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Review

The Role of Biosurfactants in the Continued Drive for Environmental Sustainability

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Abstract: Biosurfactants are microbial products that have been increasingly researched due to their many identified advantages, such as low toxicity and high activity at extreme temperatures, but more importantly, they are biodegradable and compatible with the environment. Biosurfactants are versatile products with vast applications in the clean-up of environmental pollutants through biodegradation and bioremediation. They also have applications in the food, pharmaceutical, and other industries. These advantages and wide range of applications have led to the continued interest in biosurfactants. In particular, there is a growing discussion around environmental sustainability and the important role that biosurfactants will increasingly play in the near future, for example, via the use of renewable by-products as substrates, waste reduction, and potential reuse of the treated waste. This has resulted in increased attention on these microbial products in industry. Research highlighting the potential of biosurfactants in environmental sustainability is required to drive efforts to make biosurfactants more viable for commercial and large-scale applications; making them available, cheaper and economically sustainable. The present review discusses the unique relationship between biosurfactants and environmental sustainability, especially the role that biosurfactants play in the clean-up of environmental pollutants and, therefore, increasing environmental protection.

Keywords: biosurfactants; sustainability; environmental pollution; bioremediation; biodegradation

1. Introduction

Biosurfactants are environmentally friendly microbial products with confirmed abilities for removing petroleum hydrocarbon contaminants from drill cuttings and hydrocarbon-contaminated waste streams (such as soil and refinery wastewater). They are highly favorable because of their high biodegradability, low environmental impact, low toxicity, high specificity, high stability and activity at extreme conditions, wide range of industrial applications, and structural diversity [1–9].

Biosurfactants are a diverse and heterogeneous group of microbial metabolites synthesized by bacteria, yeasts, and fungi [10]. Bacterial biosurfactants rhamnolipid and surfactin derived from *Pseudomonas* and *Bacillus* genera, respectively, are the most extensively studied biosurfactants [11]. According to Desai and Banat [6] and Mulligan [10], biosurfactants are classified into six groups based on chemical structure: (i) glycolipids, (ii) phospholipids, (iii) lipopeptides and lipoproteins, (iv) fatty acids, (v) neutral acids, and (vi) polymeric and particulate surfactants [8,12,13]. As a result of their functional and structural diversity, biosurfactants are an attractive group of molecules with the potential to be used in numerous biotechnological and industrial applications [14,15].

Biosurfactants are used for several important roles—namely, emulsification, dispersal, solubilization, mobilization, wetting, surface tension reduction, formation of micelles and foam formation—due to their ability to partition into different interfaces: liquid/solid, liquid/gas, liquid/liquid. The use of biosurfactants in these roles is possible because of their amphiphilic properties; they contain both hydrophobic and hydrophilic molecules [14,16–20]. Biosurfactants thus have remarkable potential applications in environmental restoration [5] and have also been described as one of the most promising and versatile process chemicals [20,21]. Biosurfactants are considered eco-friendly [14]. Their ecological acceptance was identified by Benincasa et al. [22] as being probably their most important advantage. Biosurfactants are aptly and rightfully described as the "multifunctional biomolecules/materials of the 21st century" [1,16]. Attention given to biosurfactants has, therefore, increased as the importance of sustainable production processes and sustainability initiatives overall are becoming more appreciated and rising to the top of the agenda of many companies [18,23]. The increased attention given to biosurfactants is also linked to the ongoing emphasis on societies that are sustainable and harmonized with the global environment [20], as well as the need for environmental protection [24]. From the literature, it appears that, while references have been made to sustainable processes of biosurfactant production, the impact and role of biosurfactants in the increasingly popular subject of sustainability has not been fully explored. The present review does not attempt to expound on the numerous applications of biosurfactants, but rather it attempts to focus through the sustainability lens on the applications of biosurfactants in reducing hydrocarbon-based environmental pollution.

