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Sustainable biosurfactant production from agro-industry waste and by-products

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Abstract
The growing concern over environmental issues linked to the improper disposal of agro-industrial residues and by-products has heightened the focus on their efficient use and valorisation. A sustainable way to use these residues and by-products as substrates can be done by biotechnological processes like microbial biosurfactant synthesis. Biosurfactants, made from renewable resources by microorganisms, are a good substitute for traditional petrochemical surfactants. They have benefits including mild production conditions, low ecotoxicity, and biodegradability. In addition to their applications as food additives and preservatives, these biosurfactants have several uses in other industries, such as wastewater treatment, agriculture, pharmaceuticals, environmental protection, cosmetics, and the petroleum sector. With an emphasis on the significance and status of sustainable production, this study attempts to offer an extensive overview of scientific research on the application of agro-industrial residues and by-products in microbial biosurfactant production. Furthermore, the paper addresses the present state and potential future directions of microbial biosurfactant production based on market analysis and research investigations.

Keywords: Microbial biosurfactants, properties of biosurfactant, agro-industry waste, biodegradable residues, sustainable production

1. Introduction
Environmental issues have led to a rise in interest in and importance for the effective use and valuation of agro-industrial wastes and residues in recent years [1]. The massive amount of effluents produced annually by enterprises associated with agriculture could have detrimental effects on the ecosystem, animal and human health, and both when released into the environment untreated [2]. Even if they are biodegradable, there must be sufficient ways to use them given their enormous production [3]. The structure and composition of agri-food wastes are complex, containing proteins, carbohydrates, polysaccharides, and polyphenolic chemicals among other elements. These wastes are renewable natural resources, easily accessible, affordable, and ecologically benign [4]. Numerous biotechnological approaches can be used to address the waste issue. They can be simply implemented and have a good impact on both environmental and public health protection, in addition to being financially advantageous [5].

In order to achieve one or more objectives (such as recycling or recovering components), assess the financial and technological advantages, select a potential market, and determine the best bioprocess solution to achieve the desired goal, it is crucial to methodically evaluate the production process and characteristics of agro-industrial wastes, residues, and by-products [6]. Approximately 1.6 billion tons of main product equivalents and 1.3 billion tons of food waste for the edible portion are produced by the food industry both during the cultivation of agricultural products and during processing. The utilization of agri-food industry waste or by-products as raw materials could result in lower production costs when produced on a large scale because the waste has no potential use [7]. New opportunities that support preservation of the environment have been made possible by the use of agro-industrial residue and by-products as raw materials to produce products with increased value. Agro-industrial wastes and by-products can be used as a substrate to significantly lower overall process costs, improving sustainability and complying with the circular agriculture concept.

This scenario is beneficial to any bioprocess that reduces production costs and waste creation while also making use of agricultural and food industry residue or by-products [8-10]. Through the advancement and growth of the biotechnological production of various high-value products, scientists worldwide have been attempting to find ways to reduce the created agro-industrial residues and wastes in recent decades. Various agro-industrial wastes, by-products, and residues are utilized to produce various bioproducts. For instance, bioethanol, biogas, and extracellular polymers have all been produced using soybean molasses [11], sugar beet molasses [14], bioethanol [15, 16], and biohydrogen [17]; sugar beet pulp [14], bioethanol, biomethane, and biohydrogen [18]; cellulase and xylanase [19], and itaconic acid [20]; bioethanol and biogas [21], fumaric acid [22], and lactic acid [23], and wheat straw for lactic acid [24], biogas, bioethanol, and biohydrogen [25] meanwhile, wastewater from various industrial processes was utilized for the production of xanthan [27, 28], lipases, proteases, and tannases [26], as well as bioethanol [29], and biomass, etc. [30].
Biosurfactants can also be made from a variety of agro-industrial residues and by-products in addition to those described above. Biosurfactants are a good substitute for conventional petrochemical surfactants as they are produced by microorganisms with renewable resources [10, 31-34]. Many scientists studied agro-industrial waste and its by-products, such as fruit and vegetable waste, starch-rich waste, industrial waste, lignocellulosic waste, oily and glycerol-based waste, and other substrates, such as frying oil waste, waste from vegetable oil processing and its by-products, dairy industrial waste, and sugar industrial waste, as suitable substrates for the production of biosurfactants [32]. As per Santos *et al*. [33], several types of industrial wastes that are commonly used as raw materials for the biosynthesis of biosurfactants are animal fat, frying oils, oil cakes, sugarcane, and olive oil mill effluent.
In addition to combining data published in the scientific literature in recent years about the use of various agro-industrial residues and by-products in the production of biosurfactants, as well as the most important aspects of their production and application, the purpose of this review is to present the present situation as well as the prospects of biosurfactant production.

