Bioresource Technology

Biosurfactants: The Green Generation of Speciality Chemicals and Potential Production Using Solid-State Fermentation (SSF) Technology

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Abstract:	Surfactants are multipurpose products found in most sectors of contemporary industry. Their large-scale manufacturing has been mainly carried out using traditional chemical processes. Some of the chemical species involved in their production are considered hazardous and some industrial processes employing them categorised as “having potential negative impact on the environment”. Biological surfactants have therefore been generally accepted worldwide as suitable sustainable greener alternatives. Biosurfactants exhibit the same functionalities of synthetic analogues while having the ability to synergize with other molecules improving performances; this strengthens the possibility of reaching different markets via innovative formulations. Recently, their use was suggested to help combat Covid-19. In this review, an analysis of recent bibliography is presented with descriptions, statistics, classifications, applications, advantages, and challenges; evincing the reasons why biosurfactants can be considered as the chemical specialities of the future. Finally, the uses of the solid-state fermentation as a production technology for biosurfactants is presented.

Dear Editors,

Please find attached a paper entitled "**Biosurfactants: The Green Generation of Speciality Chemicals and Potential Production Using Solid-State Fermentation (SSF) Technology"** for consideration for publications in Bioresource Technology.

Biosurfactant production has become quite an important type of molecules, highly sought after by a wide range of industrial processes and the production technologies are in some instances the main bottle neck.

This review therefore presents the case for Biosurfactants as the specialty chemicals for countless future industrial applications. An analysis of the state of the art with recent bibliography is presented with descriptions, statistics, classifications, and applications; evincing the reasons why biosurfactants can be considered as the chemical specialities of the future. Finally, we discuss the use of the solid-state fermentation as a production technology gap for future biosurfactants that may present a solution to future production and research.

We feel this area of importance and high curiosity for microbiologists enough to be considered for publication by Bioresource Technology.

Kindly note that:

1. An abstract with content and details have been submitted to the Editor-in-Chief (Professor A. Pandey) who approved submission.
2. All the authors mutually agree for submitting their manuscript to BITE
3. The manuscript has not been submitted earlier to BITE
4. The Subject Classification selected is 60: MICROBIAL PRODUCTS

Yours truly,

Ibrahim M Banat

Response to the second revision request

Dear Professor Pandey

Kindly find attached the second revision for this review in which we have carried out the requested revisions as follows:

Remove Fig 1; no such details on number of publications, etc should be given even in text.

Figure 1 was removed, and details of number removed from text

Remove Fig 2 by giving details in text only.

Figure 2 was removed, and details given in text

Refs can be maximum 150; delete older ones or those from books.

References were reduced to 150

Page length can be maximum 50.

Length was reduced to 50 pages

Graphical Abstract (for review)

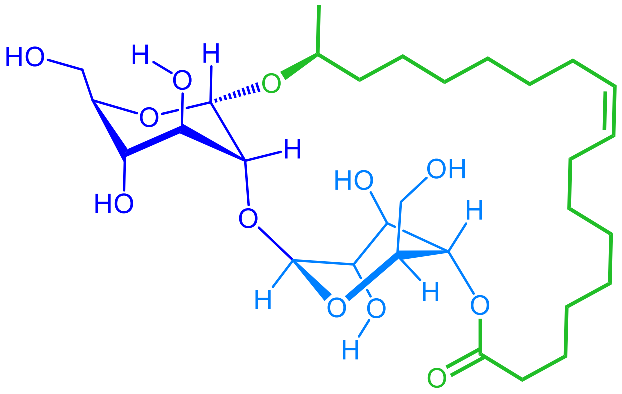
Biosurfactants

Production

Solid-state fermentation (SSF)

vs submerged fermentation

Perspectives



Applications

Pharmaceuticals

Bioremediation

Oil recovery

Cleansing

Cosmetics

Highlights

- Biosurfactants are becoming the specialty chemicals for many future industrial applications.
- Solid-state fermentation can mitigate some drawbacks of submerged liquid fermentation.
- Industry shows growing interest in biosurfactants for use in different markets.
- Covid-19 may boost future inclusion of biosurfactants in personal care products.

Biosurfactants: The Green Generation of Speciality Chemicals and Potential Production Using Solid-State Fermentation (SSF) Technology

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Abstract

Surfactants are multipurpose products found in most sectors of contemporary industry. Their large-scale manufacturing has been mainly carried out using traditional chemical processes. Some of the chemical species involved in their production are considered hazardous and some industrial processes employing them categorised as “having potential negative impact on the environment”. Biological surfactants have therefore been generally accepted worldwide as suitable sustainable greener alternatives. Biosurfactants exhibit the same functionalities of synthetic analogues while having the ability to synergize with other molecules improving performances; this strengthens the possibility of reaching different markets via innovative formulations. Recently, their use was suggested to help combat Covid-19. In this review, an analysis of recent bibliography is presented with descriptions, statistics, classifications, applications, advantages, and challenges; evincing the reasons why biosurfactants can be considered as the chemical specialities of the future. Finally, the uses of the solid-state fermentation as a production technology for biosurfactants is presented.

Keywords

Biosurfactants, glycolipids, solid-state fermentation, industrial applications, speciality chemicals.

Contents

1. Introduction

The increasing concern of the industry about sustainable processes and exploitation of eco-friendly products are the driving force for the growing interest on biosurfactants (BS).

Indeed, they are generally considered as less toxic and more biodegradable species than their synthetic counterparts and can be obtained from sustainable sources (Marchant and Banat, 2012). This interest is supported by the numerous successful applications of biosurfactants in recent years, not only in the replacement of conventional surfactants, but also because they exhibit own specific activities which find their use in different industrial sectors (Kumari et al., 2018; Rincón-Fontán et al., 2020; Sun et al., 2019; Zhao et al., 2018). However, production costs associated with BS, especially regarding the downstream processes, are still the main technological limitation for industrial exploitation (Banat et al., 2014b). Numerous studies have been focused on cost reduction, one example is the alternative approach of solid-state fermentation (SSF) which offers interesting perspectives as it is strongly tied to the concept of valorisation of biomass (e.g. the use of agro-industrial byproducts for culture media) and the reduction of downstream liquid volume treatment. This work aims to provide a comprehensive overview of the contemporary state on the subject of biosurfactants, advantages, disadvantages, challenges and production techniques, with particular emphasis on solid-state fermentation, critical process variables and a comparison with liquid fermentation. We also present some appealing applications of biosurfactants for different industrial sectors that have been the object of research and interest in the last five years including pharmaceutical, personal care, bioremediation and oil applications and some strategies for market access.

2. Surfactants: definitions, classifications and challenges

Surfactants are amphipathic chemical compounds constituted by two different molecular motifs: one hydrophilic and one lipophilic. The hydrophilic part is a polar moiety with strong affinity to polar substances such as water, while the lipophilic (or hydrophobic) shows affinity to non-polar media such as oils and fats; so, they can simultaneously interact with both polar and nonpolar substances. This dual characteristic allows surfactants to reduce the interfacial tension and confers desirable properties such as detergency, emulsifying activity, foaming, mixing and dispersion (Teixeira Souza et al., 2018). Such features are highly demanded in almost all sectors of the contemporary industry.

