International Journal of Advanced Biotechnology and Research(IJBR)
ISSN 0976-2612, Online ISSN 2278–599X,
Vol 6, Issue2, 2015, pp161-174
http://www.bipublication.com

Review Article

Review: Sophorolipids A Promising Biosurfactant and it's Applications

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[Received-25/03/2015, Published-11/04/2015]

ABSTRACT:
Sophorolipids (SLPs) are the most promising glycolipid biosurfactants produced in large quantity by several non-pathogenic yeast species, among these *Candida bombicola* ATCC 22214 is the most studied SLP producing yeast. SLPs composed by the disaccharide sophorose (2'-O-β-D-glucopyranosyl-β-D-glycopyranose) linked (β – glycosidically) to a long fatty acid chain with generally 16 to 18 atoms of carbon with one or more unsaturation. These compounds have characteristics, which are similar or even superior to the other biosurfactants and surfactants. Some of these advantages are environmental compatibility, high biodegradability, low toxicity, high selectivity and specific activity in a broad range of temperature, pH and salinity conditions. They fulfill the eco-friendly criteria combine Green chemistry and a lower carbon footprint. SLP possess a great potential for application in areas such as: Agriculture, Food, Biomedicine, Bioremediation, Cosmetics and Enhanced Oil Recovery.

Keywords: surfactants, biosurfactants, applications sophorolipids, *Candida bombicola*

[I] NTRODUCTION

Biosurfactants are surfactants produced by bacteria, yeasts and fungi. Due to their environment-friendly nature, biosurfactants have carved a niche in the market today. The current market-trends show that biosurfactants demand in the next years is going to increase manifolds based on their utility in detergent, paint, cosmetics, textile, agriculture, food and pharmaceutical industries [1]. Among of the different biosurfactants, the glycolipids are one of the most important classes of these amphiphilic compounds, being rhamnolipid, trehalolipids and SLP the best known [2].

SLP is one of the most promising and attractive biosurfactant which combines green chemistry with lower carbon footprint (without the undesirable side products or environmental downsides associated with synthetic surfactants)

[3, 4]. SLP have numerous properties that make them superior to synthetic surfactants including: stability in the wide range of pHs, temperatures, and salinity [5], low-foaming and excellent detergent properties [6], water hardness (high concentration of divalent cations) does not affect their interfacial properties, synergism between acidic and lactonic forms of SLP increase surfactants activities [7], are readily biodegradable and exhibit good surface activity (critical micelle concentration (CMC), surface tension and emulsification behavior) [8, 9]. SLP can be produced in large quantities [10] based on renewable resources [11] agro-industrial by-products and residues [12] and easy and simplified product recovery [13, 14]. Given the increasing interest in SLP biosurfactant and their highly attractive characteristics, here we explore the wide range of SLP applications.

[II] PRODUCER MICROORGANISMS

SLP are produced by several microorganisms (*Candida batistae* CBS 8550 [18], *Rhodotorula bogoriensis* [19], *Candida floricola* TM1502 [20], *Candida riodocensis* [21], *Candida rugosa* [22], *Candida kuoi* [23], *Candida stellata* [24], *Candida tropicalis* [25], *Cryptococcus sp*. VITGBN2 [26], *Cyberlindnera samutprakarnensis* JP52 [27], *Pichia anomala PY1* [28], *Rhodotorula muciliginosa* [22], *Candida bombicola* [29], *Candida apicola* [30, 31], *Torulopsis gropengiesseri* [32], *Torulopsis petrophilum* [33] and *Wickerhamiella domercqiae* Y2A [34]). Among these species *Candida bombicola* ATCC 22214 is the most studied SLP producing yeast, which exhibits both the highest yield and productivity. *Candida bombicola* is phylogenetically distant from the others pathogenic yeasts, like *Candida albicans* [15, 16]. Futhermore, *Candida bombicola* is included in microorganism with technological beneficial and have GRAS (Generally Recognized as Safe) status [17].

[II] SLP STRUCTURES

SLP are amphiphilic molecules composed of hydrophilic moiety, a sophorose disaccharide (2'-O-β-D-glucopyranosyl-β-D-glycopyranose), linked to the hydrophobic moiety, a long chain of fatty acid [Figure-1a].