2. Biosurfactants
Biosurfactants are useful amphiphilic microbial molecules that demonstrate surface activity and biological efficacy throughout a range of processes or applications. Microbes provide an alternative to conventional surfactants that are produced chemically when they grow on surfaces that are immiscible to water [35]. They can synthesize them as well. Many microorganisms produce amphiphilic substances named biosurfactants, such as filamentous fungi, yeast, and bacteria. Biosurfactants are more selective and have a lower critical micelle concentration than synthetic surfactants. They are also highly active in extreme environments with pH, salinity, and temperature [36]. Chemical surfactants are widely used in a wide range of industries and products, but they also come with several major drawbacks, including risks to one's health, safety, and the environment [37]. Chemical surfactants are currently associated with a multitude of problems, including their effects on the environment, possible risks to human health and safety, toxicity, limited bioavailability, formation of algal blooms, resistance to surfactants by microorganisms, and the bioaccumulation of various particles in pipelines and equipment that can lead to inefficient performance. These problems with chemical surfactants are being addressed by alternative surfactants, such as green surfactants (sustainable and ecologically friendly alternatives) and biosurfactants (natural, biodegradable surfactants) [38]. To improve surfactant compositions and decrease their environmental impact, companies are also looking at novel and evidence-based strategies [39]. The chemical surfactant industry and regulatory bodies have several options for addressing the problems associated with the substance. These treatments aim to reduce environmental impact, improve safety, and promote the use of surfactants that are more ecologically friendly [40]. Here are some crucial recommendations for solutions: Microorganisms play a vital role in the transition from chemical surfactants to biosurfactants, which include those obtained from plants or bacteria. These biodegradable surfactants are less dangerous and are less likely to persist and build up in ecosystems [41]. Sustainability in the evaluation of life cycles can be enhanced and plastic waste can be reduced with improved biosurfactant compositions and the use of sustainable packaging for surfactant products.
Biosurfactants offer several benefits to society such as improved industrial operations, less pollution, safety compared to synthetic surfactants, and advancement in several areas such as biotechnology, healthcare, and agriculture [42]. Their broad acceptance may lead to a more sustainable and environmentally conscious society. The pharmaceutical, food, and cosmetic industries employ these compounds for a variety of purposes as humectants, emulsifiers, detergents, and preservation agents because to their low toxicity and biodegradability. There are various environmental benefits when biosurfactants are utilized in place of synthetic surfactants, which are detrimental to the environment. These benefits include biodegradability and an environmentally friendly method [43]. They can be used subsequently in environmentally sensitive places and also decrease toxicity. They demonstrate increased oil recovery in the oil and gas industry with enhanced efficiency from a variety of reservoirs, in addition to their well-known bioremediation technique, which enhances the solubility and bioavailability of hydrophobic pollutants [44].
In many biotechnological applications, such as the food industry, pharmaceutical, cosmetic, healthcare, medical medication delivery, and agricultural pesticide formulations, these biosurfactants are critical to the constructive pattern [45]. They can be made from various substrates, although the bulk are made from renewable resources such as vegetable oils, milk waste, and distillery waste. Recent advances and developments in the synthesis of biosurfactants and their novel applications through the use of various forms of industrial farm waste as a renewable raw substrate material [46]. This review also covers the many wastes and by-products from agro-industrial activities that are used to make biosurfactants. Wastes from the processing of fruits and vegetables, oil, starch, sugar, distillery, and many more industries are among them.

2.1 Biosurfactant: Types, classifications
Typical biosurfactants are surface-active organic compounds produced by microbes, plants, or animals. They come in a variety of forms, and they are all classified according to their distinct chemical structures, microbial

origins for secondary metabolites, and other properties. These types and classifications are defined according to the following criteria [47, 48]. The most prominent examples of glycolipids, lipopeptides, phospholipids, polymeric biosurfactants, protein, and peptides are rhamnolipids, sophorolipids, and trehalolipids. Based on their chemical structure, which is embedded, they have been classified as glycolipids. Other biosurfactants produced by yeast, bacteria, and other microorganisms are classified based on their microbial origin and the type of microbe with a hydrophilic head group associated to a hydrophobic fatty acid tail. The fungi and bacteria that produce them [49]. Furthermore, biosurfactants can be categorized as antimicrobial, which typically strengthens the antimicrobial properties against pathogens, foam-forming biosurfactants, which produces stable foams of biosurfactants, low molecular weight surfactants, which lower surface tension and improve emulsification, and bio emulsifiers, which promote the formation and stabilization of emulsions [50]. The way biosurfactants behave in different systems forms the basis of this classification.

