



Bio-based rhamnolipids production and recovery from waste streams: Status and perspectives

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HIGHLIGHTS

- Rhamnolipid can be recovered from waste streams.
- The major stumbling block in rhamnolipid production is cost of production.
- Various applications of Rhamnolipid have been explained.
- Summarised opportunities for research innovations in bio-based rhamnolipids field.

GRAPHICAL ABSTRACT

ARTICLE INFO

Keywords:

Rhamnolipid
Scale-up process
Remediation
Enhanced oil recovery
Oily waste
Agro-industrial waste

ABSTRACT

Bio-based rhamnolipid production from waste streams is gaining momentum nowadays because of increasing market demand, huge range of applications and its economic and environment friendly nature. Rhamnolipid type biosurfactants are produced by microorganisms as secondary metabolites and have been used to reduce surface/interfacial tension between two different phases. Biosurfactants have been reported to be used as an alternative to chemical surfactants. *Pseudomonas* sp. has been frequently used for production of rhamnolipid. Various wastes can be used in production of rhamnolipid. Rhamnolipids are widely used in various industrial applications. The present review provides information about structure and nature of rhamnolipid, production using different waste materials and scale-up of rhamnolipid production. It also provides comprehensive literature on various industrial applications along with perspectives and challenges in this research area.

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<https://doi.org/10.1016/j.biortech.2020.124213>

Received 2 September 2020; Received in revised form 26 September 2020; Accepted 29 September 2020

Available online 6 October 2020

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1. Introduction

Surfactants are amphiphilic molecules that help to reduce interfacial tension between two different phases (solid–liquid, air–liquid and liquid–liquid) and allow them to mix and interact more easily (Jiménez-Peñalver et al., 2019; Conceição et al., 2020). Based on surface properties and chemical structure, surfactants can act as wetting agents, dispersants, detergents, foaming agents and emulsifiers (Varjani and Upasani, 2017b; Moshtagh et al., 2018). Surfactants are used in almost every product of daily life from which half of the total production is used in food, textiles, cosmetics, mining, pharmaceuticals, agriculture, etc. and other half is used in laundry and household detergents (Renterghem et al., 2018; Jiménez-Peñalver et al., 2019).

Biosurfactants are surface-active agents produced by a wide range of microorganisms (fungi, bacteria, yeast) as secondary metabolites (Díaz De Rienzo et al., 2016; Kourmentza et al., 2017). Biosurfactant producing microorganism and the yield has been narrated in Table 1. Biosurfactants can be classified based on their molecular weight, chemical structure and organisms that produce them. Fatty acids, neutral lipids and phospholipids; glycolipid, particulate and polymeric biosurfactants; lipoproteins and lipopeptides are classified based on their chemical structure (Moshtagh et al., 2018). Based on molecular weight, biosurfactants classified into two major groups (a) high molecular weight biosurfactants and (b) low molecular weight biosurfactants. Surface properties of biosurfactants vary due to the presence of different chemical structures (Jiménez-Peñalver et al., 2019). Biosurfactants are alternative to synthetic surfactants due to (i) cost effective production from waste materials or renewable feedstock; (ii) contain great environmental compatibility, low toxicity and biodegradable; and (iii) shown stable activity at extreme temperature, pH and salinity (Henkel et al., 2017; Varjani and Upasani, 2017b; Jiang et al., 2019; Wang et al., 2020).

Table 1
Biosurfactant producing microbes.

