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Review

Bioactivity and potential applications of plant-derived biosurfactants

Amir Mohammad Bagheri[1,2], Marzieh Sajadi Bami[2,3], Mana Khazaeli[4], Masoud Mirzahashemi[1,2], Payam Khazaeli[2,3,*], Mandana Ohadi[2,*] and Ibrahim M. Banat[5,*]

[1] Student Research Committee, Kerman University of Medical Sciences, Kerman, Iran
[2] Pharmaceutics Research Center, Institute of Pharmaceutical Sciences, Kerman University of Medical Sciences, Kerman, Iran
[3] Department of Pharmaceutics, Faculty of Pharmacy, Kerman University of Medical Sciences, Kerman, Iran
[4] Clinical Research Development Unit, Afzalipour Hospital, Kerman University of Medical Sciences, Kerman, Iran
[5] School of Biomedical Sciences, Faculty of Life & Health Sciences, Ulster University, Coleraine BT52 1SA, N. Ireland, UK

* **Correspondence:** Email: pkhazaeli@kmu.ac.ir; m.ohadi@kmu.ac.ir; im.banat@ulster.ac.uk.

Abstract: Synthetic surfactants are often non-biodegradable and derived from petrochemical sources, which can harm the environment. In contrast, natural surfactants, also known as biosurfactants (BSs), are typically sourced from microorganisms, plants, or animals and are generally nontoxic and biodegradable, which minimizes their ecological impact and enhances their environmental biocompatibility. Among these biomolecules, plant-derived BSs (PdBSs), particularly saponins, are the best-known members that are abundantly found in nature and traditionally have been used as emulsifiers and detergents. Their favorable physicochemical and biological properties suggest significant potential for biomedical applications. Optimizing plant resource utilization and developing commercial formulations of PdBSs could support global sustainability efforts. Furthermore, PdBSs hold great promise for scientific and commercial applications in skincare and other cosmeceutical products. In this review, we examined the potential bioactivities of PdBSs, particularly saponins, as valuable ingredients for the cosmetic industry and skincare products to promote eco-friendly practices in the cosmeceutical sector.

Keywords: biosurfactants; plant-derived biosurfactants; saponins; skincare bioactivities; cosmeceutical

1. Introduction

Surfactants are amphiphilic compounds containing hydrophilic and hydrophobic moieties. They are mostly classified as nonionic, cationic, zwitterionic, and anionic according to their charges. Primarily, the molecules facilitate the formation of emulsions by reducing surface tension between liquids of different polarities and exhibit a wide range of surface properties, including foaming, wetting, and solubilizing activity [1,2]. Surfactants, therefore, are traditionally employed in different cosmetic fields such as detergents and as wetting, emulsifying, solubilizing, dispersing, or foaming agents [1,3,4]. Soap was the first commercialized example of surfactants in the field of cosmetics. Most commercially available surfactants over the past century have been chemically synthesized from petroleum derivatives. Hence, significant environmental problems may be associated with their long-term applications. In comparison, surfactants from natural sources have fewer problems in terms of safety and environmental compatibility [5–7]. Biologically originated surfactants, commonly known as ‘green’ surfactant or biosurfactants (BSs), are natural surface-active agents, produced by a variety of living organisms, including microorganisms, plants, and animals.

Scientists have provided a narrow definition for naturally derived surfactants, as they are obtained from living organisms through some extraction route without the need for further synthesis [8–10]. Structurally, BSs are composed of amino acids or saccharide moieties as hydrophilic heads together with a hydrophobic tail portion that are typically long alkyl chains, a triterpenoid group, or a group of hydrophobic amino acids [11,12]. BSs have gained particular interest due to their availability from renewable sources, biodegradability, and low toxicity. They also have a good ecological acceptability in relation to environmental conservation, leading to increased demand. Their functional diversity results in beneficial properties and relative stability at extreme pH, salinity, and temperatures. Therefore, a variety of applications have been suggested in the field of oil recovery, bioremediation, pharmaceuticals, medicine, food, agriculture, and cosmetics [13–15]. Several parameters can affect BSs’ physicochemical characteristics and biocompatibility. Generally, BSs are categorized depending on the source (origin of the producing organism), chemical structure, or composition used in their production process. This can lead to differences in terms of physicochemical properties, emulsification capacity, and biological activities [16,17].