2.2 Biosurfactant properties and production methods

Biosurfactants exhibit a broad range of molecular structures and functions. The polar hydrophilic head is composed of phosphate carboxyl acid, alcohol, amino acids, carbohydrates, and peptides, whereas the nonpolar hydrophobic tail is composed of hydrocarbon chains of varying lengths and complexity [51]. It can be produced in a few different ways, the primary ones consisting of microorganisms or plant-based sources, and is composed of surfactants derived from biological entities, particularly bacteria and fungi. These compounds are generated as a consequence of the chemistry on the cell surface or as metabolic by-products [52]. It has been shown that these compounds provide a preferential partition between liquid interfaces that have different polarity, such as oil/water/air, and improve substrate bioavailability by reducing interfacial tension and surface tension. Several structural variations, low toxicity, environmental compatibility, enhanced biodegradability, stability at high and low temperatures, salinity, and pH, low critical micelle concentration, and a broader range of substrate specificity are additional physiological traits [53]. When compared to microbial biosurfactants, certain synthetic surfactants perform better in terms of wetting, detergency, micro-emulsification, foaming, separating phases, and exhibiting selective tension-active capabilities. The particular type of biosurfactant, the intended use, and the selection of microbe or source all influence the biosurfactant production procedure [53]. A few widely used methods to produce biosurfactants have been discussed in the section as follows. As biosurfactants can be produced from microbial sources in both constitutive and inducible forms, they are among the most diverse bio-products of modern biotechnology. Furthermore, by utilizing low-cost, renewable raw materials, industrial waste, or other by-products, the process economics of producing biosurfactants in large amounts can be improved.

3. Agricultural Waste

A sustainable and environmentally friendly approach to using organic wastes is to transform them into valuable biosurfactants through agriculture. Here are the basic steps involved in producing biosurfactants from agricultural waste [54]. Agricultural waste products are utilized in this method as the substrate for the synthesis of biosurfactants. Common agricultural wastes include crop leftovers (like rice husks and wheat straw), fruit and vegetable peels, and agro-industrial outputs (like sugarcane bagasse and maize cobs) [55]. The production of biosurfactants from agricultural waste not only makes organic residues more valuable but also reduces the environmental impact of eliminating waste and promotes sustainable practices. The selection of agricultural waste and microbes, along with process optimization, will be critical for the successful production of biosurfactants from these sustainable resources [56].

3.1 Fruit and Sugar Industry Waste

A range of organic waste products are produced by fruit producers, including peels, pulps, and seeds. The environment might be affected if this waste is not handled correctly.

However, innovative ways to turn this waste into beneficial products have developed, such as the synthesis of biosurfactants [57]. Among the several waste materials produced by the fruit processing companies are fruit peels, pulps, and seeds. Often, these items are regarded as agricultural waste or thrown away. These residues include high levels of proteins, lipids, and carbohydrates, making them suitable substrates for the production of biosurfactants. Biosurfactants produced from fruit waste can be utilized to solve waste disposal problems and add value to a resource that would otherwise go to waste [58]. Producing biosurfactants from fruit industry waste is a sustainable and ecologically friendly way to manage waste and use resources. It offers various advantageous economic and environmental advantages in addition to eliminating garbage disposal-related concerns. As it aligns with the principles of sustainability and the circular economy, the use of this green technology encourages a more moral and environmentally conscious fruit industry. Biosurfactants derived from fruit waste should soon be widely used in a range of industrial applications as a result of further research and development in this field [58].

The sugar processing industries generate vast amounts of starch-containing wastewater. The commercial production of sugar uses a range of additional resources in addition to sugarcane, such as tapioca, corn, soybeans, potato peel powder, and wheat bagasse. The enormous amounts of glucose and fructose present in the sugarcane molasses high in sucrose are astounding [59]. There are differences in the nutritional content of the molasses depending on the type of crop and the processing methods employed. Pre-treatment, water use, and logistical expenses are reduced when molasses is used. They are easy to utilize in the production of biosurfactants, save for the removal of solids and dilution [60]. Several studies have focused on the possibility of producing biosurfactants from sugar by-products. Molasses is the substrate that is used most commonly due to its high vitamin content. Several recent reviews examined at various elements of biosurfactant types and how they work in a variety of bioremediation applications, such as oil removal, hydrocarbon breakdown, dye degradation, and heavy metal extraction [61]. There is potential for using biosurfactants made from molasses feedstock in bioremediation projects because of their better emulsification and surface tension properties. It also enhances microorganisms' capacity to degrade and breakdown different kinds of persistent pollutants that are present in diverse habitats, like soil and water [62].