2. Environmental Pollution, Biosurfactants, and Sustainability

Environmental pollution is and continues to be an ongoing concern. With public awareness on the rise and as firmer environmental legislations are being passed, there is more focus on the need to develop innovative ways to tackle the problem. The search for and development of appropriate technologies that will help clean up environmental contaminants—both organic and inorganic, such as hydrocarbons—is influenced by increasing public awareness [14]. In addition to the various health concerns and negative ecological impacts, environmental pollution has increasingly been linked to waste management, sustainability, and climate change. Research on the applications of biosurfactants in mitigating environmental pollution started over two decades ago, but it seems imperative to shed light on how this ties into the overwhelming and growing topic of sustainability. Makkar and Cameotra [5] highlighted the importance of the "reduce, reuse and recycle" concept for waste management due to concerns over the rate of generation of hazardous and non-hazardous wastes, and the inherent cost of treating and disposing of it. The authors emphasized the need for cost-effective biosurfactant production to address these growing concerns.

Global efforts to reduce greenhouse gas emissions are evident in the various international climate change treaties. The Conference of the Parties (COP21) is a case in point, in which several countries agreed to put the world on a more sustainable path by ensuring that the global mean temperature does not rise above 2 °C compared to pre-industrial levels [25,26]. Biosurfactants according to Rahman and Gakpe [27] have an important role to play in reducing carbon dioxide emissions, a major greenhouse gas, from the atmosphere. Views on sustainability recognize the need to balance environmental, economic, and social concerns, considering their long-term impact [28,29]. Environmental sustainability is defined in various ways in the literature. The present article adapts the definition of a sustainable system given by Abu-Goukh et al. [29] as one that "maintains its own viability by using techniques that allow for continual reuse."

Concerns on environmental sustainability include not only climate change but also pollution and natural resources depletion. These concerns stress the need to develop management solutions and tools embracing environmental quality, one of the three identified pillars of sustainability; the other two being social justice and economic prosperity [30]. Furthermore, sustainability is being argued as the correct way of viewing the world and making good decisions. The argument posits that industrial operations that are ecologically sound are inevitable due to the "rightness" of sustainability. This perspective considers sustainability as a growing phenomenon and a game changer for industry [28]. More important is the quest to harness and apply science and technology in transitioning to sustainability, a larger movement referred to as 'sustainability science' [31]. Thus, the search for biosurfactants as alternatives to synthetic surfactants is attributed to the focus on sustainability [32].

Biosurfactants also have a significant advantage in terms of resource usage as their counterparts, 'ordinary' surfactants, are characterized as contributing to the depletion of petrochemical resources, which are non-renewable [23]. In addition, these synthetic counterparts bioaccumulate and become hazardous to the environment [27]. When compared with conventional surfactants, biosurfactants also show higher effectiveness and efficiency due to their excellent surface activity. At lesser concentrations, the surface tension they produce is lower—an indication of the efficiency of biosurfactants [33]. According to Gavrilescu and Chisti [34], a product is deemed sustainable if it performs well in comparison to its conventional counterparts, shows less toxicity, is more durable, can be recycled, and is biodegradable once its usefulness is exhausted. Biosurfactants fulfill all these conditions and more. There is, therefore, an increased momentum for research on biosurfactants due to increased environmental awareness and new regulations [3].

3. Petroleum Wastes and Environmental Pollution

Increasing societal demand, government regulations, and concerns on environmental sustainability relating to how hydrocarbons are stored and transported have led to the development of new and innovative storage and pipeline technologies, as well as remediation technologies that are environmentally compatible [1,2,5]. In the oil and gas exploration industry, two major waste streams that have been identified as major sources of environmental pollution are drilling wastes or drill cuttings and hydrocarbon-contaminated soils.

3.1. Drilling Wastes

The majority of wastes generated from drilling operations are attributed to drill cuttings [35]. Drill cuttings are comprised of soil, silt, rock fragments, and pulverized materials excavated by the drill bit. Following the separation of solids, the cuttings are collected for further treatment or management [36,37]. Drill cuttings are significant by-products of oil and gas operations and pose a major waste management problem owing to the volume generated. By volume, drill cuttings discharges are the second largest waste generated from oil and gas activities following produced water [38,39]. Furthermore, drill cuttings are potential sources of oil pollution due to their organic and inorganic contaminants content. Drill cuttings with oil-based drilling fluids are characterized by the presence of large quantities of crude oil by-products and chemicals, which can be highly toxic to humans and nature [36,37,40–42]. When disposed into landfills improperly, the toxic contaminants in drill cuttings leach into the surrounding environment, groundwater, rivers, and streams, which potentially has a detrimental effect on humans and the ecosystem. In achieving the objective of sustainable development, it is pivotal that these waste streams are managed appropriately and in ways that limit environmental contamination and pollution [43].