Surfactants can be categorized according to their origin, electrostatic status, and their hydrophilic and lipophilic balance (HLB); these categories are presented in Table 1. By origin, surfactants can be synthetic, semi-synthetic, or biological (biosurfactants). Most of the known surfactants worldwide fall in the synthetic and semi-synthetic type. Chemical surfactants mostly comprise ethylene oxide and propylene oxide copolymers and alkoxylated derivatives of alkylphenol, sorbitan esters, alcohols, and amines. Oleochemicals come from vegetable oils and fats that are subsequently modified through chemical processes. The lipophilic component is provided by a natural oil, while the ulterior synthesis conforms the hydrophilic moiety. Thus, oleochemical surfactants are also called semi-synthetic surfactants or bio-based products. Among recognized producers worldwide of both synthetic and semi-synthetic surfactants we find Akzo Nobel (Netherlands), BASF (Germany), Clariant (Switzerland), Croda (UK), Dow (USA), Evonik (Germany), Huntsman (USA), Oxiteno (Brazil), Procter & Gamble (USA), Rhodia (France), Sabic (Saudi Arabia), Sasol (South Africa), Shell (Netherlands), Solvay (Belgium) and Stepan (USA).

2.1. Drawbacks and challenges of conventional surfactants

Surfactants are the key components in the formulation of a variety of products for many different applications. However, their manufacturing has negatively impacted the environment for many years. Most of the raw materials derived from crude oil show high profiles of ecotoxicity and low profiles of biodegradability, e.g. alkylphenols and aromatic compounds (Li et al., 2013). This is the reason why such chemical species are regulated by many international organizations such as the Environmental Protection Agency (EPA), the Occupational Safety and Health Administration (OSHA), the National Institute for Occupational Safety and Health (NIOSH), the Department of Transportation (DOT) and The Food and Drug Administration (FDA), all in the USA; and the European Chemicals Agency (ECHA) in Europe. Some regulatory registries or laws include the ECL Restricted Substances List in South Korea, the

Industrial Safety and Health Law (ISHL) in Japan, the Work Place Hazardous Material Information System (WHMIS) in Canada, the Toxic Substances Control (TSCA) in USA, and many more, including international inventories of chemical substances. The negative potential of surfactants has been temporarily attended by the introduction of bio-based products, e.g. lauryl alcohol derivatives, which attenuate the synthetic nature and hazardousness of traditional chemical technologies. Nonetheless, the sacrifice of natural resources and subsequent stages of conventional chemical transformations are always required for manufacturing bio-based products. This category of “greener” semi-synthetic products has experienced significant growth in recent years in Europe and North America as a result of expanding applications in personal care, home care, and agrochemicals. In addition to safety risks associated with the use of raw materials, intermediaries, and finished products, other challenges to industry may lie in the emission of billions of kilograms of carbon dioxide (CO_2) into the atmosphere, contributing to the undesirable climate change (Griffin et al., 2018). Consequently, the chemical industry is now compelled to implement strategies for manufacturing more sustainable products through more eco-friendly processes (Zimmerman et al., 2020) without sacrificing product efficiencies. This should make biotechnological production of biosurfactants a more desirable technological alternative that will resolve such drawbacks in the long term.

3. Biosurfactants: attributes and interest

Biosurfactants (BS), also known as microbial (biological) surfactants, are secondary metabolites that are produced at the end of the exponential growth phase of microorganisms including bacteria, yeasts, and moulds. Biologically speaking, these molecules are involved in cell development, biofilm formation, and regulation of osmotic pressure. They are also implicated in cell survival under disadvantageous circumstances such as the need to use non-bioavailable hydrophobic substances (like hydrocarbons) as their sole carbon source. In this last case, excreted BS are involved in the diffusion of this inaccessible substrate through the cell membrane (Santos et al., 2016). BS can either be excreted or remain inside the cell. Because BS are produced through complex enzymatic reactions, such biomolecules often have complex chemical structures that can be modulated through careful selection of the culture medium or via genetic engineering (Brück et al., 2019).

3.1. Scientific and technological interest

The large advantages of versatile BS over synthetic products have drawn the attention of industrial research. Biosurfactants can be produced from renewable sources, generally have low toxicity, are highly biodegradable, often display better environmental compatibility, and usually remain stable at wide ranges of pH and temperatures (Das and Kumar, 2018; Gaur et al., 2019). Increased environmental awareness among consumers combined with new environmental legislations has provided further impetus for serious consideration of BS as possible alternatives to existing products (Marchant and Banat, 2012). This has been evidenced by the significant rise of publications not only of scientific articles, but also of patents on the topic. The following is a summary of the search for bibliographic information from the database SciFinder of Chemical Abstract Service (CAS). The keyword “biosurfactants” was used, and repeated references were considered as one. From 1963 to mid-September 2020 the count of publications was around 10,130. Although publishable activity on BS dates back > 57 years, the boom came up within the last twenty years. Only in the last five years, around 40% of the total known bibliography on BS has been reported; it is estimated that at least two documents on BS are published every day. This increase could be the result of the global growth of scientific literature in recent years, including reports on biotechnological products and processes. However, it is important to note that the trend shown by patentable activity (technological interest) in BS has not been proportional. The interest in patenting seems to be gaining ground over time. In early 2000s, around 10% of the body of publications were patents while, in the last five years, that proportion has doubled. This shows a growing and accelerated interest for the industrial exploitation.

Among the institutions with significant publishable activity one finds: East China University of Science and Technology, Chinese Academy of Sciences, Hunan University

(China), Locus IP Company LLC (USA), Zhejiang University (China), China National Petroleum Corporation, Jiangnan University (China), and the Ghent University (Belgium).

This spreading concern in BS has economic impact as the global surfactant market accounted for USD 43.6 billion in 2017, and is projected to reach USD 66.4 billion by 2025, registering a compound annual growth rate (CAGR) of 5.4% from 2018 to 2025 (Shasttri and Sumant, 2018). Biosurfactants however, account for a small percentage of the global surfactant market; and the precise value is unknown due to the incorrect indiscriminate use of the term “biosurfactant” by some producers of environmental-friendly synthetic surfactants and the practices of some market research companies which include oleochemicals under this category. Some of the few known producers in the world of authentic biosurfactants are Evonik (Germany), Ecover (Belgium), Jeneil Biotech (USA), Saraya (Japan), AGAE (USA), Soliance (France; now Givaudan, Swiss), GlycoSurf (USA), TensioGreen (USA), NatSurfact (now Stepan, USA), Rhamnolipid (USA), MG Intobio (South Korea), Victex (China), and Kingorigin (China) (Glam Research, 2020).

3.2. Classification of biosurfactants

Biosurfactants are amphiphilic molecules formed by two contrasting moieties: one hydrophilic and one lipophilic. The hydrophilic part of BS is constituted of carbohydrates, amino acids, proteins, phosphates, carboxylic acids, or alcohol motifs. The lipophilic fragments are chains of carbon atoms as in fatty acids. Both molecular components are assembled via linking biochemical functionalities such as ethers (C–O–C), amides (N–C=O), and esters (O–C=O). According to the kind of each moiety, BS are frequently classified as glycolipids, lipopolysaccharides, lipopeptides, phospholipids, and fatty acids; each group has specific physicochemical features and physiological roles (Henkel and Hausmann, 2019). Among all types of BS, glycolipids have the potential to be produced on a large scale due to their convenient yield compared to other BS such as lipoproteins. It is expected that BS produced at higher yields will lead to lower costs of production (Dhanarajan and Sen, 2014). Glycolipids are the consequence of the condensation of fatty acids (lipids) and carbohydrates. Their names are taken from the identity of the carbohydrate. Ergo, glycolipids containing sophorose are called sophorolipids; those containing rhamnose are named rhamnolipids; those with trehalose, trehalose-lipids, and so on. From all glycolipid types, sophorolipids and rhamnolipids have been among the most studied species (Funston et al., 2016; Irorere et al., 2017). Sophorolipids can be found as a variety of structures; the most known architectures are open and cyclic arrangements (Delbeke et al., 2016). Open sophorolipids are those displaying the chemical functionality of carboxylic acid (COOH) at the end of the lipophilic chain. Cyclic forms are those having an ester functionality as a result of the condensation between the fatty acid and one of the hydroxyl motifs of the sophorose. Cyclic esters are called lactones. In this way, there are acidic and lactonized forms of sophorolipids. Other molecular variations are (i) the presence or absence of acetyl groups on the carbohydrate moiety, (ii) the length of the alkyl chain, (iii) the number of unsaturation in the fatty chain, (iv) the position of the hydroxyl group in the fatty chain, (v) the position of the hydroxyl group of the carbohydrate that is etherified with the fatty alcohol, and (vi) the position of the hydroxyl group of the carbohydrate that is esterified with the fatty acid in lactone forms, among others.