Sr. No.	Biosurfactants	Microbial culture	Yield	References
1	Sophorolipid	<i>Starmerella ombicola</i>	115.2 g/L	Kaur et al., 2019
		<i>Candida albicans</i> SC5314 and <i>Candida glabrata</i> CBS138	–	Gaur et al., 2019b
		<i>Candida bombicola</i>	623 g/L	Dolman et al., 2017
		<i>Starmerella bombicola</i>	26 g/L	Shah et al., 2017
			21 g/L	
			19 g/L	
		<i>Cutaneotrichosporon mucoides</i> UFMG-CM-Y6148	0.167 g L ⁻¹ h ⁻¹	Marcelino et al., 2019
		<i>Starmerella bombicola</i>	–	Huang and Wages, 2016
2	Rhamnolipid	<i>Pseudomonas aeruginosa</i> DAB	17.3 g/L	He et al., 2017
		<i>Pseudomonas aeruginosa</i> KVD-HR42	5.90 ± 2.1 g/L	Deepika et al., 2016
		<i>Pseudomonas aeruginosa</i> PAO1	0.43 g/L	Radzuan et al., 2017
			–	Wang et al., 2019
3	Trehalose lipids	<i>Rhodococcus qingshengii</i> FF	7.97 g/L	Delegan et al., 2020
		<i>Gordonia</i> sp. 1D	–	Mei et al., 2016
		<i>Pseudomonas fragi</i> ATCC 4973	2.89 g/L	
		<i>Rhodococcus erythropolis</i>	25 g/L	Patil and Pratap, 2018
4	Ornithine lipid	<i>Pseudomonas aeruginosa</i>	–	Lewenza et al., 2011; Kim et al., 2018
		<i>Thiobacillus thiooxidans</i>	–	Roy, 2017

According to Jiménez-Peñalver et al. (2019) the global turnover of surfactants in 2016 was US\$31 Billion and by 2024 it is expected to grow US\$40 Billion. Surfactants have been used in soil remediation, degradation of crude oil, wastewater treatment, etc. (He et al., 2020). 344 thousand tons of biosurfactants were globally sold in 2013 and by 2020 it is expected to reach 461 thousand tons. Additionally, in 2016 the global market of biosurfactants was estimated at US\$3.99 billion and is expected to reach US\$5.52 billion by 2022 (Singh et al., 2018; Wang et al., 2018, 2020).

Most common biosurfactants are glycolipids and are formed of saccharides (mono, di, tri or tetra) of glucose, rhamnose, mannose or galactose that are attached to aliphatic acids (long-chain) with an ether or ester linkage. Most studied class of biosurfactants are rhamnolipids, which are anionic glycolipids formed of units of β – hydroxyalkanoic acids and rhamnose residue (Pérez-Armendáriz et al., 2019). Literatures are available that show production of rhamnolipid using various waste materials such as refinery, petroleum, fruit, dairy, agricultural, bakery and other industrial waste. Waste materials used for the production of rhamnolipids are cost-effective. Rhamnolipids are highly used in various applications that include industrial (detergent, food, pharmaceutical, dairy, etc.), medical, bioremediation, microbial enhanced oil recovery.

The present review intends to expand the literature about production of rhamnolipids from different waste streams. It includes information about nature and chemical structure of rhamnolipids and scale-up of rhamnolipid production. It summarizes perspectives and challenges for research in rhamnolipid production from wastes. Already published literature at various periods have focused on a limited aspect in bio-based rhamnolipid production. However this review provides comprehensive findings pertaining to developments in the topics presented as sections of this paper.

2. Nature and chemical structure of rhamnolipid

Rhamnolipids are a type of glycolipids, low molecular weight and most popular biosurfactant due to their great physicochemical properties (Zhao et al., 2018; Jahan et al., 2019; Varjani and Upasani, 2019; Drakontis and Amin, 2020). It is a diverse group of molecules with more than 60 reported congeners (Tiso et al., 2017). Rhamnolipid name is due to presence of rhamnose moiety, it is generally produced by *Pseudomonas aeruginosa* (Satpute et al., 2017). They contain fatty acid tail (β – hydroxydecanoic acid) with lengths of 8, 10, 12 and 14 carbons and one or two glycosyl head groups (rhamnose moiety) (Elshikh et al., 2017; Henkel et al., 2017; Zhao et al., 2018; Pérez-Armendáriz et al., 2019). Rhamnolipids can be classified structurally based on presence of number of rhamnose group (i) monorhamnolipid and (ii) dirhamnolipid (Elshikh et al., 2017). Growth and environmental conditions influence production of rhamnolipids which can lead rhamnolipids with different degree of unsaturation, degree of branching and length of chain for fatty acids (Drakontis and Amin, 2020). According to Drakontis and Amin (2020) with the use of different concentration of bacterial species, 60 different rhamnolipid homologues and congeners can be produced. Rhamnolipids are more suitable for various industrial applications due to its great surface and biological activities (Zhao et al., 2018; Drakontis and Amin, 2020).