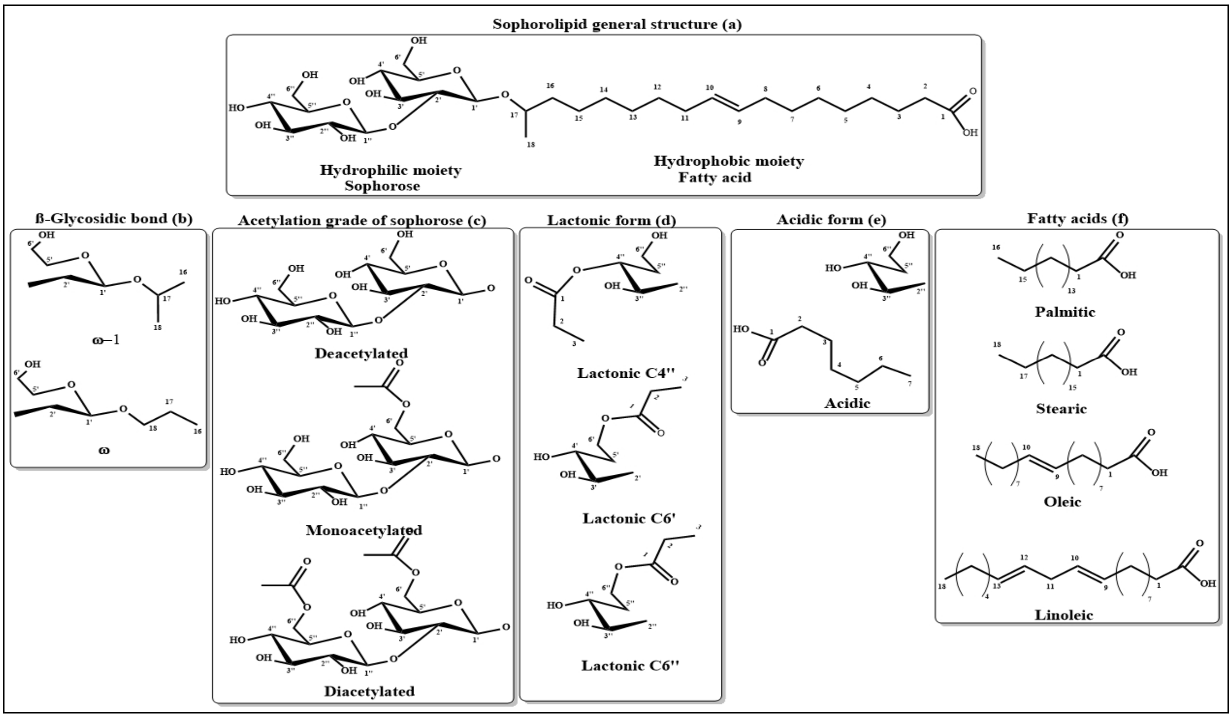

Fig: 1. General structure and structural variation of SLP.

They are produced as a mix of structurally related molecules, reaching up to 40 different types and associated isomers [35]. The high number of different structures arises from several possible combinations of: **(a)** the β-glycosidic bond links the anomeric carbon of the sophorose (C1') to the ω-carbon (terminal) or ω-1 hydroxilated (sub-terminal) from the fatty acid [Figure-1b]. [36, 30]; **(b)** acetylation of the hydroxyl groups of the sugar moiety; sophorose C6' and C6'' carbons might be deacetylated, monoacetylated or diacetylated [Figure-1c] [36, 37]; **(c)** presence of lactonic or acidic forms; lactonic form - carboxyl group of the fatty acid moiety is esterified to the sophorose in C4'', C6' or C6'' (esterification in C4" is more frequent) [Figure-1d], acidic form – the carboxyl group of the fatty acid moiety is not esterified [Figure-1e] [36]; **(d)** the fatty acid chain might vary in size (mostly between C16 and C18), with presence of unsaturation (saturated, monounsaturated or polyunsaturated) [Figure-1f] [38]; -presence of stereoisomers [39] and SLP might also occur in the polymeric form (dimeric or trimeric) [40].