4. Potential applications

Because BS reduce surface tension exactly in the same way as chemical and oleochemical surfactants do, they can find the same application niches. The following section describes some recent examples of applications of BS in different industrial sectors.

4.1 Pharmaceutical applications of biosurfactants

Due to their anti-adhesion and enzyme inhibition effects, BS can be useful active ingredients in fungicides, bactericides, insecticides, antivirals, among others. For this reason, these have been used in many studies that aim to introduce BS into therapeutic applications (Fracchia et al., 2015). As mentioned above, BS are naturally produced by microorganisms during biofilm formation, smoothing the architecture of microcolonies and maintaining the channels needed for distributing vital fluids. These attenuating properties of isolated BS can be useful to ensure the anti-adherence of human pathogens and, therefore, to inhibit their capacity to form biofilms at potential sites of infection (Anjum et al., 2016; Sun et al., 2018).

In view of their amphiphilic nature, many of the antibiotic effects of BS involve damage to lipid bilayers constituting cell membranes. Some BS allow the formation of pores in membranes which leads to disequilibrium in ion exchange and consequently to cell death. It also has been shown that another bactericidal mechanism exhibited by some BS involves the generation of intracellular reactive oxygen species (ROS) (Gaur et al., 2020). Moreover, to avoid the recurrence of resistant microbial strains, the combination of more than one type of active molecule may be desirable, rather than one (single) molecule (Wani and Ahmad, 2020). The antimicrobial properties of BS have been investigated in synergistic combination with other species, e.g. caprylic acid (Díaz De Rienzo et al., 2016) and silver and iron oxide nanoparticles (Khalid et al., 2019), among others.

Some BS also exhibit antiviral properties. Particularly, surfactin can prevent infection of epithelial cells caused by enveloped viruses –including herpes viruses– inhibiting membrane fusion between virus and host cells. This inhibition can be carried out against porcine epidemic diarrhoea virus at low BS concentrations without cytotoxicity (Yuan et al., 2018). Surfactin produced by the probiotic *Bacillus subtilis* also showed efficiency in the inactivation of transmissible gastroenteritis coronavirus (Wang et al., 2017).

Very recently, the use of BS has been suggested to combat SARS-CoV-2, responsible for the Covid-19 pandemic, a situation which has resulted in strong worldwide ongoing negative impacts on health, societies, and economies. It is noted that BS could help to mitigate transmission, incubation, and disease development (Smith et al., 2020). Since coronaviruses, like any other viruses, are completely dependent on their lipid membrane that keeps and stores their genetic information and viral machinery (proteins and enzymes), biosurfactants have the ability to deactivate SARS-CoV2 through a simple membranal disruption such as most detergents do. Another possible mechanism of action could be the destabilization of viral envelope and membrane proteins, such as the spikes of glycoprotein that allows the virus to anchor itself to human cell receptors, e.g. angiotensin-converting enzyme 2 (ACE2) receptor (Mittal et al., 2020). Therefore, the use of BS as active agents in handwashing and cleaning products can prevent the spread of the virus. Moreover, these can also be adequate excipients or adjuvants for medicines to treat symptoms and be good elements in the production of antiviral masks.

Besides the antimicrobial and antiviral properties, BS can find other health applications such as immunomodulation, both activation and suppression of immune system and anticancer effects, e.g. inhibition of the cell cycle, apoptosis, inhibition of the metastatic capacity of tumour cells, etc. (Guerfali et al., 2019; Sajid et al., 2020).

4.2 Personal care applications of biosurfactants

The emulsifying properties of BS are attractive for the formulation of cosmetics and personal care products, because these can fulfil all the critical functions of synthetic surfactants (Vecino et al., 2017) and modulate the rheological properties of such formulations (Xu and Amin, 2019). For example, a BS obtained from *Lactobacillus paracasei* managed to stabilize an emulsion consisting of essential oils and natural antioxidants just as the commercial surfactant sodium dodecyl sulfate does (Ferreira et al., 2017). Another example is the study of replacement commercial chemical surfactants such as sodium laureth sulfate by BS in shampoos (Fernández-Peña et al., 2020). Other works have introduced BS in mixtures with chemical surfactants for cleansing agents (Brigitte et al., 2017a; Hartung et al., 2013). Here, the ratio biosurfactant/surfactant plays a critical role in the properties of the final formulation.

A biosurfactant extract from corn steep liquor –an agricultural byproduct– showed promising results as a cosmetic formulation agent. This extract exhibited interesting surface-active properties. It appeared to be a suitable co-stabilizer for nanoemulsions and nanocrystals increasing dermal penetration. Besides its advantages as a formulation agent, the extract also exhibited antioxidant and skin protective properties (Knoth et al., 2019). Moreover, BS appeared to be effective stabilizing agents of vitamin C in cosmetic formulations (Rincón-Fontán et al., 2020). Finally, synergistic effects in association with zinc oxide against

Cutibacterium acnes have been found, allowing the reduction of zinc concentrations in formulations to treat acne (Rodríguez-López et al., 2020).

As previously mentioned, BS may be used in cosmetics, not only for their formulation properties but also for their valuable bioactivities. In this regards, yeast biosurfactants showed promising results to treat dermatophytosis caused by *Trichophyton mentagrophytes* (Sen et al., 2020). A mouthwash containing a mixture of biosurfactants from *Pseudomonas aeruginosa* and *Candida bombicola* (now *Starmerella bombicola*) was effective against cariogenic microorganisms and was significantly less toxic than commercially available mouthwashes (Farias et al., 2019). Commercially speaking, Henkel AG & Co. KGaA (Germany) owns various patents involving BS for cosmetic formulations, e.g. soap, scrub and emulsion agents (Brigitte et al., 2017b; Schelges and Tretyakova, 2017a, 2017b, 2017c).