3. Rhamnolipids from various waste streams

Large amount of waste is produced each year by restaurants, houses and industries (Mishra et al., 2020). Improper disposal of waste can cause various environmental issues (Pérez-Armendáriz et al., 2019). Waste like oil, petroleum, agricultural and food can be used to produce various biosurfactants (rhamnolipids and sophorolipids, etc.) with help of various microbial cultures (Rajmohan et al., 2020). From all microorganisms, *Pseudomonas aeruginosa* is highly used for producing rhamnolipid because they can survive extreme environmental conditions (Li, 2017; Varjani et al., 2020a).

3.1. Oily waste

Biosurfactants can be produced using industrial wastes such as food, oil refineries and petroleum oily waste as low cost raw material (Müller and Hausmann, 2011). Rhamnolipid production from different oily wastes employing microorganisms is shown in Table 2. Pérez-Armendáriz et al. (2019) have prepared 4 different factorial designs and performed 32 treatments for rhamnolipid production from which the highest rhamnolipid yield was obtained from factorial design 4 and treatment 8. Factorial design 4 contained waste canola oil as a source of carbon and sodium nitrate as a source of nitrogen and produced 3585.31 ± 66.24 mg/L rhamnolipid using *Pseudomonas aeruginosa*. Ōzda et al. (2017) have reported 12.1 g/L production of rhamnolipid

Table 2
Rhamnolipid production from different oily wastes employing microorganisms.

Sr. No.	Organisms	Type of waste	Yield	Reference
1	<i>Pseudomonas aeruginosa</i> PAO1	Palm Fatty Acid Distillate (PFAD)	0.43 g/L	Radzuan et al., 2017
2	<i>Pseudomonas aeruginosa</i> PrhLAB <i>Pseudomonas aeruginosa</i> SG <i>Pseudomonas stutzeri</i> Rh1	Crude glycerol	2.87 g/L 1.98 g/L 0.87 g/L	Zhao et al., 2019
3	<i>Pseudomonas aeruginosa</i> MR01	SOM medium including soybean oil 6% (V/V)	24–36 mg/L	Lotfabad et al., 2017
4	<i>Pseudomonas aeruginosa</i>	Sunflower acid oil	4.9 g/L	Jadhav et al., 2019
5	<i>Pseudomonas aeruginosa</i>	Petroleum oil wastes	2.7 g/L	Mostafa et al., 2019
6	<i>Stenotrophomonas maltophilia</i> IITR87 <i>Ochrobactrum anthropic</i> IITR07 <i>Pseudomonas aeruginosa</i> IITR48	Crude oil	570 mg/L 294 mg/L 270 mg/L	Tripathi et al., 2019
7	<i>Pseudomonas aeruginosa</i> ORA9	Mineral medium with soybean fried oil	2.3 ± 0.8 g/L	Gómez et al., 2017
8	<i>Pseudomonas aeruginosa</i> GS9-119 and <i>Pseudomonas aeruginosa</i> DS10-129	Soybean oil Safflower oil Glycerol	4.31 g/L 2.98 g/L 1.77 g/L	Rahman et al., 2002
9	<i>Pseudomonas aeruginosa</i> LBI	Soybean oil soap-stock	11.7 g/L	Nitschke et al., 2009
10	<i>Pseudomonas aeruginosa</i> AB93066	Cooking oil fume condensates	12.3 g/l	Wu et al., 2019
11	<i>Pseudomonas aeruginosa</i> NCIM 5514	Bushnell-Hass medium with 1% crude oil	3.146 ± 0.087 g/L	Varjani and Upasani, 2019
12	<i>Pseudomonas aeruginosa</i>	Kitchen waste oil	2.47 g/L	Chen et al., 2018
13	<i>Pseudomonas aeruginosa</i> estA	Crude glycerin	17.6 g/L	Dobler et al., 2020
14	<i>Pseudomonas aeruginosa</i> #112	Oil mill wastewater	5.1 g/L	Gudiña et al., 2016
15	<i>Pseudomonas aeruginosa</i>	Olive mill (OMW) waste	29.5 mg/L	Ramírez et al., 2016
16	<i>Pseudomonas aeruginosa</i> AMB AS7	Coconut oil sludge and oil cake	5.53 g/L	Samykanu and Achary, 2017
17	<i>Pseudomonas aeruginosa</i> J4	Diesel Kerosene	1300 mg/L 709 mg/L	Wei et al., 2005