[III] APPLICATIONS

As mentioned earlier, SLP are produced as a mix of structurally related molecules (like acidic and lactonic forms), consequently their properties and applications are directly related to the composition of the mix (structure activity relationship). Lactonic forms are more hydrophobic [41] and have been reported to have better biocide activities [42], anticancer [43], spermicide, cytotoxic and proinflammatory activities [44]. On other hand, acidic forms are better foaming agents, have higher water solubility [7] and have been reported to present better use in food industry, bioremediation and cosmetics [45]. In addition, the composition of the SLP mix and proportion of the acidic or lactonic forms depends on several factors, such as: strain; medium composition - carbon sources (hydrophilic or hydrophobic) [46], nitrogen and salt sources [47, 48]; environmental conditions (temperature, pH, agitation, aeration and period of culture) [49]; and operation process (batch, feed batch and continuous) [39, 50].

Besides of the composition, SLP have been currently commercialized in many countries by various companies [Table-1]. SLPs are active ingredient in several products of beauty and personal care (bath products, acne pads, anti-dandruff products, pencil-shaped lip rouge, lip cream, lipsticks, and toothpaste), household cleaner's products and bio pesticides [51]. In next topics, we explore the some of the most prominent SLP applications envisaging their highly attractive characteristics and the recent advances in the SLP applications field.

Company	Location	Focus on
Allied Carbon Solutions Ltd.	Japan	Agricultural products, ecological research
DSM Nutritional Products	USA	Pharmaceutical products, cosmetics and food products
Ecover Belgium	Belgium	Cleaning products, cosmetics, bioremediation, pest control, pharmaceuticals
Groupe Soliance	France	Cosmetics
Henkel	Germany	Glass cleaning products, laundry, beauty products
Kaneka Co.	Japan	Cosmetics and toiletry products
MG Intobio Co. Ltd.	South Korea	Beauty and personal care, bath supplies e.g., soaps with new functions
Saraya Co. Ltd.	Japan	Cleaning products, hygiene products
Synthezyme LLC	USA	Cleaning products, cosmetics, fungicides, crude oil emulsification

Table: 1. SLP producing companies around the world.

3.1. Agriculture

In agriculture, SLP can be used for phytopathogens control (biocidal properties) and as adjuvant in formulation of herbicides (surfactant properties). SLP show antifungal properties against plant pathogenic fungi, including *Phytophthora* sp. and *Pythium* sp. Damping-off is a soil borne root disease caused by these phytopathogens.

These diseases spread rapidly through soil by migrating with water in form of zoospore, and infecting seeds, leaves, and stem of water-culturing plants. SLP are very effective in inhibition of mycelial growth, motility as well as in the lysis of zoospore. Along with the low toxicity and biodegradability, the antifungal properties suggest that SLP possess great potential as promising and environment-compatible bio control agent [52].

SLP have excellent promise as natural surfactants/emulsifiers for post emergence herbicides. Post emergence herbicide formulations contain adjuvants to allow greater adherence to the plant surface and for increased penetration of the plant cuticle. Non-ionic surfactants, such as polyethoxylated tallowamines (POEA) currently used in several post emergence herbicides are petroleum-base, ecotoxic and toxic to a wide range of organisms. SLP can replace synthetic surfactants like POEA. Lactonic SLP from *Candida bombicola* (LacSLP), acidic SLP from *Candida kuoi* (AcSLP) form emulsions with lipophilic contact herbicide lemongrass oil (LGO). The AcSLP formed longer-lasting and stable emulsions with LGO better than commercial POEAs.

The herbicide damage ratings (HDR) values are greater with the AcSLP/LGO and LacSLP mixtures than with LGO applied alone or together with POEA. Additionally, the low-foaming by the SLP preparations is highly desirable to minimize air entrapment, which can cause pump and sprayer malfunctions [53].