Most BSs display strong surface activity and adsorption to various interfaces as well as self-assembling properties when present above the critical micelle concentration (CMC) [11,18,19]. PdBSs, in particular, are sustainable biomolecules obtained from low-cost renewable sources, offering better biocompatibility and biodegradability compared to their synthetic counterparts. There is a history from ancient times of using these surface-active agents to promote personal hygiene as cleansing materials, like detergents and cleansers. Several plants are known to produce BSs with a wide spectrum of biological properties, such as antioxidant and anti-inflammatory activities [20,21]. Due to their favorable physicochemical properties, interfacial activities, and unique biological effects, combined with the growing demand for “green” materials, these BSs have shown potential in different pharmaceutical, cosmetic, and medical products [20,22]. In this review, we aimed to explore potential biomedical applications of plant-based BSs along with a recommendation for future research directions.

2. BSs of plant origins as alternative counterparts

The term BS covers a wide range of natural surface-active compounds, produced by numerous living organisms as secondary metabolites. Apart from the source of their production and extraction, BSs can be classified according to their chemical structure and molecular weight. They constitute a complex mixture of structural dispersity. Low molecular weight BSs are usually microbial-based, including glycolipids or lipopeptides, whereas, high molecular weight BSs are often microbial exocellular biopolymers (polysaccharides, proteins, liposaccharides, or lipoproteins) [11,19].

Plants are unlimited bioreactors that produce bioactive molecules [23–25]. PdBSs are widely distributed in nature, associated with lower toxicity and with negligible harmful environmental effects over the synthetic counterparts. Their mild production conditions and multi-functional properties make them suitable for various industrial and biomedical applications [26,27]. They also offer better biodegradability and biocompatibility, as well as high interfacial activity and self-assembling properties to form a variety of vesicular structures.

In the field of cosmetics, several studies have shown that chemical surfactants can occasionally manifest some damaging effects on the skin, causing irritation and allergic reactions. These materials remain for long periods in the natural environments. As a result, they may bioaccumulate in human skin and generate harmful effects that can cause dermal toxicity after long-term use. In addition, the use of surfactants produced using petroleum raw materials in their manufacturing processes may lead to organ (heart, kidney, lung, etc.) toxicity, erythrocyte hemolysis, and/or blood coagulation disorders [26,28,29]. They can also attenuate the barrier function of skin. In the epidermis, synthetic surfactants can facilitate the penetration of exogenous substances and increase transepidermal water loss by compromising intercellular lipid structures. Such negative effects are particularly noted with anionic surfactants such as sodium lauryl sulphate (SLS) and sodium laurate, both of which are widely used in skin care products. Further, they can interfere with the skin microbiome and alter its enzymatic activity [26,30,31].

Natural surfactants, in comparison, are of less concern regarding negative or harmful effects on environmental and human health. This means that among surfactants of the same origin (Regulation No. 1223/2009), BSs are generally considered to have high ecological/environmental compatibility [4,32]. The development of cosmetic products with safe ingredients based on sustainability values and clean formulation goals proposes a gentle relationship with natural beauty. Therefore, the personal hygiene industry is being urged to adopt "green cosmetic principles" and search for alternatives suitable for replacing materials that do not meet these criteria [26].

Several plants have been identified for their ability to produce BS. Generally, PdBSs can be sorted as phospholipids, proteins, polysaccharides, and saponins (Figure 1) [11,33]. Compared to other BSs, especially microbial-originated, these plant-derived bioactive molecules have greater extraction yield as well as unique interfacial and biological activities. For instance, glycyrrhizin, derived from liquorice root, contributes to its sweetness and can be used as a flavoring agent [34].