4.3 Biosurfactants in household cleaning

Surface activities are inherent in cleaning agents and the trend of substitution of surfactants by BS has been of great interest for household cleaning products. Many studies highlight the potential use of BS in cleaning formulations (Fei et al., 2020). This substitution may however be partial, to reduce the initial quantity of synthetic compounds. This way, a lipopeptide biosurfactant used as a laundry detergent showed promising results and additively worked with a commercial detergent (Bouassida et al., 2018). From a perspective of stain removal action, microorganisms that simultaneously can produce good yields of both enzymes and biosurfactants by using the same culture medium are particularly valuable as their crude extracts exhibit synergistic effects (Hmidet et al., 2019). Thus, Bhange et al. (2016) produced keratinolytic protease, amylase, and a biosurfactant from *B. subtilis* using a single optimized medium. It is known that water temperature affects the effectiveness of detergents; therefore, lowering water temperatures may result in an economic and environmental challenge for cleaning treatments. Synthetic surfactants can crystallize at lower temperatures and therefore lose their surface activities at conditions where BS remain active. Consequently, processes involving BS can be carried out at lower temperatures. Following this idea, a special focus is given to BS-producing microorganisms isolated from cold environments (Perfumo et al., 2018). Unilever (Rotterdam-London, Netherland-United Kingdom) has various patents related to household products, some of them are: laundry comprising BS and lipases from *Psychromonas ingrahamii* –a psychrophilic bacterium– active at low temperatures (De Rose et al., 2017a, 2017b); cleaning fluids comprising mixtures of surfactants and BS (Jones and Stevenson, 2016), and BS mixtures to protect coloured or dyed substrates from dye transfer during exposure to aqueous cleansing solutions (Torodov Petkov and Stevenson, 2016).

4.4 Biosurfactants in oil recovery

Petroleum also known as ‘black gold’ is the main source of energy for the contemporary world. Crude oil is found below the earth's surface or trapped inside rocks as a result of the transformation of accumulated organic matter into sediments from the geological past located in different parts of the earth where it can be extracted by well drilling. The natural pressure of an oil reservoir makes it flow from the bottom to the surface. However, as the extraction progresses, this pressure decreases, and the application of liquids or gases is required to re-pressurize and obtain the remaining oil. During these operations, formulated chemical agents that can perform lubrication, wetting, demulsification, corrosion inhibition, wax inhibition, flow improvement, among others, are normally required. These products are called oilfield chemicals and are typically made up of polymeric materials of petrochemical origin whose raw materials, intermediates, or final components are regulated due to their ecotoxicity profiles. In recent years, the possibility of replacing chemical compounds with BS has been investigated (Ke et al., 2019; Sivasankar and Suresh Kumar, 2017; Zhao et al., 2018).

Recent examples are the inventions of Locus Oil IP Company, who has patented compositions and methods for oil recovery (Farmer et al., 2019, 2018b), upgrading heavy crude oil (Farmer et al., 2018a), and removing paraffins (Farmer et al., 2020). Another example is Baker Hughes Inc. (Houston, USA) who owns various biosurfactants-related patents. One involves the application of a mixture of BS to prevent the corrosion inside the wells during treatments (Gunawan et al., 2015) and other involves the addition of BS to hydrocarbon-based fluids to reduce their viscosity (Campbell and Weers, 2016). Varjani and Upasani (2016) showed that a thermo- and halo-tolerant rhamnolipid produced by *P. aeruginosa* could improve the oil recovery over the residual oil saturation of 8.82% in a core flooding system. Surfactin, when applied to the oil recovery process exhibits interesting pH dependency, e.g. emulsification in alkaline conditions and demulsification in acidic conditions. When in presence with surfactin, oil can thus undergo two different behaviours through a simple pH adjustment (Long et al., 2017).

4.5 Biosurfactants for bioremediation and pollutants removal

Remediation of aquatic and terrestrial polluted environments is a challenging topic as physical collection methods often allow a limited recovery, and chemical methods can generate new damages to the environment (Dave, 2011). In this context, bioremediation offers attractive perspectives. Bioremediation may be carried out following two mechanisms: (i) one direct which involves the presence of the microorganism that degrades *in situ* the contaminant through its metabolism and (ii) one indirect that involves the use of microbial compounds (such as biosurfactants) to modify the physicochemical properties and help the recovery of the contaminant (Francis and Nancharaiah, 2015). When speaking of bioremediation, one often thinks of contamination of environments with hydrocarbons, which, incidentally, are these environments where many biosurfactant-producing microorganisms have been isolated (Datta et al., 2018; Pi et al., 2017; Sarkar et al., 2017; Sun et al., 2019). Biosurfactants, secreted by microorganisms and released into the hydrophobic medium, increase hydrocarbon bioavailability to the (same) microorganisms. In other words, the degradation of hydrocarbons in the presence of microorganisms is enhanced by the production of BS (Xue et al., 2019). For that matter, strategies of biostimulation and bioaugmentation of native microorganisms showed promising results in the degradation of sludge generated in an oil refinery (Roy et al., 2018).

Amongst the various chemical molecules, polycyclic aromatic hydrocarbons (PAH), produced from incomplete combustion, are particularly recalcitrant (Patel and Patel, 2020). A strain of *P. aeruginosa* was efficient degrading crude oil and PAHs such as pyrene and fluoranthene. Biosurfactants isolated from this same strain showed interesting results in hydrocarbons remobilization from oil-contaminated soils (Chebbi et al., 2017). Another strain of *Acinetobacter baumannii* isolated from a petroleum-contaminated soil was able to degrade pyrene. The growth of this strain on PAH as the sole carbon source was accompanied by BS production (Gupta et al., 2020). Selected strains can this way being combined in a bacterial consortium to improve the degradation of multiple PAH present in crude oil (Kumari et al., 2018). Direct volatile hydrocarbon removal can also be carried out using BS. Saponins in biotrickling filters significantly participated in hexane removal (Tu et al., 2015). It also has been reported that a biofilm containing a strain of *Pseudomonas* functioned as a (bio)filter for volatile organic compounds both degrading hexane and producing biosurfactants. Microorganisms that produce BS from hydrocarbons are valuable in biofilter systems because these can remove the pollution, avoiding biomass accumulation (He et al., 2020). Among the indirect bioremediation mechanisms involving BS, phytoremediation is a cost-effective technique to treat soils contaminated with crude oil. Liao et al. (2016) have shown that the addition of BS to the contaminated soil improved the oil degradation by the soil microorganisms in the presence of corn (*Zea mays* L.) through increased hydrocarbons accessibility and that rhamnolipids favoured the PAH uptake in the plant roots. A study revealed that the supplementation of BS from *Pseudozyma sp.* to a medium containing crude oil as sole carbon source, improved the oil degradation by *Pseudomonas putida* up to 46% (Sajna et al., 2015).

Composting is also an efficient way of handling biologically active and potentially hazardous species to obtain stabilized inert materials with potential fertilizer properties. The addition of BS during the chicken manure composting process was reported to improve the overall final qualities of such compost in terms of sanitization (higher peak of temperature during the thermophilic phase), fertilization (higher seed germination index), formation of humic acids (lower E4/E6 ratio) and organic matter degradation (higher cellulase activity). A metagenomic study revealed that these improved qualities were the consequence of increased diversity in microbial communities and subsequent diversity in metabolism, especially that related to carbohydrate metabolism (Yin et al., 2019). Still during chicken manure composting, it has also been showed that the addition of rhamnolipids significantly reduced the relative abundance of the antibiotic resistance genes among the microbial communities through a mechanism of decrease of the bioavailability of the heavy metals present in the environment (Zhang et al., 2016).

Following the same idea, the addition of rhamnolipids during the fermentation of waste activated sludge improved the hydrolysis and acidification processes, notably by favouring the growth of functional microorganisms compared to the action of synthetic surfactants (Zhou et al., 2015). This process, when supplemented with free nitrous acid and tea saponin (a biosurfactant) improved the sludge solubilization, reducing the fermentation time and improving the short-chain fatty acids production (Xu et al., 2016). When considering anaerobic treatment of sludge, it has been shown that a pre-treatment consisting in the biomass disintegration using a biosurfactant-producing strain of *Planococcus jake* of a previously deflocculated sludge improved the biodigestibility (Kavitha et al., 2015). Pre-treatment of waste activated sludge with BS also enhanced the release of phosphorus, thus facilitating its recovery from the sludge (He et al., 2016).