3.2. Food

Surfactants have been used in the food industry for many centuries. Lecithin from egg yolk and proteins from milk are natural surfactants (which form foams, gels, emulsions, etc.) and are used in preparation of many food products as salad creams, deserts, margarine, etc. Surfactants also contribute to creaminess, appearance, palatability, texture, stability and rheology proprieties of foods [54]. In the food industries the emulsifying property of SLP can be used for improve the physical properties (volume, texture, viscosity, stability and general eating characteristics) of products of vegetable fat emulsion-based or starch-based and animal food products [55]. SLP added to wheat flour or a product containing it, modifies quality of final product. Production of bread from the wheat flour containing the SLP promotes better volume, appearance and shelf-life of bread [56].

Microbial and chemical contaminations in food have severe consequences for public health and also have a significant adverse economic impact. Vegetables and fruits and are handled by agricultural workers and consumers in food distribution channels, which provides opportunities for contamination with microbial hazards such as *Salmonella* spp., verotoxin producing *Escherichia coli* (VTEC) and Norovirus (NoV) [57]. Germicides composition for cleaning fruits, vegetables, food processing equipment, surfaces and utensils, includes a mixture of surfactant (anionic surfactant - sodium lauryl sulfate or biosurfactant like SLP) and fruit acids (glycolic, lactic, malic, citric and tartaric acid). Besides acting as agent surfactant/emulsify SLP act as antimicrobial/germicidal agent. SLP present in germicide formulation in amounts of 1% are sufficient to kill 100% of *Escherichia coli*, *Salmonella typhi* e *Shigella dysenteriae* in 30 seconds after application of germicide [58]. Other germicidal formulation suitable for cleaning fruits and vegetables containing SLP is effective against the majority of the gram-negative microorganism affecting agriculture. The treatment with this formulation resulted in > 90 % reduction of *Salmonella typhimurium* ATCC 23564, > 99 % reduction *Escherichia coli* ATCC 8739 and 100% reduction of Erwinia *chrysanthemi* ATCC 11663 and *Xanthomonas campestris* ATCC 13951 after 10 minutes of exposure. Furthermore these formulation decreases microbial spoilage and increase shelf life in fruits and vegetables (chikoos, tomatoes, lemons and cucumber) [59].

Fruits are highly perishable products; the quality is affected by post-harvest handling, transportation, storage and marketing. Pathogenic fungi isolated from root (*Penicillium*, *Aspergillus flavus*, *Aspergillus niger*, *Graymould*, *Mucro* e *Yeasts*) are the main cause of diseases and rot of fruits during transporting and storing. SLP from *Wickerhamiella domercqiae* Y2A show antimicrobial activity against these pathogenic fungi. SLP inhibits proliferation, spore germination and the spread of mycelium. These findings suggest that SLP can be used in the prevention of fungal infections in fruits, during the process of harvesting, transportation and storage, increasing the quality and shelf life of fruits. SLP mechanism is not clear, presumably SLP change or damage cell wall or membrane structure [60].

Food contamination may also result from biofilm. Biofilm act as a protective matrix of primarily polysaccharide material produced by, and containing, bacteria which stick to surfaces. These biofilms are potential sources of contamination, which may lead to food spoilage and disease transmission. Thus controlling the adherence of microorganisms to food contact surfaces is an essential step in providing safe and quality products to consumers [54]. SLP presents antimicrobial properties and the ability to inhibit and disrupt biofilms formation by gram-positive (*Ralstonia eutropha* ATCC 17699) and gram-negative microorganisms (*Bacillus subtilis* BBK006) [61].

3.3. Biomedicine

SLP have further potential and applications as they act as biologically active compounds in biomedicine, particularly as anti-microbial, anti-tumor, antiviral and immune-modulator. Most of these biological activities probably due to the fact that the SLP has the ability to destabilize cell membranes structure change membrane permeability and modifying the cell surface that will eventually lead to cell lysis [62, 63, 41].

3.3.1 Anticancer activity

SLP display anticancer activity against several kinds of tumoral cells and might have a potential use for cancer treatment. SLP synthesized by *Wickerhamiella domercqiae* show cytotoxic effects in several cancerous cell lines. SLP exhibited significant inhibition of cell proliferation on cancer cells of H7402 (liver cancer line). The cytotoxic effect of SLP in liver cell lines H7402 is due to the ability of these molecules to induce apoptosis (block cell cycle at G1 phase and partly at S phase, increase of activity caspase-3 and increase of intracellular concentration of Ca_2^+) [64].