3.2. Hydrocarbon-Contaminated Soils

Certain activities relating to the oil and gas industry—which includes oil spills from exploration and transportation, pipeline leakages, leakages from underground storage tanks in service stations and aboveground storage tanks in industries, as well as release of oil that occurs accidentally during drilling operations—result in the accumulation of hydrocarbon-contaminated soils [8,32,44,45]. Another rather unfortunate source of this form of environmental pollution has also been identified as the intentional discharge of oil wastes into soils and water bodies [41]. Hydrocarbon-contaminated soils invariably become another major source of environmental pollution, particularly in instances of mishandling, inadequate treatment, and or improper disposal. Hydrocarbon contamination occurs in all stages of crude oil production, processing, and use [41]. Essentially, whether a country produces oil and gas or not, the fact that hydrocarbons serve as an energy source for the country makes environmental pollution a major area of concern. Thus, environmental pollution is not a localized or country-specific problem, but rather a global issue. Therefore, contamination of the environment by hydrocarbons from contaminated soils remains a contemporary concern [1].

3.3. Way Forward

The call for innovative remediation processes that are not only environmentally friendly but which also have a low carbon footprint brings bioremediation—with the application of—to the forefront as a treatment process for drill cuttings and hydrocarbon-contaminated soils. While the characteristics of each waste stream and relevant regulatory requirements are to be considered, the eventual goal regarding sustainability is to have treated products that can be reused. The possibility of reuse reduces the burden of disposal of drill cuttings and hydrocarbon-contaminated soils into the environment [46]. With regards to combating environmental pollution caused by petroleum wastes, the application of biosurfactants includes oil residue removal from storage tanks, microbial enhanced oil recovery (MEOR), oil spill clean-up, as well as soil and water bioremediation, amongst others. Essentially, effective biosurfactants have a role to play in sustainability as they have the inherent benefit of having a low impact on the environment [1,32].

Drill cuttings, hydrocarbon-contaminated soils, and other waste streams related to the oil and gas industry will collectively be referred to as 'petroleum wastes' in the present review.

4. Treatment Techniques of Petroleum Wastes

Numerous disposal and treatment techniques for petroleum wastes have been identified in the literature. Various countries have recommended guidelines to ensure that these waste streams are treated and detoxified before discharge and disposal [47]. These treatment methods range from chemical to physical and biological methods [24]. Physical treatment methods (such as incineration, thermal desorption, and solidification/stabilization), biological treatment methods (such as surfactant-enhanced washing, bioremediation, and phytoremediation), and chemical treatment methods have been described in the literature [40,47]. While physical and chemical treatment methods (or physicochemical methods) are fast, they result only in the transfer of contaminants to a different environmental medium and could result in the production of harmful by-products [32].

The management of waste, in general, has become merged with the three notions of responsibility, reliability, and continuity. These notions make it essential that in treating each type of waste stream, all related consequences for the environment must be thoroughly considered [48]. The process of hydrocarbon biodegradation is a vital technique in the remediation of contaminated sites due to its prominent ecological significance [49]. Thus, the selection of a waste treatment technique should be premised on complete removal of contaminants from polluted sites and the prevention of further contamination to ensure environmental sustainability. This stance has attracted the attention of researchers over the years in employing bioremediation and biodegradation as sustainable treatment processes for petroleum wastes.