using *Pseudomonas aeruginosa* OG1 in the presence of 10 g/L ram horn peptone (RHP) and waste frying oil. Sood et al. (2020) have reported 19.22 g/L rhamnolipid production in basal medium amended with rice bran oil and 21.77 g/L rhamnolipid production in glycerol amended Luria Bertani (LB) medium using *Pseudomonas aeruginosa* CR1.

3.2. Agro-industrial waste

High content of lipids and carbohydrates are present in the agro-industrial waste hence it can be used to produce biosurfactants (Nitschke et al., 2004). Published literature shows production of rhamnolipid from various wastes such as oil mill wastewater (Gudiña et al., 2016), paneer whey (Patowary et al., 2016), barley pulp (Kaskatepe et al., 2017), orange peel (George and Jayachandran, 2008) and cassava waste (Costa et al., 2009; Tianran et al., 2019), etc. Rhamnolipid production from different agro-industrial and other wastes employing microorganisms is shown in Table 3. Joy et al. (2019) have reported 4.13 ± 0.12 g/L rhamnolipid production after 192 h using *Achromobacter* sp. PS1 from lingo-cellulosic residues (sugarcane bagasse, rice-straw and wheat-straw). Patowary et al. (2016) have reported production of 2.7 g/L rhamnolipid using paneer whey as a source of carbon with help of *Pseudomonas aeruginosa* SR17 which was increased to 4.8 g/L when media was supplemented with 2% mineral salts and glucose.

3.3. Other wastes

Apart from above other wastes can also be used as a source of carbon for production of rhamnolipid such as bakery waste, shrimp shell waste, rice grains, fruit industrial waste, whey waste, dairy waste, etc. Patowary et al. (2018) have reported 11.56 g/L rhamnolipid from bakery waste supplemented with mineral salt media using *Pseudomonas aeruginosa* PG1. Kadam and savant (2019) have isolated *Pseudomonas stutzeri* L1 from marine fishing port located in Mumbai and produced 4–6 g/L rhamnolipid using shrimp shell waste. Borah et al. (2019) have produced 14.87 g/L rhamnolipid by providing rice based distillers dried grains with solubles (rDDGS) as a carbon source to *Pseudomonas aeruginosa* SS14.

4. Scale-up of rhamnolipid production

Biosurfactants possesses important advantages over chemical

Table 3
Rhamnolipid production from different agro-industrial and other wastes employing microorganisms.

Sr. No.	Organisms	Waste	Yield	Reference
1	<i>Pseudomonas aeruginosa</i> SR17	Paneer whey	2.7 g/L	Patowary et al., 2016
2	<i>Pseudomonas azotoformans</i> AJ15	Agro industrial waste	1.6 g/L	Das and Kumar, 2018
3	<i>Pseudomonas aeruginosa</i> ATCC 9027 <i>Pseudomonas pachastrellae</i> LOS20 <i>Pseudomonas putida</i> IBS036	Barley pulp	9.3 g/L 8.5 g/L 6.7 g/L	Kaskatepe et al., 2017
4	<i>Pseudomonas aeruginosa</i> MTCC 2297	Orange peel	9.18 g/L	George and Jayachandran, 2008
5	<i>Pseudomonas aeruginosa</i>	Cassava wastewater	660 mg/L	Costa et al., 2009
6	<i>Pseudomonas aeruginosa</i> ATCC 10,145	Cassava residues	18.28 g/L	Tianran et al., 2019
7	<i>Achromobacter</i> sp. (PS1)	Lignocellulosic residues	4.13 ± 0.12 g/L	Joy et al., 2019

