adhesion activity of rhamnolipid BSs on voice prostheses to silicone rubber. After 4 h of treatment with (4 g/L concentration) rhamnolips, an average of 66% antiadhesion activity occurred for S. salivarius GB 24/9 and C. tropicalis GB 9/9. Preformed microbial mat/biofilm had a 96% detachment of microorganisms adhered to the silicone rubber. They concluded that pretreatment with surface active compounds may be a promising strategy to reduce the microbial colonization rate of silicone rubber voice prostheses used after total laryngectomy surgery. Laryngectomy is a surgical treatment for the extensive cancer of larynx, which alters swallowing and respiration in patients, which is followed up with a surgical voice restoration procedure comprising tracheoesophageal puncture techniques with an insertion of a “voice prosthesis” to improve successful voice rehabilitation. After the surgery, microbial colonization on the silicon rubber voice prostheses is a major drawback of these devices. Antimicrobials are usually used to prevent the colonization of silicone rubber voice prostheses by
microorganisms, but long-term medication may induce the development of resis-
tant strains (Rodrigues et al., 2007). However, antiadhesion results reported by
Rodrigues et al. (2006a,b) suggest an alternate way of using microbial BSs as
antiadhesive agent; in this process, the BSs used not necessarily have to be an
antimicrobial agent and that approach may prevent the antimicrobial resistance
development among the microbes involved in adhesion.

Another interesting example for the therapeutic application of BSs is sophoro-
lipids, a family of natural and easily chemoenzymatically modified microbial gly-
colipid, showed promising immune modulator activity in a rat model of sepsis.
Sophorolipid administration after the induction of intra-abdominal sepsis signifi-
cantly decreased the rat mortality in this model. This may be mediated in part by
decreased macrophage nitric oxide production and modulation of inflammatory
responses (Bluth et al., 2006).

Enhanced healing of full-thickness burn wounds using dirhamnolipid was
reported by Stipcevic et al. (2006). In this study, treatment of full-thickness burn
wounds with topical 0.1% dirhamnolipid accelerated the closure of wounds by 32%
within 21 days of the treatment as compared to control where no rhamnolipids used.
Dirhamnolipid was well tolerated by the animals (rat), which indicates the nontoxici-
ty toward mammalian cells. This study indicated the possible potential application
of dirhamnolipid in accelerating normal wound healing and perhaps in overcoming
defects associated with healing failure in chronic wounds. BSs isolated from marine
microbes may have similar properties, which requires further research. The earlier
results clearly indicate that evaluation of marine BSs for therapeutic applications
may bring more interesting properties into light and add more values to marine BSs.

**Biosurfactants and nanotechnology**: The biological synthesis of nanoparticles has
gained considerable attention in view of their exceptional biocompatibility and low
toxicity. The use of surfactants as nanoparticle stabilizing agents is an emerging field;
however, synthetic surfactants are not environmentally friendly. The application of BSs
as an alternate to synthetic surfactants for nanoparticle stabilization could be a green
ecofriendly approach. BS-mediated nanoparticle syntheses have been reported for
microbially produced rhamnolipids (Kumar et al., 2010) and sophorolipids (Kasture
et al., 2008) isolated from nonmarine sources. Synthesis of silver nanoparticles by gly-
colipid BS isolated from marine *B. casei* MSA19 was reported by Kiran et al. (2010b).
They used an *in situ* water-in-oil microemulsion phase for the particle synthesis. The
glycolipid BS was used as a particle-stabilizing agent by forming reverse micelles. The
silver nanoparticles synthesized in this study were uniform and stable for 2 months.
Therefore, the BS-mediated nanoparticle synthesis can be considered as “green” stabi-
lizer of nanoparticles and could be extended to other marine microbial BSs.

**CONCLUSION**

Although BSs have been the subject of intense investigation during the past few decades,
relatively small numbers of microorganisms and research output have focused on their
production from marine microorganisms. Nevertheless, some marine microbial com-
unities, including *Acinetobacter, Arthrobacter, Pseudomonas, Halomonas, Bacillus,*
Rhodococcus, Enterobacter, Azotobacter, Corynebacterium, and Lactobacillus, have been explored for the production of surface active molecules both BSs and bioemulsifiers. Such biological surfactants have important potential application in different industries, and the marine ecosystems can provide an excellent opportunity to select unique and diverse producing microorganisms and chemical products. Effective screening and purification techniques are essential in order to explore and discover unique and effective BSs and bioemulsifiers able to be produced using cost-effective technology processes and at acceptable yields and quality. Promising recent biotechnological approaches coupled with highlighting of the importance of the marine resource for such novel compounds and their environmental credentials are expected to support both search and potential industrial application of BSs in many industrial applications.

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REFERENCES