5 Solid-state fermentation (SSF) for biosurfactant production

There are currently two ways to produce BS: the submerged fermentation (SmF), also called liquid fermentation, and the solid-state fermentation (SSF). SSF is a microbial process occurring mostly on the surface of solid materials that have the property to absorb or contain water, with or without soluble nutrient (He et al., 2019; Pandey, 2003). SmF is the best-known methodology in the scientific literature and patents while SSF occupies a still very small but emerging space. Both techniques can use the same producing microorganisms, but results can be significantly different due to the large differences in conditions between the two types of cultivation regimen. Moreover, for a given bioprocess, SSF is often known to reduce the global cost in comparison to liquid fermentation (Sadh et al., 2018). The low water volume in SSF has a large impact on the economy of the process mainly due to smaller bioreactor size, reduced downstream processing, and lower sterilization costs. Besides, many SSF processes focus on the utilization of cheap agro-industrial byproducts as a culture medium (Venil et al., 2017). Although, it is not limited to SSF as studies using SmF for BS production also involve agro-industrial byproducts valorisation (Kourmentza et al., 2018; Moya Ramírez et al., 2015; Radzuan et al., 2017; Sharma et al., 2020).

To observe tendencies, an exhaustive study has been carried out on the scientific literature to highlight the microorganism type, biosurfactant type, production scale, and bioreactor type related to the BS production using SSF (Figure 1). One-third of research articles involves using strains of fungi and two-third for bacteria (Figure 1A). This is interesting because SSF processes traditionally involve more fungi than bacteria for their ability to grow at lower water activity values. Indeed, the low moisture content in the SSF medium means that fermentation can theoretically only be carried out by a limited number of microorganisms, mainly yeasts and fungi. This is justified by the fact that the evolution of higher fungi take place on solid growth substrates. Another interesting observation is that around 70% of the microorganisms that have been used were unicellular, whereas SSF processes are generally claimed to be optimized for filamentous growth which can penetrate through the interparticle spaces into the depth of the solid medium. The invasion of the solid matrix is optimized by both the hydrolytic enzymes secretion and the application of a mechanical force at the apex of the hypha, increasing the surface contact (King et al., 2017). The nutrients translocation within the filamentous web is also better adapted to cope with nutrient-poor areas to seek resources in media where nutrients are heterogeneously distributed. The two classes of BS produced through SSF are glycolipids and lipopeptides, with 26% of undetermined BS (Figure 1B). The production scale involves up to 80% laboratory-scale ranging from 0 to 250 g of medium, it is thus not surprising that 58% of the articles used flasks for microbial cultures (Figure 1C and D); only 2% of the scientific studies of BS production involve a scale ranging from 5 to 10 kg.

5.1 Important factors for biosurfactant production in SSF

The most common factors influencing BS production may be physical (like temperature) or chemical (like pH and the nutrient sources). SSF involves microbial cultures in the near absence of free running water. Therefore, its moisture content is also of critical importance.

5.1.1 Effect of pH on biosurfactant production

The pH values of the medium strongly affect many enzymatic, secondary metabolites production and transport of various components across the cell membrane. It is well-known that fungi can adapt to more acidic conditions than most bacteria. Concerning BS production in SSF, optimal pH conditions follow this trend. The best pH values for *A. fumigatus* and *P. djamor* are 4.5 and 5.5, respectively (Velioğlu and Ürek, 2016). Biosurfactant productions involving yeasts like *Starmerella bombicola* require pH values around 6 (Cerda et al., 2019; Jiménez-Peñalver et al., 2016). Regarding bacteria like *P. aeruginosa* and *B. subtilis*, optimal pH values range from neutral to slightly basic (7–8) (Zhu et al., 2013).

5.1.2 Effect of temperature on biosurfactant production

Temperature is a critical parameter in SSF. Indeed, as the bioprocess progresses, metabolic heat is generated by the microorganism and because the solid media generally exhibit low thermal conductivities, the heat may accumulate in the medium leading to detrimental temperature increase and thermal gradients (Pandey, 2003). As optimum activity of each type of microorganisms takes place in a relatively well-defined range of temperatures, at which these operate most efficiently. BS production is depending on temperature. Filamentous fungi and yeasts require optimum values between 25°C and 30°C for optimal BS production (Jiménez-Peñalver et al., 2016; Lourenço et al., 2018). Rhamnolipid production requires optimal temperatures ranging from 30°C to 37°C following the strain of *P. aeruginosa* (Wu et al., 2017). Temperature greatly affects lipopeptide production, as in the case of *Bacillus cereus* (Nalini et al., 2016).

5.1.3 Effect of moisture content on biosurfactant production

Like temperature, the initial moisture content of the medium may vary as the bioprocess progresses and the microorganism consumes the water and/or it is evaporated by the metabolic heat leading to water gradients in the bioreactor. The water content of the medium is therefore a critical factor in SSF systems as it affects the microbial growth rate and extent on the substrates and determines the product yield; low water content could retard cell growth and metabolite production. The water content of the medium is a critical factor in SSF systems that affects the microbial growth rate, extent on the substrates and determines the product yield. Low water content could retard cell growth and metabolite production. Appropriate water content would provide an ideal microenvironment for supporting growth and enhancing metabolite production (Zhu et al., 2013). BS producing filamentous fungi like *A. fumigatus* and *T. versicolor* and yeasts like *S. bombicola* exhibit optimal moisture values between 44.7% and 50% (Jiménez-Peñalver et al., 2016; Lourenço et al., 2018). These moisture values are particularly important because lower values tend to limit the growth of potential contaminants in SSF. Bacteria often require higher values of moisture (generally fungi and yeast have water activity requirements of around 0.5–0.6 and bacteria around 0.8–0.9) that may generate alternative issues of solid medium compaction leading to reduced gaseous transfers and favouring contamination (He et al., 2019); although successful examples of SSF carried out with bacteria do exist (Costa et al., 2018).

5.1.4 Effect of the medium composition on biosurfactant production

Several carbon substrates have been used in many investigations. Indeed, the type and quantity of BS are influenced by the carbon source. Both the composition and concentration of the carbon source seem to be essential factors of BS congeners, yields and physicochemical properties. Yet, hydrophobic carbon sources were reported to be better than hydrophilic ones in promoting BS production (Ismail et al., 2015). The importance of hydrophobicity of the carbon sources for BS production is underlined by the fact that many producing microbes are commonly isolated from soils or water contaminated with hydrophobic wastes. BS production however generally requires a medium containing the simultaneous presence of a hydrophilic and a hydrophobic carbon sources in the culture medium (Teixeira Souza et al., 2018). As a consequence, many solid media employed in SSF use oil containing byproducts from the oil extraction industry, or include vegetal oils –like sunflower seed oil– or crude oils –like diesel– in their final compositions (Jiménez-Peñalver et al., 2016).

Another important consideration to develop a production bioprocess is media consistency, quality, and availability in sufficient quantities. For that matter, it is interesting to supply solid byproducts directly from their producing industries to ensure availability of large quantities with standardized composition. Table 2 shows a list of solid media used for BS production by SSF in the scientific literature and highlights the diversity of potential of biomass valorisation.