surfactants. However, their production is still at laboratory level and needs further examination for industrial scale production. Good scale-up method used for production of rhamnolipid can decrease material cost as well as labour intensity (Amani, 2018). Production of rhamnolipid at large scale requires following steps (i) Microbial growth: rhamnolipid producing bacterial growth on petri plate containing growth media, (ii) Shake flask (small scale): bacterial growth used to test the production of rhamnolipid and study optimization production, (iii) Small scale fermenter (laboratory scale): bacterial culture than inoculated into the laboratory scale fermenter, and (iv) Large fermenter (pilot scale or industry level): used to produce huge amount of rhamnolipid developed at laboratory scale (Fedorenko et al., 2015; Li et al., 2015; Chong and Li, 2017; Heryani and Putra, 2017; Salea et al., 2017; Ye et al., 2018; Barros et al., 2019). This scale-up process is necessary for large scale product manufacturing, since every process varies in the condition which affects the production.

Gong et al. (2020) have performed scale-up for production of rhamnolipid using air pressure pulsation solid-state fermentation (APP-SSF) and achieved 39.8 g/L rhamnolipid production in a 30L APP-SSF fermenter using 10% *Pseudomonas aeruginosa* SKY as inoculum, and incubation was performed at 37 °C for 168 h at 50 rpm. Rhamnolipid produced by this method at large-scale contains high productivity, low cost and low impurities of production. Amani (2018) has performed rhamnolipid production experiment using 2.5 L and 20 L bioreactor using *Pseudomonas aeruginosa* MM1011. Maximum production of rhamnolipid (8.3 g/L) was reported in 20 L bioreactor which was 10% better than in 2.5 L bioreactor after 7 days at 37 °C.

5. Applications

Rhamnolipids have found various applications in bioremediation of polluted environments (hydrocarbon, heavy metals, pesticides, dyes and plastics etc), microbial enhanced oil recovery, agricultural, beverages, cosmetics, foods, pharmaceuticals (Singh et al., 2009; Jiménez-Peñalver et al., 2019; Rajmohan et al., 2019; Biselli et al., 2020; Shi et al., 2020; Varjani et al., 2020b). Some rhamnolipids contain antifungal, antiviral and antibacterial properties which make them useful for fighting against infections and diseases (Souza et al., 2017).

5.1. Bioremediation

Biosurfactants are used to intensify the bioremediation process (Varjani et al., 2017; Staninska-Pięta et al., 2019). Rhamnolipid have been used to remediate heavy metals, dyes, pesticides, hydrocarbons, oil spills and contaminated soils, etc. (Varjani, 2017; Patel et al., 2018; Lee and Kim, 2019; Varjani et al., 2019; Wei et al., 2020; Kumar et al., 2020). Rhamnolipids help in remediation process by emulsifying or solubilizing hydrocarbons and modifying bacterial cell surface properties for intensification of interfacial uptake of hydrocarbons (Liu et al., 2018). Bhosale et al. (2019) have reported 92.72% decolorization of methyl violet dye using rhamnolipid functionalized iron oxide nanoparticles (RL@IONPs) as photocatalyst (8 mg) and sodium dodecyl sulfate (SDS) as absorbent (0.12 mg). Rhamnolipid was produced by *Pseudomonas aeruginosa* ATCC 9027 using 10 mL culture medium. Olanmi and Thring (2020) have used rhamnolipid at 500 mg/L concentration for reduction of petroleum hydrocarbons. The maximum petroleum hydrocarbons reduction rate for total petroleum hydrocarbon (TPH) fractions F2 (C10-C16), F3 (C16-C34) and F4 (C34-C50) was 58.5%, 48.4%, 63.5% and 59.8%, respectively for petroleum contaminated soil. J. Chen et al., 2017; W. Chen et al., 2017 have reported 80.21%, 47.85%, 63.54% and 86.87% removal of Cu, Cr, Pb and Cd, respectively using 0.8% rhamnolipid for experiment of 12 h at pH 7.0. Gaur et al. (2019a) produced 1.6 g/L rhamnolipid using *Lysinibacillus sphaericus* IITR51. Rhamnolipid at concentration of 90 mg/L was reported for higher dissolution of γ -hexachlorocyclohexane, β -endosulfan and α -endosulfan up to 1.8, 2.9 and 7.2 folds, respectively than at other