SLP produced by *Wickerhamiella domercqiae* exhibited different cytotoxic effects in cell lines KYSE 109 and KYSE 450 (human esophageal cancer). Diacetylated lactonic SLP promote a better inhibition on these two cell lines than that of monoacetylated lactonic SLP. Concerning the unsaturation degree of hydroxyl fatty acid in SLP, the monoisaturated SLP had the strongest cytotoxic effect, diinsaturated SLP had a little weaker cytotoxic effect, while saturated sophorolipid had the weakest cytotoxic effect (only 20% of cells were inhibited at 60 mg/mL concentration). Monoisaturated or diunsaturated and monoacetylated or diacetylated acidic SL groups have little anticancer activity. In other words there is correlation of SLP congeners and anti-cancer activities [43].

SLP mediated cytotoxic responses to pancreatic cancer cell lines. SLP natural mixture (containing a combination of eight isoforms lactonic and acidic SLP) or derivatives (ethyl ester, methyl ester, ethyl ester monoacetate, ethyl ester diacetate, acidic SLP and diacetylated lactonic SLP) show diverse responses against human pancreatic carcinoma cells. These different responses are due to different mechanisms to kill pancreatic cancer cells by necrosis. The anticancer responses are dose and derivative-dependent. The cytotoxicity of SLP is specific to malignant cells since no cytotoxicity was observed against normal human cells, which minimize the side effects commonly associated with current therapeutic regimes [65].

3.3.2 Anti-microbial activity

The antimicrobial activity of SLP is due to their biological activity through certain mechanisms that involve destabilization and alteration of the permeability of the cellular membrane and rupture of cells causing extrusion of the cell contents [9, 66]. Besides antibacterial agent, SLP also act as antialgal [67], antifungal [52], antimycoplasma [58] and antiviral agents [44].

The antimicrobial activity of SLP depends on their chemical structure and the cell wall structure of microorganisms. Differences in the degree of inhibition of gram positive and negative bacteria are due differences in cell wall structure and osmolarities. SLP from *Candida bombicola* (diacetylated lactonic SLP, monoacetylated lactonic SLP, deacetylated lactonic SLP and monoacetylated acidic SLP) act in different ways: (a) no inhibition is observed in the case of the gram-negative *Pseudomonas aeruginosa* and the yeast *Candida albicans*; (b) diacetylated and monoacetylated lactonic SLP are better inhibitors of gram-positive bacteria (*Bacillus subtilis*, *Staphylococcus epidermidis*, *Streptococcus faecium*, and *Propionibacterium acnes*) than deacetylated lactonic SLP and monoacetylated acidic SLP. Most of these bacteria are found frequently in the obstructed sebaceous glands of the skin causing reduced respiration and acnes, which makes SLP potential ingredients in the production of cosmetic, hygienic and pharmacological–dermatological products [68].

SLP produces by *Candida bombicola* with hydrophobic moiety derived from lauryl–myristyl alcohol (SLPLA) have a potent antimicrobial activity against gram negative, gram positive and yeast. Against gram negative bacteria SLPLA show a complete inhibition (*Escherichia coli* (gastroenteritis, urinary tract infections and neonatal meningitis) and *Pseudomonas aeruginosa* (cross infections in hospitals and clinics)) and gram positive bacteria (*Staphylococcus aureus* (food-poisoning and skin infections) and *Bacillus subtilis* (food contamination)). For gram positive bacteria the treatment with the SLPLA results in the rupture of cells (lysis), for gram negative bacteria promotes shrinking of the cells or the presence of irregularities on the cell surface rather than breakdown or rupture [66].

Besides acting as an antimicrobial agent SLP may work synergistically in association with antibiotics. SLP enhance the activity of tetracycline. Tetracycline alone against *Staphylococcus aureus* could not promote total inhibition until the end of 6h of exposure, association tetracycline + SLP promote total inhibition before of 4h of exposure. The association of cefaclor + SLP also showed better efficiency against *Escherichia coli* than cefaclor alone (48% more inhibition within 2 h of exposure as compared to cefaclor alone) [41].