In SSF, the physical properties of the media are also essential to provide an environment suitable for microbial growth and metabolite productions, BS production being generally an aerobic process. Factors such as the shape and size of solid particle, medium porosity, mass and energy transfers, hydrophilic and hydrophobic nature of solid particles are usually interdependent and essential to consider in SSF. A good medium texture is therefore essential and some media include solid support like wheat straw or sugarcane bagasse (El-Housseiny et al., 2019; Zhu et al., 2013). These solid compounds only act as supports; they are not used directly in the nutrition of the microorganism but create a suitable physical environment reducing the porosity changes during the process. Fungal development may clog the empty spaces in the medium, the support material therefore, maintains the physical properties favourable for mass and heat transfers to take place, allowing for example, the gaseous phase inside the interparticle void to be regenerated in oxygen while it is consumed by the fungus (Carboué et al., 2018).

5.1.5 Effect of nutrient supplementation on biosurfactant production

Natural byproducts have complex compositions and usually provide multiple nutrients to microorganisms that grow on them. However, these compounds are usually present in suboptimal quantities and, in this case, nutrient supplementation is needed to provide all necessary compounds for optimum growth and production (Soccol et al., 2017). Some examples of supplements are copper and iron. Indeed, iron is recognized to be an important enzyme activator, specifically for the isocitrate lyase, an enzyme involved in cell growth on hydrophobic substrates. Each microorganism has its optimal cultivation conditions and requires specific compounds depending on the expected products. Thus, many studies imply experimental designs to search for the factors with significant positive effect and their optimal levels to increase BS production (Jiménez-Peñalver et al., 2018).

5.2 Scale up of SSF process for the production of biosurfactants

The scaling up of SSF process is often considered a technological bottleneck because the mass and energy transfers issues, leading to the accumulation of heat and the apparition of water and gas gradients inside the bioreactor bed, are amplified as the process scale increases (Lopez-Ramirez et al., 2018). In the case of aerobic bacterial metabolism which involves an important part of BS producing microorganisms, the metabolic heat generated could even be more amplified (bacteria generally grow faster than fungi).

Two mechanisms are usually presented as critical in managing heat removal at higher SSF production scales: cooling with water evaporation and agitation. Water evaporation is an endothermic process, for that reason, aeration with water-saturated air can be used to remove the metabolic heat produced during microbial growth and also to avoid the medium drying (Saucedo-Castañeda et al., 1994). Agitation counters the energy and mass gradients formation through bed mixing. The combination of both mechanisms is often required at industrial scales, as agitation facilitates the homogenization of the system and thus an equal distribution of the moisture and oxygen through the medium. In general, bioreactors are classified depending on the mechanisms of aeration and agitation. The type of microorganism strongly influences the choice of bioreactor. Filamentous microorganisms, for example, may be particularly sensitive to the shear forces (generated during agitation) that lead to the detachment of microorganisms from the solid medium, damage to mycelia, and ultimately to the reduction of BS production. So, it is often necessary to find a compromise between mass and energy transfers qualities and mycelial damages due to agitation. Some studies have reported good productions of spores and enzymes with filamentous fungi belonging to the genera *Aspergillus* and *Trichoderma* in agitated SSF systems with lower rotational speeds – ranging from 1 to 6 rpm – and/or intermittent mixings (Carboué et al., 2019; Finkler et al., 2017; Lopez-Ramirez et al., 2018).

Even though, reports of BS production using SSF at higher scales are very scarce (Figure 1C). Ano et al., (2009) carried out SSF in an agitated and aerated bioreactor on 2 kg of dry weight okara to produce iturin A using a strain of *B. subtilis*. Biosurfactant production was significantly reduced when mixing was carried out during the process, probably due to the reduction of biofilm formation. Under static conditions, they observed an important temperature gradient across the bed during the process but were able to control it with aeration of humidified air. The production of BS was very low when compared to those obtained at lower scales using the same substrate and strain. In another investigation at a laboratory scale (100 g of medium), Jiménez-Peñalver et al. (2016) showed that intermittent mixing increased the bioavailability of the substrates to the yeast and led to an increased production of sophorolipids. This result indicates that the process could be scaled up, not only to improve the yield but also to reduce channelling and overheating problems. To date, the largest production scale reported in the literature was achieve using a *Bacillus amyloliquefaciens* strain producing surfactins, in a forcefully aerated and agitated (rotational speed of 50 rpm) bioreactor on 9.25 kg of solid medium (Zhu et al., 2013). Interestingly, they did not observe any difference in the production yields between the static laboratory scaled culture and the agitated pilot-scaled culture, highlighting the absence of detrimental agitation effects on their process despite a higher rotational speed than the ones used for filamentous microorganisms.

Interestingly, the fact that BS producing microorganisms are a major part unicellular (bacteria and yeasts) may also change the established paradigm stating that the SSF is more adapted for filamentous microorganisms, allowing successful scale up through the implementation of stronger agitation regimes, thanks to a higher tolerance of unicellular microorganisms to the shear forces reducing heat and mass transfer limitations. We can therefore think that BS production not only benefits from the scientific advances made in SSF, but also actively participates to develop the discipline.

5.3 Comparison of SSF vs SmF for the production of biosurfactants

Many investigations have highlighted that BS are produced in higher quantities using SSF in comparison to SmF, using same culture conditions e.g. temperature, nutrients concentration, agitation, etc. The product yield of hydrophobins (in mg/g of biomass) produced by *P. ostraeus* for example, was two-fold higher when produced in SSF than in SmF. Indeed, these proteins were secreted during adhesion of mycelia to solid support as these molecules are responsible for surface hydrophobicity of mycelia during binding to the hydrophobic substrate (Kulkarni et al., 2020). Rhamnolipids production in SSF was also reported at threefold higher than in SmF by El-Housseiny et al., (2019). Mizumoto et al. (2006) also observed similar results, as they obtained an iturin A production tenfold higher using SSF than that in SmF. They explained this difference with various hypotheses: as a secondary metabolite, iturin A is produced after the exponential growth phase, when nutrients become scarce in the medium. In SmF, the nutrients and oxygen are homogeneously distributed abundantly in the liquid medium, leading their bacterial strain to produce biomass rather than iturin A. In SSF systems, however, nutritional stress may be observed, as nutrients uptake becomes a limiting step due to heterogeneities in the liquid phase, thus promoting the secondary metabolism. Another hypothesis was based on the biological structure differences observed between the two types of process: in SSF, there is the formation of a biofilm that may be more suitable for iturin A production than the planktonic form of liquid culture.

The higher production obtained for BS in SSF compared to SmF however, is not a general rule: Sitohy et al. (2010) have shown that SmF gave higher quantities of BS using bacteria and yeast cultures than when SSF was used. This effect relies mostly on the strain and the culture conditions used, hence, ideally, a comparison should be made between SSF and SmF for every process, not only including quantitative and qualitative considerations, but also economical ones to choose the best option. Besides, it is also interesting to mention that these studies reporting better production of BS using SSF rather than SmF were mainly carried out at laboratory scale.