concentrations i.e. 45 mg/L, 60 mg/L, 75 mg/L, 90 mg/L, and 105 mg/L. They have reported application of rhamnolipid for enhanced dissolution and increased bioavailability of pollutants.

5.2. Microbial enhanced oil recovery

Microbial enhanced oil recovery (MEOR) has been used as a tertiary process when primary and secondary treatment processes are no longer able to recover oil (Varjani and Upasani, 2016a). Rhamnolipids (biosurfactants) are key elements in oil recovery process due to their tolerant capability to withstand extreme environmental conditions, nontoxic and eco-friendly nature (Varjani and Upasani, 2016b; Das and Kumar, 2019; Elakkiya et al., 2020; Wei et al., 2020). Elakkiya et al. (2020) produced rhamnolipid (0.34 mg/mL) from cassava solid waste using *Pseudomonas aeruginosa* TEN01 and achieved highest oil recovery 14.28% using biosurfactant based silver nanoparticle which was similar to chemically produced silver nanoparticle. Haloi et al. (2020) have used *Pseudomonas* sp. TMB2 (KX661384) for production of 2.8 ± 0.5 g/L rhamnolipid and reported overall 27.11% oil recovery efficiency with an additional 16.7% recovery after secondary brine flooding from rock plug NH1. Cãmara et al. (2019) have produced rhamnolipid using *Pseudomonas aeruginosa* for oil recovery. They have reported $11.91 \pm 0.39\%$ improved advanced recovery by microorganisms from a total recovery factor of $50.45 \pm 0.79\%$.

5.3. Medical applications

Rhamnolipid possesses antimicrobial properties and can be used as biopesticides. Rhamnolipids are more effective against gram-positive bacteria than gram-negative bacteria due to presence of outer membrane in gram-negative bacteria which works as a protective layer (Murugan et al., 2018; Naughton et al., 2019). Literatures are available that shows various applications of rhamnolipid biosurfactant in the field of biomedicine as anticancer, antimicrobial, antitumor, antiviral, immune modulators and wound treating agent (J. Chen et al., 2017; W. Chen et al., 2017; Kumar and Das, 2018). Yi et al. (2019) have prepared nanoparticles of rhamnolipid using flax seed oil and loaded them with model drug pheophorbide a (Pba). They have used photodynamic *in vivo* therapy and rhamnolipid nanoparticle to achieve complete suppression of tumor. J. Chen et al., 2017; W. Chen et al., 2017 have reported antimicrobial activity of rhamnolipid mixture produced by *P. aeruginosa* sp.

Niaz et al. (2019) have performed inhibitory activity assay with rhamnolipid at minimal inhibitory concentrations (MICs) at 5, 10, 50 and 1000 $\mu\text{g/mL}$ against *P. aeruginosa*, *S. aureus*, *E. coli* and *L. monocytogenes*, respectively. Results propose that all foodborne pathogens used in study were sensitive to rhamnolipid at very low concentrations except *L. monocytogenes*. They have reported 80% decrease in generation of biofilm biomass when treated with nisin-loaded rhamnosome nano-vesicles (RSNVs). Gaur et al. (2019b) have reported production of rhamnolipid by *Lysinibacillus sphaericus* IITR51. It showed antibacterial activity against pathogenic bacteria such as *Bacillus subtilis* MTCC 441, *Aeromonas hydrophila* MTCC 1143, *Pseudomonas aeruginosa* MTCC 424, *Vibrio cholerae* MTCC 3904, *Escherichia coli* MTCC 723 and *Klebsiella pneumoniae* MTCC 109. Gaur et al. (2020) have produced 2.5 and 1.8 g/L rhamnolipid using *Planococcus rifietoensis* IITR53 and *Planococcus halotolerans* IITR55 and reported antibacterial activity against *Yersinia enterocolitica* MTCC 859, *Vibrio cholerae* MTCC 3904, *Clostridium perfringens* MTCC 450, *Streptococcus mutans* MTCC 497, *Salmonella typhimurium* MTCC 98 and *Streptococcus oralis* MTCC 2696.