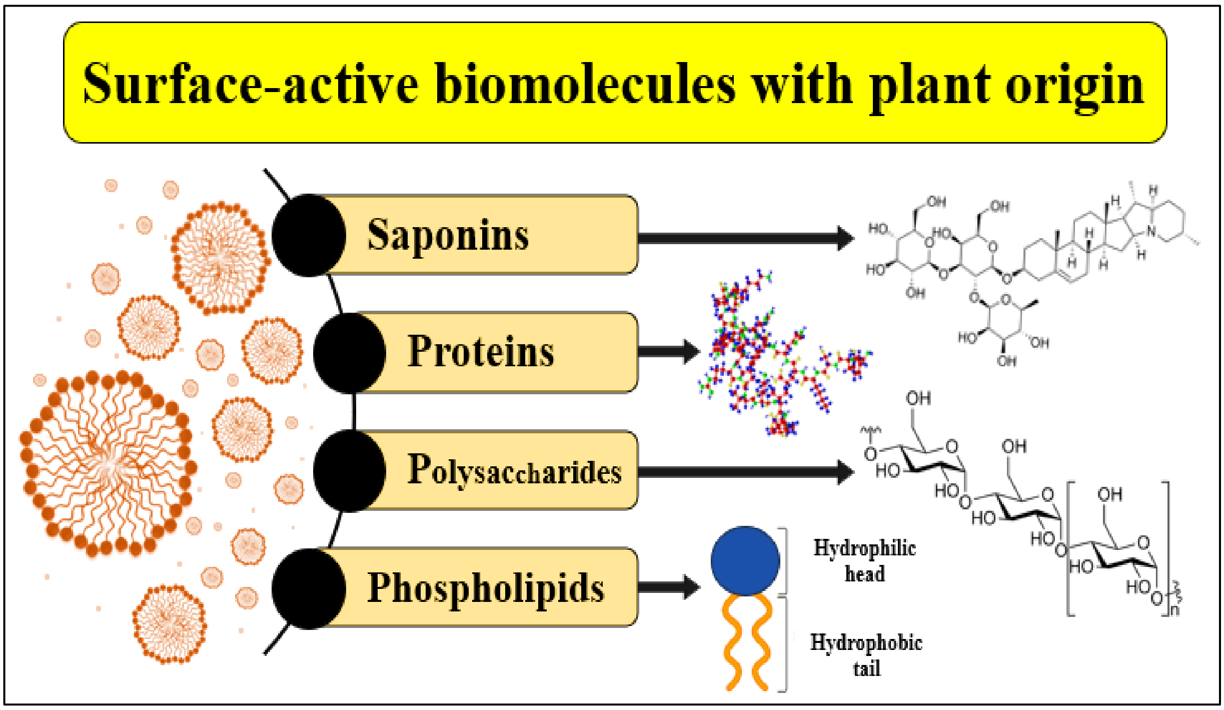

Figure 1. The most common types of biomolecules with potential surface activities derived from plant sources.

The availability and cost are also other issues, as they can be produced from widely cultivated crops, despite the need for specific culture media and growth environments in the case of microbial products. In addition, plant-derived materials are generally considered a safer option with fewer regulatory hurdles. Moreover, given the positive view of societies toward plants and plant-derived materials, market considerations are more easily applicable compared to other types of BSs, especially those of microbial origin [35–37]. Table 1 represents the critical comparison between PdBSs and microbials in the case of source, production, structure, scalability considerations, and sustainability [38–42]. PdBSs can easily be obtained from renewable herbal resources through various extraction methods, such as maceration, the Soxhlet method, liquid-liquid process, and reflux extraction [43,44]. These techniques are largely simple and do not require complex setups despite being time-consuming, requiring large volumes of solvents, and low efficiency in most cases [22,45–47]. However, the introduction of green technologies such as ultrasound-assisted extraction, microwave-assisted extraction, and accelerated solvent extraction has shown remarkable developments, as they require relatively lower quantities of extraction solvents and time-consuming steps, as well as being highly efficient [22,48].

Table 1. The comparison between BSs of plant and microbial origin.