Polyhexamethylene biguanide (PHMB) possess the anti-fungal activities and is used for disinfectant swimming pool, contact lens and antimicrobial wound dressings. Non-woven textiles with PHMB are effective against *Trichophyton rubrum* and *Trichophyton mentagrophytes*. Non-woven textiles containing PHMB with SLP increase PHMB permeation into the stratum corneum significantly reduced colony forming units of *Trichophyton rubrum* and *Trichophyton mentagrophytes* suggesting that

PHMB and SLP are effectiveness for *Tinea pedis* prevention [69].

3.3.3 Anti-viral and spermicide activity

SLP and its structural analogs have spermicidal and anti-HIV activities. The virucidal and sperm immobilizing activity are similar to those of Nonoxynol-9 (commercial spermicide and potential HIV transmission-preventative agent). Structure-activity relationship showed that the acetylation of sophorose head groups and esterification of the carboxyl groups of the fatty acids show the same effects on specific activity. Di-acetylated ethyl ester of SLP is the most potent spermicidal and anti-HIV agent followed by mono-acetylated and no-acetylated ethyl esters. The relationship between chain length of fatty acids and spermicidal and virucidal are not the same. Shorter-carbon-chain has higher potency as virucidal agents and lower spermicidal activity. Longer-carbon-chain has lower potency as virucidal agents and higher spermicidal activity. Acidic SLP were weak spermicides and exhibited good antiviral activity against HIV and is the least cytotoxic of structural analogs tested. Lactonic forms of SLP exhibited high spermicidal, cytotoxic, and proinflammatory activities with low virucidal activity [44].

The Herpes simplex virus (HSV) causes of a great number of infections both in the orofacial and in the genital area. Natural mixtures of lactonic, non-lactonic, ethyl, methyl esters and diacetylated ethyl esters of SLP produced by *Candida bombicola* can act as an anti-HSV agent. From five tested compounds the best activity was displayed by Ethyl 17-L-[(2'-O-β- D-glucopyranosyl-β-D-glucopyranosyl)-oxy]-cis-9-octadecenoate, which showed high anti-herpes virus activity [70].

3.3.4 Immuno-modulatory activity

Septic shock is a common and frequent cause of death in hospitals. In patients with sepsis caused by gram-negative bacteria, bacterial components including DNA, endotoxin and specifically cell wall lipopolysaccharide (LPS), are believed to be causative factors of septic shock via induction of cytokine cascades. Septic shock can result in activation of the coagulation cascade and apoptosis, causing further organ damage and disseminated intravascular coagulation. Administration of SLP after induction of intra-abdominal sepsis significantly decreases mortality in a rat model of septic peritonitis. This mortality decrease might be, at least in part, mediated by decreased of macrophage number, decrease of nitric oxide and proinflammatory cytokines production and modulation of inflammatory responses [71]. Since the sepsis model used is induced by bacteremia, it is possible that SLP decrease sepsis by exerting antimicrobial properties. In addition, SLP exhibit anti-inflammatory effects in other diseases and can continue to reduce sepsis-related mortality with different vehicles, dosing regimens, and derivatives [72]. Furthermore, SLP maximally decreased IgE production in U266 cells (IgE producing myeloma cell line), possibly through affecting plasma cell activity. This suggests that SLP possess anti-inflammatory activity and may provide a novel therapy in diseases of altered IgE regulation (BLUTH et al., 2006). SLP act as an anti-inflammatory agent and potential therapy in diseases of altered IgE regulation. SLP decrease IgE production in U266 cells by down regulating important genes involved in IgE pathobiology in a synergistic manner [73].

3.3.5 Drug delivery system

SLP are an interesting category of asymmetric bolaamphiphiles. SLP self-assemble into various structures due to their structural and amphiphilic properties, these structures have different shapes and sizes depending upon factors such as the temperature, pH and incubation-time of the reaction mixture. SLP also demonstrate metal reducing and capping capabilities exerting greater control on the reaction parameters and condense the step involved in synthesis of nanomaterial, which can be used as antimicrobial agent, biosensing, drug delivery systems, magnetic resonance imaging enhancers and others biomedical applications [74, 75, 76].