At present, the technological aspects, especially regarding process control, are more developed for the SmF than for SSF, and although there are counter-examples, SmF is the most prevalent cultivation method used in the fermentation industry (Prado et al., 2016). As an example, Novozymes, which is the world-leading enzyme producer, currently applies SmF for cellulase production (Hansen et al., 2015). Industrial BS productions make no exception and are still widely carried out using SmF (Brumano et al., 2016). The main reason for the lack of industrial-scaled SSF bioreactor is the absence of efficient mathematical models backing the bioreactor designs and automated control system that could successfully represent and overcome the heterogeneity of the bioreactor bed with respect to the heat and mass transfers (Arora et al., 2018). Technical issues specific to the BS production in SmF however are particularly encountered at the industrial scale. One of them is the production of foam because of the important air-liquid interface. In SmF, liquid phase constitutes the culture medium and in the case of BS production, an excess of foam is often generated during the fermentation, especially at intense agitation and aeration which is generally the case of microorganisms that produce BS (predominantly under aerobic conditions), favouring the dispersion at the interface between phases and the risk of contaminations. Microorganisms are carried into the foam layer by froth flotation; thus, foaming may decrease the effective biocatalyst concentration in the bulk liquid, affecting the global bioprocess performance and often creating interferences with the measurement and sampling material. As a consequence, many industrial-scaled BS productions processes require the use of antifoam agents that increases the overall cost of the process. SSF enhance O_2 transfer without foam production mitigating the risk of contamination. The use of SSF, involving reduced amounts of free water, therefore could be an alternate method for BS production (Krieger et al., 2010).

Regarding the downstream process, the extraction in SSF is usually considered more difficult than in SmF because of the complex nature of the agro-industrial byproducts used as solid medium that display a bigger diversity of interaction (medium-product and medium-solvent) which as a result can lead to the presence of residual impurities in the crude extract. Nonetheless, in practice, the required degree of purity for a product depends on the intended application (Singhania et al., 2009). Thereby, some sectors like health or cosmetics, e.g. involving direct contact with living beings including humans, are particularly sensitive to the composition and require very high grades of purity. For this type of finer applications, improved separation techniques such as preparative HPLC will be required; even these types of applications will require using more refined raw materials. On the other hand, the direct use of fermented medium or crude extracts without further purification is appropriate for many other applications ranging from oil industry to pollutant removal or general environmental applications. In the case where microorganisms would still be present and active in the product (e.g. dry fermented medium containing conidia), it may be important to carry out the bioprocess with GRAS microorganisms.

It has been widely mentioned that production costs associated with BS production, especially the downstream processes, can limit their general application (Jimoh and Lin, 2019; Najmi et al., 2018). Because of that, an important emphasis is put on the search for mechanisms to decrease the total cost of the process. In the last five years, innovative technologies of integrated process of fermentation and simultaneous extraction have emerged, involving for example integrated gravity-based separation processes that greatly improve productivity, process cycles and production costs (Dolman et al., 2019). Although developed for SmF, integrated these separation processes can be envisaged in the future for SSF, particularly in the case of continuous or semi-continuous processes involving a plug-flow bioreactor with separated fermentation and extraction compartments which is similar to the process developed by Gibbons et al. (1988) for a semicontinuous production and extraction of ethanol.

6 Future potentials

The future of biosurfactant uses is huge because they cover and sometimes exceed the scope of synthetic surfactants. Their implementation in productive and daily life will involve most ecological aspects such as (i) reducing exposure of dangerous chemical substances, not only for humans but also for plants and animals, (ii) reducing carbon footprint, and (iii) boosting the circular economy. Small amounts of these biological surfactants have been shown to produce the same effects in terms of surface activities as commercial chemical surfactants. Therefore, finished surfactant bio-based products (detergents, shampoos, soaps, cleaning agents, etc.) could simply contain biosurfactants in very small quantities either as main components or adjuvant components that enhances overall activity. Using modest but significant loads of biosurfactants into formulations automatically would reduce the scale of their production and consequently the scale of their purification processes (if necessary). This approach can bring biosurfactants to markets in a shorter time than expected. Not too many commercial examples are emerging nowadays in different parts of the world.

The generation of innovative technologies for production, control, separation, purification, characterization, and performance evaluations shows a promising future for biotechnological exploitation of biosurfactants. Many studies therefore work on overcoming the technological bottlenecks and, amongst them, SSF can be an interesting candidate. Although the publishable activity on BS production via SSF is more recent and does not follow the same exponential tendency as SmF, it is likely to think that this culture technique will turn into something established in the near future in the biotechnological industry. This will not only take place in the academic world, but also as a relevant strategy for chemical industry to produce biobased products with interesting yields, lower costs and through a possible valorisation of byproducts and industrial wastes. The advances in SSF are accompanied by the evolution of chemical engineering, modelling and biotechnology, which contribute to understanding and decreasing specific technological limitations (e.g. heat removal) and facilitating its integration in processes at pilot and industrial scales (Jin et al., 2020, 2019; Pessoa et al., 2019; Zeng et al., 2019).

Processes involving microorganisms with good tolerance to higher agitation may also hold an interesting potential approach for scale-up.

Finally, the increase of good and efficient relationships between academia and industry worldwide, mediated by the public opinion on a better recognition of the sustainability aspect in the production practices will also contribute to this impulse. The current battle against the Covid-19 may become a good example as a driving force behind such evolution.

7 Conclusions

Biosurfactants is a fascinating topic for innovation, research and sustainable development. Interest has become notable in recent years due to the discovery of new applications in relevant industrial sectors and the growing urgency of greener industrial processes. However, the use of biosurfactants on a large scale is still limited by competitive production costs. Consequently, the imminent replacement of synthetic materials by biosurfactants is not realistic, but a partial and progressive introduction of biosurfactants is more likely to occur in small quantities via innovative formulations that will play essential roles in the transition from the petrochemical industry towards the circular economy.

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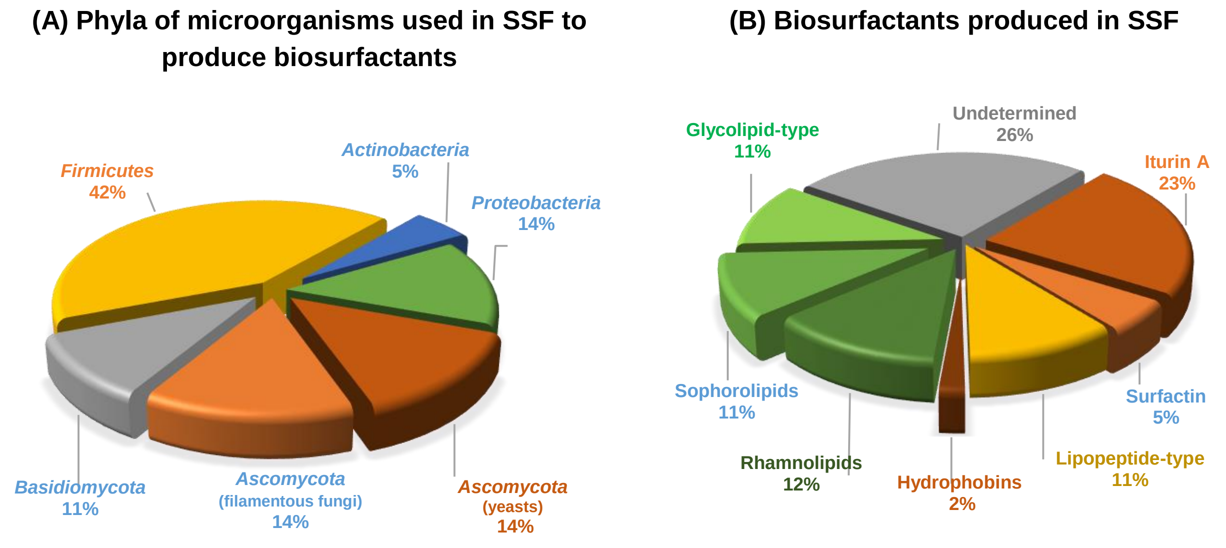
Table 1. Classification of surfactants by origin, ionic status, and hydrophilic-lipophilic balance (HLB).