5. Bioremediation, Biodegradation, and Biosurfactants

Bioremediation is a biological technique or process used to reduce contaminants in the environment. It involves the transformation or mineralization of organic contaminants by living organisms, leading to substances that are less harmful [17,33]. By the process of bioremediation, contaminants are converted into water and carbon dioxide (CO_2) using the natural degradation capabilities of microorganisms [2,16]. The produced substances subsequently become integrated into the various biogeochemical cycles [17,33]. Hydrocarbon contaminants are, however, not always readily available to microorganisms; the components of the contaminants are bound to soil particles. This reduces their bioavailability and results in poor efficiency of the biodegradation process [2,4,50]. Hence, biosurfactants are produced by microorganisms as secondary metabolites [12,51], particularly when growing on water-insoluble substrates [52,53] such as hydrocarbons. Production of biosurfactants can be either extracellular or as cell-bound molecules [15,51]. Extracellular production of biosurfactants leads to the emulsification of the substrate (i.e., hydrocarbon). On the other hand, biosurfactants produced as part of the cell membrane of the microorganism function in facilitating the passage of substrates through the membrane [6,10]. To this end, the use of biosurfactant-producing microorganisms in the biodegradation of hydrocarbons and biopreparation of polluted sites is considered an effective microbiological treatment method of environmental pollutants [14].

Commercial biosurfactants can also be applied to increase the availability of contaminants and aid the rate of biodegradation [2,16,32,33,54]. The application of biosurfactants for clean-up of environmental pollutants has been explored for their ability to (a) increase the bioavailability of contaminants to microorganisms through bioremediation enhanced with the addition of biosurfactants, and (b) solubilize and mobilize hydrocarbons in soils through biosurfactant-enhanced washing resulting in removal of the contaminants [1,14,55]. These biosurfactant applications differ in the mode of action and the properties of the biosurfactants. The applications are based either on the biosurfactant effects on the metabolic activity of microorganisms or the inherent physicochemical properties of the biosurfactants [33,55]. Mazaheri Assadi and Tabatabaee [56] thus affirmed that the knowledge of the chemical and physical nature of the contaminated area is required if biosurfactants are to be successfully applied in petroleum bioremediation. To ensure commercialization of biosurfactants, the biosurfactants used should also be suitable in terms of the physical and chemical nature of the contaminated sites [33].

6. Other Environmental Applications of Biosurfactants

A review by Marchant and Banat [18] recognize biosurfactants as having the potential to be used as sustainable ingredients in more than a few commercial products. Banat et al. [55] in their review of industrial applications of biosurfactants stated that biosurfactants are mainly applied in oil recovery and processing. The use of biosurfactants is one of the methods that not only allows for the recovery of oil from oily sludge but also allows for the reuse or recycling of the valuable hydrocarbons recovered from the oily sludge. Oily sludge generated from petroleum processing plants is another source of environmental pollution. Chirwa et al. [57] investigated the use of crude biosurfactants in oil recovery from oily sludge in comparison to commercial surfactant. While the rate of recovery was slower with the use of biosurfactants, the effective concentrations of the commercial surfactant used were higher than the crude biosurfactant concentrations. This observation demonstrates the feasibility of biosurfactant application in oil recovery from waste sludge. Sen [58] described in detail the role biosurfactants play in oil mobilization by emulsification in microbial enhanced oil recovery (MEOR). Schaller et al. [59] explored the potential use of surfactin biosurfactant as an agent for enhanced oil recovery and presented results that favored their application and cost-effectiveness. Almeida et al. [60] also studied the potential of 163 bacterial strains in MEOR and demonstrated the potential use of 10 of the bacterial strains in oil recovery. From the results presented, a consortium containing isolates of three *Bacillus* species produced the highest recovery rate of 18%. The ability of one of the bacterial isolates to produce solvents and surfactants amongst other products was attributed to be the likely cause for the additional oil recovery rate observed in the consortium.

In the bigger sustainability picture, the need to treat and stabilize oily sludge prior to disposal is not a choice but a necessity. The recovery of oil from oily sludge before disposal reduces its environmental impact. In addition, the recovered oil also serves as an energy source [57], which has led to the renewed and intensified efforts to treat oily sludge. Of course, with the possibilities highlighted for applications of biosurfactants in previous paragraphs, their usefulness in combating environmental pollution in this area is undoubtable—from an environmental sustainability standpoint.