Sodium salt of acidic SLP (SLPNa) spontaneously forms vesicles that can act as a skin penetration enhancer for active ingredients. The main active component of triterpene glycosides is mogrosides V (anti-atherosclerotic effects, anti-cancer activity, anti-allergy activity, and anti-diabetic effects in animal models). SLPNa vesicles increase significantly the amount of mogroside V that penetrate through the skin [77].

Lactoferrin (LCF), a multifunctional glycoprotein, activate dermal fibroblasts (stimulate dermal cells for wound re-epithelialization). SLP increases the transdermal absorption of LCF through a model skin increases. The effects of SLP on the LCF activities on dermal fibroblasts reveal that SLP not depressed the effect of LCF to any extent (cell proliferation activities and levels of collagen IV, elastic fiber components, and hyaluronan synthases). Instead, SLP increased the tropoelastin gene expression, suggesting a significant synergism between LCF and SLP (enhancement effects on cell proliferation, collagen synthesis, and hyaluronan synthesis) [78].

Gold nanoparticles are biocompatible, non-cytotoxicity and are used as drug delivery system. Biocompatible SLP-conjugated gellan gum reduced and capped gold nanoparticles show anticancer activity against gliomas cell. The simple SLP conjugated gellan gum reduced/capped gold nanoparticles shows greater efficacy in killing the human glioma cell line LN-229 and human glioma stem cell line HNGC-2. When doxorubicin hydrochloride (anthracycline antibiotic) is also conjugated to these gold nanoparticles, the cytotoxic effects became more prominent. Thus, the nanoparticles were able to significantly inhibit the cell viability indicating that the combination therapy (SLP + doxorubicin) has a greater potential in eradication of glioma cancer cells and even glioma stem cells [79].

3.4. Cosmetics

SLP biosurfactant have been produced and commercially applied as active ingedient in cosmetics products for body and skin applications. They are used as emulsifiers, foaming agentes, solubilizers, wetting agents and detergents [80]. Among of several expected characteristics for cosmetics application, SLP show low cytotoxicity towards human keratinocytes and fibroblasts [37, 7]. In addition, SLP promote the metabolism of fibroblasts and collagen neosynthesis in the dermis of the skin, acting as an agent that restructures repairs and tones up skin [81]. SLP stimulate leptin synthesis through adipocytes, which may reduce subcutaneous fat overload, which make its role in cellulitis treatment [82].

The increase in elastase activity from dermal fibroblastos leads to aging skin and the appearance of wrinkles. SLP inhibit free radical formation through inhibition of elastase activity [83]. SLP act as activator of macrophages, fibrinolytic agent (healing agent the treatment of wounds), desquamating agent and depigmenting agent through a partial inhibition of melanogenesis in the treatment of brown spots [84]. In addition, their bactericides and bacteriostatic properties play role for control of dandruff, acne treatment and as an active ingredient in deodorants [85].

3.5. Bioremediation

Bioremediation is a process that uses microorganisms for accelerate degradation of environmental contaminants. Biosurfactants produce by bacteria; fungi and yeast increase the surface area, solubility and bioavailability of hydrophobic water-insoluble substrates, stimulating the growth of oil-degrading microrganisms and improve their ability to utilize hydrocarbons [86].

One problem faced today is the decontamination of soils polluted with poorly soluble poly-cyclic aromatic hydrocarbons (PAHs) like anthracene, fluorene, phenanthrene and pyrene. Phenanthrene is a model substrate for studies of biodegradation. SLP increases the solubility and availability of phenanthren stimulating the microbial biodegradation by *Sphingomonas yanoikuyae*. The maximum biodegradation *Sphingomonas yanoikuyae* is 1.3 mg/L-h in the presence of SLP compared to 0.8 mg/L-h without SLP [87].