3.2 Wheat Straw and Rice Husks as Feedstock

Rice husks and wheat straws can be used to synthesize important biosurfactants from biomass waste in a sustainable and environmentally friendly approach [63]. Whey is the liquid fluid produced during the production of cheese and casein. Whey is a very nutrient-dense food due to its high protein and carbohydrate content and slight fat content. Basically, two distinct kinds of commercially available dairy products are used to produce whey. This process also yields biodegradable surfactants with many applications, reducing the adverse environmental effects of agricultural waste [64]. Agricultural residues such as rice husks and wheat straw are rich in nutrients and sometimes regarded as waste products. Pollution and disposal issues arise when burning or allowing them to decompose. However, lignin, cellulose, and hemicellulose - three lignocellulosic materials - contain complex carbohydrates that can be treated to yield beneficial byproducts such as biosurfactants [65].

Producing biosurfactants from rice husks and wheat straws is a promising prospect, but there are several challenges along the way. Among them include assuring cost-effectiveness, optimizing fermentation efficiency, and raising the production of biosurfactants [57]. To enhance the production of biosurfactants, more research is being conducted to discover novel microbial strains and get a deeper understanding of genetic engineering techniques [66]. Biosurfactant production from rice husks and wheat straws is a viable and sustainable way to convert agricultural waste into useful products. This biotechnological method not only offers environmentally friendly surfactant alternatives to synthetic ones, but it also helps with waste disposal and advances green chemistry initiatives. As long as science and technology continue to advance, producing biosurfactants from agricultural waste has a substantial potential to aid in the creation of a more sustainable and circular economy [67].

3.3 Dairy waste

Dairy waste contains a large amount of organic stuff, which poses a serious environmental risk. It can cause pollution and the production of greenhouse gases if not managed properly. However, there has recently been a lot of interest in the concept of using dairy waste to create biosurfactants [68]. Activities that include using dairy products result in a significant amount of dairy waste. Because of its composition and characteristics, dairy wastewater is more suitable for the type of operations that are conducted in the dairy industry. In this regard, the qualities of effluent from dairy facilities differ greatly. The phrase "dairy waste" refers to a variety of by-products that are produced when milk, cheese, and yogurt are processed [69]. These by-products are perfect substrates for bacteria that produce biosurfactants because they contain lipids, proteins, lactose, and other organic substances [70]. Lactose and protein in dairy effluent encourage microbial growth, which produces beneficial by-products [68]. The main components of dairy waste that are used to make biosurfactants are proteins. Using dairy waste to make biosurfactants is a sustainable and environmentally responsible way to manage waste. Beyond its potential to turn dairy waste into a valuable resource, it has a wide range of applications in other industries. In response to the need for environmentally sustainable solutions to address ecological challenges worldwide, the synthesis of biosurfactants from dairy waste is a novel and stimulating strategy that encourages waste reduction and the use of eco-friendly methodologies [71].

4. Industrial waste

The production of biosurfactants is primarily hampered by the production economy; the type and amount of raw materials required can have a significant impact on production costs. Raw ingredients are thought to be between 10% and 30% of the total manufacturing expenses in the process of producing biosurfactants [72]. Therefore, using low-cost raw materials, such as agro-industrial wastes, is preferred to reduce costs. A sustainable source of organic biomaterials based on renewable substrates is agro-industrial wastes.

Due to its favourable economics, low investment and energy costs, ability to decrease environmental pollution, relative ease of operation, availability of less costly substrates in large quantities, and eco-friendliness, bioconversion of these waste materials is regarded as a technology of greatest significance for the near future [31]. Thus, it is a viable and advantageous option to produce biosurfactants from agro-industrial waste [73]. A few examples of these low-cost agro-industrial waste substrates are cassava wastewater, soybean waste, groundnut wastewater, and palm oil mill effluent. Utilizing these waste products decreases garbage disposal while simultaneously producing biosurfactants [31].

4.1 Cassava wastewaters

This is a highly utilized starch-rich substrate that is produced during the production of cassava flour, and it is an ideal alternative substrate for fermentation processes [74]. The most important nutrients found in cassava waste are sugars and mineral salts, which make them suitable substrates for biotechnological processes. *B. subtilis* was also employed to produce surfactin from cassava wastewater [75]. *Pseudomonas aeruginosa* simultaneously produced polyhydroxyalkanoates and rhamnolipids using cassava wastewater as a substrate, according to [76].