7. Limitations of Large-Scale Applications of Biosurfactants

Despite the many identified advantages of biosurfactants, a common theme in literature is the inability of biosurfactants to compete commercially with their synthetic counterparts due to the high cost of production and sometimes low yield [20,33,61–65]. As reported by Hazra et al. [66], biosurfactants are 20–30% more expensive than synthetic surfactants, thus impeding their large-scale applications. To address the cost aspects of biosurfactant production, the first point of call is the substrates. The need for cost-effective substrates in the production of biosurfactants is underlined by the cost attributed to the choice of substrate used in the production process. Reports on the cost implication of substrates vary in literature. It ranges from 10–30% of the production cost [21,33,65] to 50% of the final product cost [1,67]. The second point of call is the production process. In various biotechnology processes, purification accounts for a huge part of the production cost. This ranges from 60% [24] to 70–80% [16]. For these reasons, research on biosurfactants is now focused on avenues to optimize their production processes as well as the use of low-cost substrates. This will in no small way minimize the overall cost of production and also lead to the scale-up of industrial production of biosurfactants [55].

In particular, research into avenues to minimize cost and optimize the production process of biosurfactants is intertwined with their potential as agents of sustainability. The need to highlight the economic feasibility of biosurfactant production for commercial applications in the sustainability discussion is validated by the statement, "sustainability is only sustainable when it is profitable" [28].

8. Biosurfactants as Agents of Sustainability

The economics of biosurfactant production for environmental applications and their role in environmental sustainability are linked in two major areas.

8.1. Low-Cost Substrates

Banat et al. [64] and Makkar and Cameotra [5] reviewed the use of renewable substrates in biosurfactant production. These reviews highlight years of research on the use of cheap and non-conventional substrates. Examples of substrates used include agro-industrial wastes, residues from crops, as well as dairy and food-processing by-products. High carbohydrate and high lipid content of agro-industrial products make them very useful as substrates [68]. Luna et al. [1] used agro-industrial by-products, ground-nut oil refinery residue, and corn steep liquor as substrates to produce an anionic glycolipid from *Candida sphaerica*. Das and Mukherjee [20] used potato peels to demonstrate appreciable production of a lipopeptide biosurfactant from strains of *Bacillus subtilis*. Rhamnolipids were produced from cassava wastewater and waste cooking oil by Costa et al. [69] using *Pseudomonas aeruginosa*. Surfactin was produced by Gurjar and Sengupta [63] using rice mill polishing residue. Sobrinho et al. [62] utilized corn steep liquor and ground-nut oil refinery residue to produce an anionic glycolipid. Coimbra et al. [49] also demonstrated the potential application of crude biosurfactants using a low-cost medium in soil bioremediation.

The use of cheap substrates has the obvious advantage of reducing the cost of biosurfactant production [24]. However, it confers lasting advantages in terms of sustainability beyond their impact in reducing the cost of production of biosurfactants. The use of industrial waste streams and by-products as substrates fosters environmental preservation [1,16]. In the same vein, the sustainability of the biosurfactant production process, both economically and environmentally, will be boosted when value is added to these waste streams [65]. These substrates do not compete directly with food [23]. By using the wastes, their potential polluting effect is reduced as the majority of the residues would otherwise be disposed of by combustion [14,63]. Treatment and disposal of these waste streams is a substantial financial burden on industries. Their use as substrates would reduce the cost expended on waste management [69]. Furthermore, these substrates of interest are majorly renewable resources [2,5,23]. They are also referred to as 'green' products [16] or 'greener compounds' [70]. This designation is used to corroborate the high biodegradation rate of biosurfactants amongst other advantages in comparison to traditional surfactants.

Indeed, the 'greening process' leads to a reduced carbon footprint. This underscores another push towards sustainability, a move that is evidently driving the market to more efficient technologies that will foster the large-scale production of biosurfactants [55]. Biosurfactants are thus considered sustainable when produced from sustainable feedstocks by microorganisms [18]. The use of inexpensive raw materials, particularly waste from the agro-industry, will further engrain the future of biosurfactants in environmental applications [19].