5.4. Other applications

Rhamnolipid is a low foaming agent. Its foaming capability can be increased by the combination with alpha olefin sulfonate (AOS) or

sodium lauryl ether sulfate (SLES). Due to its low foaming capability rhamnolipid based liquid detergents can be used for washing machines as laundry detergents (Jadhav et al., 2019). Around 5,00,000 tons of emulsifiers are produced each year for food industry applications (Gudiña and Rodrigues, 2019). Rhamnolipids are used in food industries as wetting or foaming agents/stabilizers (to support stability of food ingredients) and emulsifiers (for texture and consistency of food), thereby it helps in increasing shelf life of food products.

6. Research needs and future directions

Bio-based surfactant production from waste streams would be a favourable way for resource recovery. However, developments need to be carried out for enabling economically & ecologically feasible production and recovery technologies. Rhamnolipid biosurfactant can be produced by various microorganisms using different industrial wastes/raw materials; however, it requires further examination for scale-up to produce rhamnolipid. Many researchers have used *Pseudomonas* sp. for production of rhamnolipid (Li, 2017; Varjani and Upasani, 2016c, 2019; Das and Kumar, 2018). Rhamnolipid has various industrial applications but it is limited due to its high cost for production (Benrebah et al., 2007). Different microorganisms can be used to produce biosurfactants with different structures and characteristics having different application efficiency (Varjani and Upasani, 2017a; Dell'Anno et al., 2018). Carbon sources and fermentation conditions can affect yield of rhamnolipid (Li, 2017). There are many bottlenecks that are required to be resolved to support biosurfactant production and recovery from waste streams as an advantageous option for resource recovery. After production, recovery would certainly add to the total cost for biosurfactant production using waste streams. It is necessary to recover maximum surfactant produced from waste streams. For this care should be taken in order not to have too much cost which would not be feasible economically. The challenge would be selection of cost-effective method for recovery which would lead to maximum biosurfactant recovery at minimal cost.

- Future research should examine various factors that may affect rhamnolipid production.
- For application of biosurfactants in remediation of polluted sites or enhanced oil recovery in depth efficiency of rhamnolipid type biosurfactants should be studied. Application of rhamnolipid should be studied under extreme environmental conditions.
- The quality and production yield of rhamnolipid can be improved using genetic engineering.
- New technologies and strategies are required to improve yield and decrease production costs. There is a need for in depth cost-benefit analysis for biosurfactant recovery methods.
- Rhamnolipid production using wastes as raw materials need to be performed at large scale to support waste valorisation concept.

7. Conclusions

Production of bio-based rhamnolipids from waste streams is gaining interest of researchers. Rhamnolipids have found applications in various industries such as petroleum, agriculture, cosmetics and medicine. Systematic research is required to be performed to study the effect of operational conditions for rhamnolipids production and recovery from wastes. There is a need for in depth cost-benefit analysis for recovery of biosurfactants. Large scale production and purification of rhamnolipids increase cost which can be reduced using waste materials for its production. It is opined that employing wastes as resource would make the process more environmental friendly and cost effective.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence

the work reported in this paper.

Acknowledgement

Authors are grateful to the management of Gujarat Pollution Control Board, Gandhinagar, Gujarat, India for providing necessary facilities to perform literature review presented in this paper.

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