Subject		Type of BS	
		Plant derived	Microbial derived
Source		Plant tissues (seeds, roots, leaves, etc.)	Bacterial/fungal fermentation
Production	Method	Direct extraction	Fermentation-based
	Time	days to months; plant growth + extraction process	Hours to days; microbial growth + extraction process
	Seasonal Dependency	Positive; dependent on harvest cycles	vegetative; year-round production possible
Structure	Complexity	Very high	Moderate to high
	Class type	Glycosides (saponins), as well as phospholipids, proteins, and polysaccharides	Typically, glycolipids, lipopeptides, and polymeric surfactants
	Purity	Usually heterogeneous mixtures (vary depending on plant part and season)	Can be achieved with high purity through controlled fermentation
Scalability consideration	Scale-up potential	Limited due to agricultural limitations (water scarcity, soil degradation, pests, etc.)	High due to scalable fermentation process
	Process Control	Difficult (climate changes, Labor Shortages, genetic variability, soil and Farmland Loss, etc.)	Excellent due to controllable parameters (type of media, temperature, nutrition, etc.)
	Yield	Typically, Low but can be improved	Can be very high
Sustainability	Land/Water use	High (farms and agricultural)	Minimal (fermentation)
	Biodegradability	High due to their inherent “green” nature	Usually good; often biodegrades rapidly

3. Why do plants produce BSs?

Although there is no clear evidence of why plants produce BSs, they are suggested to play crucial roles, primarily to increase their survival rate within tough environments. Due to their interfacial properties, they can assist nutrient absorption from the surrounding habitat soils and waters by enhancing the penetration of essential growth substances into deep-root zones by enhancing wetting ability. PdBSs may also facilitate cellular entry of micronutrients (sugars, amino acids, lipids, etc.) and exit of waste by-products (gums, resins, oils, etc.) [18,19,49]. Further, PdBSs are expected to help host resistance against herbivores. Additionally, these surface-active molecules can be associated with the plant defense system to cause insecticidal and feeding deterrent effects [50]. For instance, the surface-active agents extracted from *Eruca sativa* Mill. and *Cymbopogon winterianus* had a high antifeedant activity toward the elm leaf beetle (*Xanthogaleruca luteola*) and *Spodoptera litura* moth, respectively [51,52]. In addition, triterpenes extracted from *Manilkara subsericea* are recognized as a good source of insecticidal agents against cotton pests, such as *Dysdercus peruvianus in vivo* [53]. Moreover, in competitive interactions, plants can suppress the growth of nearby organisms by producing BSs as allelopathic agents [54]. An oak-derived BS called Avenacin is a potent antifungal compound that effectively protects its host from take-all diseases [12]. Similarly, *Medicago sativa*-derived BSs negatively affect other crops (like weeds) and suppress their growth *in vivo* [12,55].

The biological properties of PdBSs are primarily attributed to their amphiphilic characteristics, which enable membrane attachment and pore formation. In this respect, they can react by forming a complex with amphipathic lipids of membranes and change their permeability. Therefore, these surface-active molecules can also help to assure host resistance toward different infectious attacks. Showing specific antiproliferative and antimicrobial effects, PdBSs can disrupt the cell membrane of harmful microorganisms and prevent their growth [22,56]. Surface-active agents extracted from *Chenopodium quinoa* showed remarkable harmful damage against *Staphylococcus aureus*, *Staphylococcus epidermidis*, and *Bacillus cereus* by triggering cell wall degradation and disruption of cytoplasmic membranes *in vitro* [57]. Similarly, BSs derived from *Ziziphus joazeiro* have shown antifungal activity against *Aspergillus niger* and *Candida albicans in vitro* [58]. In addition, researchers have reported their ability not only to promote plant growth, but also to handle stressful conditions such as extreme temperatures, salinity, and dehydration. In such situations, they are produced to restore membrane integrity and regulate homeostasis as well as stimulate tissue development [59–61]. Moreover, by enhancing the endogenous antioxidant system, these surface-active molecules can terminate reactive oxygen species (ROS) and play an important role in environmental adaptation [43]. In this respect, the utilization of PdBSs in cosmetic products can provide a suitable antioxidant potential and improve the penetration of nutrients into the deep layers of the skin, as well as the regulation of topical homeostasis.

4. Surfactants of plant origins are relevant for potential cosmetic applications

In recent years, concerns about environmental pollution related to human activities have threatened plant health and emerged as one of the greatest existential global burdens. Therefore, substituting synthetic products with natural ones has become a trend. PdBSs can be used for various purposes, such as cleaning hair and skin, facilitating the formation of emulsions and foams, and enhancing wetting capacity due to their amphiphilic nature and interfacial properties [62]. Most of the surfactants in these products are chemically synthesized from petroleum, which are not biodegradable and might show different levels of biotoxicity. Therefore, increased case reports of adverse effects, such as skin irritation, have encouraged the introduction of less aggressive alternatives [62,63]. Several natural substances and green surfactants have been introduced with high biocompatibility. Due to the higher extraction yield compared to microbial BSs and adequate surface properties, PdBSs are considered suitable candidates for skincare products, replacing traditional chemically synthesized counterparts [64,65].