Exposure to the heavy metals through ingestion or uptake of drinking water (particularly where water is reused) and foods can lead to accumulation in animals, plants and humans, which is a serious health public issue. Sources of metals include domestic and industrial effluents, the atmosphere, runoff and lithosphere. The main treatments for metal-contaminated sediments include solidification/stabilization and washing. SLP can remove heavy metals from metal-contaminated sediment (110 mg/kg copper and 3300 mg/kg zinc). A single washing with with 4% SLP removed 25% of the copper and 60% of the zinc. The mechanism for metal removal by the biosurfactants occurs through sorption of the surfactant on to the soil surface and complexation with the metal, detachment of the metal from the soil into the soil solution and hence association with surfactant micelles [88].

Oil pollution causes a great environmental problem to terrestrial and marine ecosystems. The components of petroleum have low aqueous solubility and strong binding and sorption onto solids particules. A common remediation process of contaminated sites is based on the extraction by organic solvents or surfactants. SLP improve the bioremediation of sites contaminated with hydrocarbons increasing the bioavailability of microbial consortia for biodegradation. Addition of SLP in soil increased biodegradation of model compounds: 2-methylnaphthalene (95% degradation in 2 days), hexadecane (97%, 6 days), and pristane (85%, 6 days). SLP show effective biodegradation of crude oil in soil (80% biodegradation of saturates and 72% aromatics in 8 weeks) [89].

Harmful algal blooms, especially toxic dinoflagellate red tide, is one the most serious marine environmental problems to have aroused the world's attention. The deleterious effects of harmful algal blooms seriously constrain the sustainable development of coastal areas and cases of human poisoning resulting from algal toxins have been reported each year. The SLP shows potential in controlling harmful algal blooms by potent inhibition on harmful algae against several species like *Alexandrium tamarense*, *Heterosigma akashiwo*, *Cochlodinium polykrikoides* [67] *Scrispsiella trochoidea*, *Prorocentrum minimum*, *Cochlodinium polykrikoides* and *Heterosigma akashiwo* [9].

3.6. Microbial Enhanced Oil Recovery

Process of oil production leaving behind residual oil in the reservoirs. The residual oil represents about 2–4 trillion barrels or 67% of the total oil reserve. In oil industry to increase the production of crude oil is utilized the enhanced oil recovery (EOR). Microbial enhanced oil recovery (MEOR) employs microorganisms to pull out remaining oil from the reservoirs. Up to 50% of the residual oil can be recovery with low operation cost [90].

SLP and others biosurfactants can improve oil drainage into well bore, wetting of solid surfaces, reduction of oil viscosity, stimulating release of oil entrapped by capillaries and oil pour point, lowering of interfacial tension and dissolving of oil [91, 92]. The efficiency of the SLP in reducing the interfacial tension between water and various hydrophobic substances makes it more attractive for use in microbial enhanced oil recovery (MEOR) and enhanced oil recovery (EOR) [93]. SLP can affect liquid-liquid interfaces by the lower the interfacial tensions and can also act on solid-liquid interfaces. These proprieties can be used to release bitumen from tar sands or, more technically, bituminous sands an unconventional oil/petroleum deposit [94].

Oil drilling is a process that involves drilling and pumping of oil. The drill cuttings from oil e gas exploration coming up to the surface impregnated with large amount of oil. SLP can be used for cleansing solid particles (drill cuttings) impregnated with a polluting fluid comprising hydrocarbon [95] and regeneration of hydrocarbons from dregs and muds [96].

[IV] CONCLUSION

This review presented the properties of SLP and their applications in many areas including agriculture, food, biomedicine, bioremediation, cosmetics and microbial enhanced oil recovery. Several scientific publications have been reporting that SLP could be a potential alternative for the synthetic surfactant. Currently various companies around the world market products derived from SLP as beauty and personal care products, cleaning products and agricultural products. They have the labels "bio-based" or "green" or "eco-friendly" or "sustainable". The reason behind the large interest in SLP is due to their wide structural and functional diversity and a wide range of applications in various areas.

ACKNOWLEDGEMENT

The authors thank to Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES/PNPD), Brazil and Fundação Araucaria, Brazil for financial support.

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