Category			**Example**
Origin	synthetic		nonylphenol ethoxylates
	oleochemical		lauryl alcohol ethoxylates
	biosurfactants		glycolipids
Ionic status	ionic	cationic (+)	ammonium salts
		anionic (-)	lauryl sulfates
		zwitterionic (+/-)	betaines
	non-ionic		oxirane and 2-methyoxirane copolymers
HLB	01 – 03		antifoaming agents
	03 – 08		w/o emulsifiers
	07 – 10		wetting agents
	08 – 16		o/w emulsifiers
	13 – 16		detergents
	16 – 19		solubilizing agents

Table 2. Producer microorganisms, biosurfactants, solid media and type of reactor for known SSF.

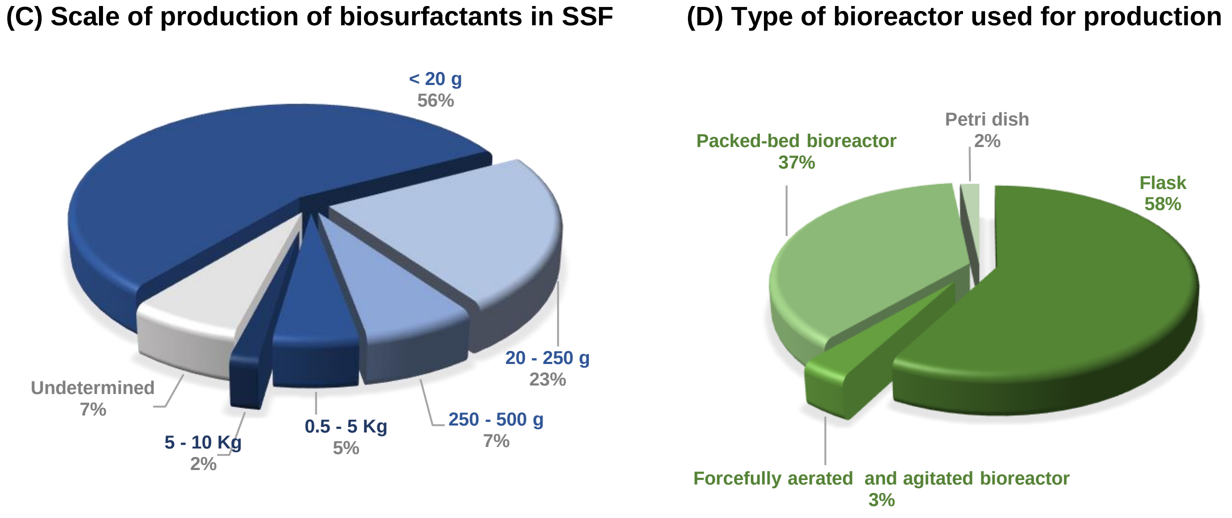
Microorganism	**Type of BS**	**Complemented solid medium**	**Bioreactor**	**Reference**
Aspergillus fumigatus	Undetermined	Defatted rice bran and husk and diesel oil	Flask	(Martins et al., 2009)
		Rice bran	Flask	(Castiglioni et al., 2013)
Aspergillus niger	Undetermined	Wheat bran, corncob and sugarcane molasse	Flask	(Kreling et al., 2020)
		Banana stalk powder		(Asgher et al., 2020)
Bacillus amyloliquefaciens XZ-173	Surfactin	Soybean flour and rice straw	Flask	(Zhu et al., 2012)
			Forcefully aerated and agitated bioreactor (9 kg)	(Zhu et al., 2013)
Bacillus cereus SNAU01	Lipopeptide	Peanut oil cake	Flask	(Nalini et al., 2016)
*B*acillus *subtilis* DM-03	lipopeptides	Potato peels	Flasks	(Das and Mukherjee, 2007)
Bacillus subtilis NB22	Iturin A	Okara	8 L Bottle (3 kg)	(Ohno et al., 1996)
Bacillus subtilis RB14-CS	Iturin A	Okara	Flask	(Mizumoto and Shoda, 2006)
Bacillus subtilis SPB1	Lipopeptides	Tuna fish flour and potato waste flour	Flask	(Mnif et al., 2013)
Bacillus subtilis iso 1	Iturin A	Defatted soybean meal, wheat bran and rice husk	Column	(Piedrahíta-Aguirre et al., 2014)
Bacillus subtilis TrigorCor 1448	Iturin A, fengycin	Wheat middlings	Packed-bed bioreactor	(Pryor et al., 2007)
Candida guilliermondii	Undetermined	Okara	Flask	(Sitohy et al. 2010)

Candida tropicalis	Undetermined	Instant noddle waste	Flask	(Ribeaux et al., 2020)
Nocardiopsis sp. MSA13A	Undetermined	Treated molasses from distillery	Flask	(Kiran et al., 2014)
Nocardiopsis lucentensis MSA04	Glycolipids	Wheat bran	Flask	(Kiran et al., 2010)
Pleurotus ostreatus	Undetermined	Sunflower seed shell and sunflower seed oil	Flask	(Velioğlu and Ürek, 2016)
Pleurotus ostreatus	Hydrophobin like proteins	Sesame and coconut oil cake	Flask	(Kulkarni et al., 2020)
Pseudomonas aeruginosa IRMD-2010	Rhamnolipids	Oil-corn germ meal and corn bran	Packed-bed bioreactor	(Ranjbar and Hejazi, 2019)
Pseudomonas aeruginosa UFPEDA 614	Rhamnolipids	Sugarcane bagasse and corn bran	Flask	(Camilios-Neto et al., 2011)
Pseudomonas aeruginosa RG18	Undetermined	Rapeseed meal, wheat bran and glycerol	Flask	(Wu et al., 2017)
Pseudomonas aeruginosa SS14	Rhamnolipid	Rice distillers dried grain	Flask	(Borah et al., 2019)
Serratia rubidaea SNAU02	Rhamnolipid	Mahua oil cake	Flask	(Nalini and Parthasarathi, 2014)
Starmerella bombicola	Sophorolipids	Polyurethane foam impregnated with molasses and stearic acid	Packed-bed bioreactor	(Jiménez-Peñalver et al., 2018)
		Hygienised digestate supplemented with external sugar and fat sources		(Cerda et al., 2019)
		Winterization oil cake, sugar beet molasses		(Jiménez- Peñalver et al., 2020)
Starmella bombicola ATCC 22214	Sophorolipids	Winterization oil cake, sugar beet molasses and wheat straw	Packed-bed bioreactor	(Jiménez-Peñalver et al., 2016)
		Winterization oil cake, sugar beet molasses and wheat straw		(Rodríguez et al., 2020)
Trametes versicolor CECT 20817	Undetermined	Two-phase olive mill waste, wheat bran and olive stones	Flasks	(Lourenço et al., 2018)



(A) Phyla of microorganisms used in SSF to produce biosurfactants

(B) Biosurfactants produced in SSF



(C) Scale of production of biosurfactants in SSF

(D) Type of bioreactor used for production

Figure 1. Analysis of the scientific literature involving biosurfactants production using SSF: A, phylum of the producing microorganism; B, class of obtained biosurfactants; C, scale of production (in g of solid medium); D, type of bioreactor employed to perform the SSF.

Declaration of interest

All authors declare no financial of personal with any organization that could influence this work.