4.2 Palm Oil Mill waste (POMW)

High concentrations of fat, oil, and grease are found in POMW, a high-strength organic waste slurry [77]. Microorganisms employ a wide range of nutritional contents as a source of energy for growth, which leads to the production of valuable metabolites such as biosurfactants [78]. Biosurfactants produced from areas affected by palm oil were found by many researchers. [79]. The surface tension of water was reported to decrease from 72 mN/m to 27 mN/m when synthesizing biosurfactants from POME utilizing *Nevskia ramose NA3* [80]. All of the bacteria that were isolated from POME to produce biosurfactants decreased the water's surface tension from 72 mN/m to 40 mN/m [81].

4.3 Groundnut waste/Peanut oil cake

Groundnut oil refinery residue is a solid residue with a high protein content that is low in lysine and rich in arginine [82]. It is also a great source of fats and carbohydrates. Additionally, six Candida strains cultured in soluble (n-hexadecane) and insoluble (soybean oil, ground-nut oil refinery byproduct, corn steep liquor, and glucose) substrates were reported to produce biosurfactants by [83]. 90% of the hydrophobic pollutants in the sand were removed by these biosurfactants. The synthesis of biosurfactants using peanut oil cake was carried out by [84]. The results suggested that *Bacillus megaterium*, *Azotobacter chroococcum*, and *Corynebacterium* kutscheri could be employed as biosurfactant producers using these substrates and that peanut oil cake produced higher yields. In a recent publication, the scientists described how *Lactobacillus delbrueckii* produces biosurfactants by using peanut oil cake as a carbon source. The biosurfactant that was produced (5.35 mg/ml) had significant ability to promote biodegradation [85].

4.4 Soybean waste

Soy molasses, a by-product of processing soybean oil, is around 60% solid carbohydrate and has a high fermentable carbohydrate content (30% w/v), making it an excellent choice for the cost-effective synthesis of biosurfactants [31]. Utilizing soybean oil refinery by-product as a substrate, many researchers found optimized biosurfactant production by *Candida lipolytica* through the application of sequential factorial design [86]. Three culture parameters were assessed in this study: the amount of refinery residue, the amount of glutamic acid, and the amount of yeast extract. The biosurfactant product exhibited significant emulsifying and surface activity, and it remained highly stable across a broad pH (2-12), temperature (0-120 °C), and salt (2-10% NaCl) range.

5. Conclusions

Due to the growing awareness of environmental preservation, the unavoidable depletion of fossil fuels and natural resources, as well as the many advantages that sustainable development offers society, it has become increasingly important in recent decades. Effective wastewater and waste management is essential for sustainable industrial and agricultural productivity as well as human, animal, and environmental health. For waste to be reduced and reused or recycled, circular agro-industrial production and bio-economic waste management are crucial. Waste is transformed into energy while enhancing resource use in a circular economy, balancing industrial operations, economic growth, and environmental security. According to the principles of sustainable development, biotechnological processes that produce biosurfactants by applying agro-industrial residues and secondary or waste products to produce them directly contribute to environmental protection. This is because these processes use the residues and waste created in other technological or biotechnological processes as a raw material, thereby solving potential environmental problems.

Biosurfactants, which fall into four categories, can be made from a variety of agro-industrial leftovers and by-products. Residues from agricultural fields (stalks) molasses, whey, glycerol, bagasse, and oil cakes), industrial wastes (peels, pomace, frying oil, and wastewaters), and agricultural process residues (corncobs, chaff, and husks). Among by-products with great commercial and practical utility value, biosurfactants occupy an important position. These biomolecules with surface activity are becoming more and more popular on the global market as environmentally friendly and sustainable alternatives for petroleum-based products. Because of their greater environmental performance, multifunctionality, range of biological properties, lower toxicity, biocompatibility, biodegradability, and tolerance of pH and temperature variations, biosurfactants are chosen over chemical surfactants. The high cost of produce has prevented microbial biosurfactants from being extensively commercialized, despite their advantageous qualities. The primary variables influencing the commercial application of biosurfactants are the economics of production, substrates, microorganisms, and product separation and purification processes. The viability of biosurfactant production is dependent upon the ability to produce more economically viable bioprocesses using cheaper substrates, i.e., increasing the product yield while lowering the cost of raw supplies. Sustainability and the circular economy are enhanced by higher productivity from waste and renewable raw materials as well as by the stability and biodegradability of products like biosurfactants.

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