It is also worthy of mention that the use of industrial waste as low-cost substrates for biosurfactant production has been researched for over two decades. In 1993, Mercadé et al. [71] reported the production of rhamnolipid using olive oil mill effluent as the sole source of carbon. Despite years of research, Wan Nawawi et al. [61] expounded the need for ongoing research in this area as the selection of appropriate waste substrates for biosurfactant production remains a challenge. In choosing a waste substrate, it is essential to have one that has lipids, carbohydrates, and other nutrients in the right balance to support microorganism growth optimally, as well as maximize biosurfactant production [33,63]. The choice of substrate is quite important, amongst other production factors such as strain type of the biosurfactant-producing microorganism and environmental factors such as pH and temperature. The substrate used influences not only the type and nature of the biosurfactants vis-a-vis their physicochemical properties but also the quantity/yield and quality of their production [27,72]. Therefore, while researching low-cost substrates, their effect on the final product should be noted and appropriate provisions made.

8.2. Production and Downstream Processes

Biosurfactants used in environmental applications do not require the same rigorous and expensive purification processes needed for medicinal or cosmetic applications. Not only can biosurfactant production processes be potentially inexpensive when extensive refining is not required [17,67], there is increased attention on and appreciation of sustainable production processes for biosurfactants [23]. For environmental applications, the use of crude broths and mixtures of low-cost carbon sources as substrates makes biosurfactants a more viable option than other surfactants, both environmentally and economically [3,16].

Methods of biosurfactant extraction include acidic, acetone and ammonium sulfate precipitation, centrifugation, adsorption, crystallization, ultrafiltration, and extraction with organic solvents [5,16,73]. Extraction with organic solvents has been reported to favor reuse of solvents and high yield of biosurfactants [73]. However, the use of organic solvents poses other challenges to the downstream processing of biosurfactants. This process of extraction and purification of biosurfactants involves the use of large quantities of various expensive and hazardous organic solvents. One of the most widely used solvent combinations involves chloroform. Chloroform is toxic and has potentially harmful effects on the environment and human health [3,16]. Thus, the added advantage of using crude biosurfactants without purification in environmental applications is that it prevents the use of toxic solvents and other organic solvents. This makes the production process cheaper and also lends support to the sustainability discussion. Eliminating or reducing the use of toxic solvents is vital for biosurfactant production because, in achieving sustainability, production processes should incorporate a 'design for environment' [34].

In recognition of the need for cost-effective and sustainable production processes, Makkar and Cameotra [67] suggested biosurfactant recovery by gravity separation of the surfactant-rich phase from the fermentation broth. Foam fractionation was also identified by Santos et al. [16] as a solvent-free method for the separation of biosurfactants from the culture medium.

Low-temperature biosurfactants from cold-adapted microorganisms have also been identified by Perfumo et al. [74] as a newly developing area with promising energy-saving and sustainable (green) products and processes. According to the authors, these biosurfactants can be produced in the absence of heat, an attribute that fosters the development of biotechnological processes with low energy demand and the added advantage of limiting the environmental impacts of the biosurfactants [74].

The use of sustainable production processes, in general, is profitable because the wasteful use of materials, as well as the energy demand for processing, is reduced. Sustainable production processes also lead to a reduction in greenhouse gas emissions and other pollutants [23,34].

9. Sustainable Production of Biosurfactants and Their Prospects in Environmental Sustainability

An overriding consideration for the sustained production of biosurfactants in the future is their economic viability. The future of biosurfactants in environmental sustainability, their potential applications and increased usage in the market are hinged on the economics of the production process. The selection, design, and engineering of the production processes of biosurfactants should aim at low capital and in-expensive costs of operation [67]. This is of major importance for environmental applications because large amounts of biosurfactants are required [33]. In building the business case for industrial applications of biosurfactants, three factors—identified by Makkar and Cameotra [5]—must be favorable. These are cost, functionality, and production capacity.