In ancient communities, there is a history of using these surfactants as detergents. However, PdBSs can be used in different cosmetic products, such as makeup preparations, toothpastes, shampoos, skin moisturizers, and deodorants [4,66] due to their antioxidant properties and antimicrobial activities through various mechanisms. Moreover, these natural surfactants may also have further biological properties, including stimulation of fibroblast growth, promotion of collagen biosynthesis, and enhanced anti-inflammatory properties [67–69]. Therefore, they can provide age-supportive outcomes [49].

Nowadays, several skincare products are reported with PdBSs. According to their contents, they can show different properties from a simple cleansing formulation to an efficient anti-aging product since they can accelerate fibroblast regeneration, increase cell-cell communication, and provide a better topical moisturization effect [26]. Rather than the typically aggressive synthetic surfactants, PdBSs can also modulate the skin microbiome and help maintain its proper composition [70]. Further, biological activities of green surfactants, including the activation of cellular processes for autophagy and DNA repair, are also believed to reduce skin diseases and associated damage [71]. Figure 2 provides a summary of the most adopted potential applications of PdBSs in skincare products.

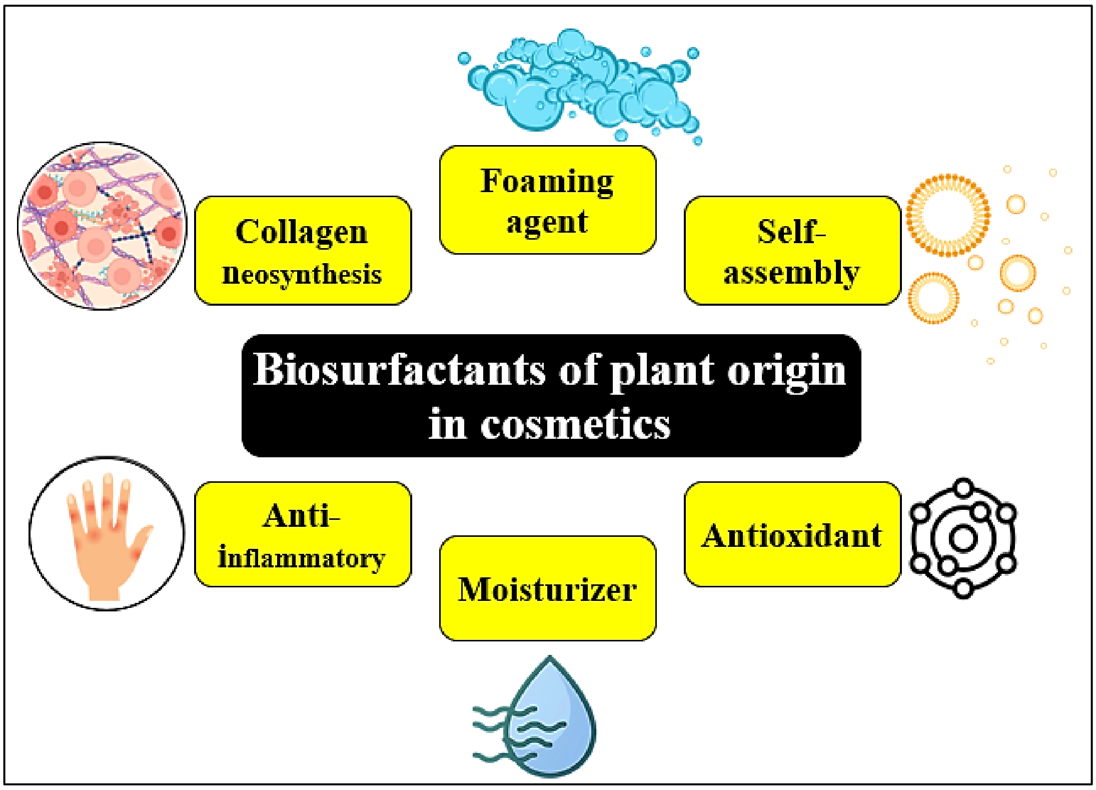

Figure 2. Some examples of the most widely noted potential applications of PdBSs in the field of skin care products and cosmetics.