From an economic view, Rufino et al. [75] reiterated the need to develop processes using inexpensive raw materials to successfully produce biosurfactants. In this context, an additional factor in biosurfactant production that should be addressed to secure their future in the sustainability discussion is optimization of the production process—including the recovery process—with the goal of making the process more economical [19,75]. Santos et al. [16] also stated a similar opinion, that the challenge of large-scale production of biosurfactants should be addressed from an economic standpoint. Therefore, for industrial applications of biosurfactants to be both economically viable and environmentally sustainable, it is crucial to develop a process that uses low-cost substrates and gives high product yield [1]. It is also important to bear in mind that the cost of the production process of biosurfactants is greatly influenced by the proposed area of application of the biosurfactants and the target market [16]. Overall, the future of biosurfactants in industrial applications is expected to be more prominent in the oil sector: in microbial enhanced oil recovery from oily sludge and oil wells, bioremediation, and cleaning of oil tanks [64]. Thus, it is of utmost importance that investments are made in strategies that will pave the way to the commercial production of biosurfactants [33].

Banat et al. [64] asserted that the various results reported from research on biosurfactants' present potential are not only encouraging but would also drive the industry. In terms of economics, with the use of renewable substrates, sustainable production processes should be more profitable as dependence on non-renewable resources is reduced [34]. Novel and efficient methods for biosurfactant isolation in the production process will also increase the economic feasibility of biosurfactant production [14]. The ability to use wastes to produce biosurfactants is a big part of the sustainability picture. Taking into consideration the fact that environmental sustainability advocates the reuse of wastes as opposed to their disposal, waste accumulation in the environment would be reduced. Reduction in production cost promises tremendous growth in the commercial application of biosurfactants in years to come, and with ongoing research, this is looking more feasible. The question is how soon into the future can this level of inexpensive commercial environmental application of biosurfactants be achieved. In other words, some level of caution must be exercised in making assertions about the 'when.'

Biosurfactants further offer advantages in the goal of environmental sustainability specifically with the possibility of reuse of treated petroleum wastes. For example, after treatment and characterization, drill cuttings can be reused in construction applications for road spreading, as aggregates, as filler or fine aggregate in bituminous mixtures, as well as in restoration of coastal wetlands [36,76,77]. The possibility of secondary contamination when improperly treated petroleum wastes are reused is a limitation. To check secondary contamination, reuse of waste streams must be subjected to high standards of environmental regulations and stipulations on permitted levels of residual hydrocarbon content. In addition to the sustainability benefits of reusing treated drill cuttings, the cost-effectiveness of this approach is an advantage. Reuse results in the reduction of costs that would have otherwise been expended on the transportation of drill cuttings to disposal sites, and other associated charges such as the cost of acceptance charges at landfills [77]. In this respect, the need to identify alternative ways of using clean and treated drill cuttings and other petroleum wastes cannot be over-emphasized. It is an issue that must be accorded great urgency [77].

10. Concluding Remarks and Recommendations

Biosurfactants are creating an exciting and noticeable wave across industries—particularly in cleaning up environmental pollutants in petroleum wastes. Their versatility and identified advantages give these microbial products a promising future in industrial applications. The increasing role of biosurfactants in environmental sustainability also confers on them huge importance that cannot be ignored. To fully harness the advantages of biosurfactants in environmental sustainability, production processes that make them competitive in cost and yield to their synthetic counterparts must be developed and expanded upon, thus ensuring their economic sustainability. Research into the use of free to low-cost waste products as substrates highlights enormous potential for biosurfactant use in large-scale and commercial environmental applications. Further research is needed to develop production processes to increase yield and minimize the cost of purification when purification is a requirement for application. The discovery of novel low-temperature biosurfactants also poses an exciting area for research and industry, both in the potential role and application of the biosurfactants in cold regions and the development of low-energy production processes. An area identified for further research is the investigation of the life cycle sustainability assessment of biosurfactants. The research should focus on all stages, from production and consumption to disposal. Such research would also take into consideration all impact categories: carbon footprint, toxicity-related impacts, and resource depletion impacts as suggested by Laurent et al. [30]. This will go a long way in assuaging lingering concerns on the sustainability of biosurfactants. Without a doubt, biosurfactants are multifunctional materials that will revamp environmental sustainability not only in the 21st century but beyond.

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