4.1. Saponins and their potential skincare applications

Among surface-active agents with plant origins, saponins are widely distributed in this kingdom. As a class of non-ionic BSs, saponins are naturally occurring glycosidic compounds consisting of nonpolar aglycone structures (a steroidal or triterpenoid) moieties, also known as sapogenins, linked to polar glycone structures (oligosaccharide) moieties [72,73]. For centuries, they have been traditionally used as detergents with high acceptability. Saponins are generally found in leaves, fruits, pericarps, roots, flowers, and seeds of plants. In addition, these PdBSs are easily isolated, preserving enhanced solubilization properties under different environmental factors of pH, ionic strength, heavy metal, and compatibility with eco-friendly and biodegradable nature [72,74]. Along with excellent physicochemical and biological properties, saponin-rich plants offer a promising source of green surfactants, both for research studies and commercial purposes. In this respect, there is a growing number of saponins used in cosmetic and skincare products. For instance, saponins derived from *Acacia concinna*, *Albizia procera*, and *Saponaria officinalis* have demonstrated significant washing properties, with no evidence of skin dehydration, sensitivity, or flaking when used traditionally as soap [10,22,75,76].

At low concentrations, surfactants tend to accumulate on the surface of solvents with the hydrophilic head pointing toward the water molecules and the hydrophobic tail away from them. Typically, above the CMC, amphiphilic molecules (such as saponins) spontaneously aggregate to minimize free energy. Hence, they can self-assemble and form micellar structures that can be spherical, rod-like, or ellipsoidal, depending on their aglycone conformations [77,78]. Structurally, the nonpolar part of the molecules (triterpenoid or steroidal aglycone) forms the hydrophobic core, while oligosaccharide chains (sugar units often with uronic acids) assemble the hydrophilic shell. In this context, more sugar units lead to increased hydrophilicity and higher CMC, as well as better solubility. However, by producing micellar structures, BSs can affect the surface tension of water. Their amphiphilic structure enables them to align with the hydrophobic part outward at the air-water interface; this not only reduces the surface energy, but also creates a dense, cohesive, and elastic film that can result in better emulsification and foaming properties. Moreover, on the skin, although BSs are prone to penetrate and disrupt the *stratum corneum*, they cause less protein denaturation than chemical surfactants (like SLS). In other words, PdBSs are less disruptive to the lamellar structure of the skin's intercellular lipids, which is crucial for healthy barrier function and hydration. Furthermore, BSs may integrate into the skin lipid matrix and form mixed micelles or liquid crystalline structures using skin lipids, without dissolving them, potentially contributing to repairing the damaged barriers [79–82].

4.1.1. Washing and cleansing properties

As mentioned, saponins are mostly known for their detergency and wetting properties to clean grime and grease from substrate [83,84]. Chen *et al.* [85] reported moderate cleansing properties of saponins extracted from *Camellia oleifera* compared to SLS and Tween 80 *in vitro*. Accordingly, as a substitute for conventional surfactants, they can facilitate the solubilization of water-insoluble materials (reducing the surface tension of water from 72 mN/m to 50.0 mN/m at the 0.5% concentration). Although saponins have been historically used in household detergents and personal care products, further studies have shown opportunities for the optimization of these surface-active compounds and the introduction of superior products. For instance, Pradhan *et al.* [83] compared cleansing properties of BSs extracted from Pyagi Phool *(Zephyranthes carinata* H.*)* and Ritha *(Sapindus mukorossi* G.*)* to a synthetic commercial surfactant. Based on their results, BSs extracted from both Pyagi Phool (with the CMC of 0.64 mg/ml) and Ritha (with the CMC of 7.5 mg/ml) plants show remarkable surface-active properties *in vitro*.

PdBSs can also be used as foaming agents for various personal care applications [86]. In this process, rapid foam formation, stability over the usage period, adequate foaming strength, and a satisfactory foaming level are necessary. However, commercial products often use hazardous alkanolamide foam stabilizers [22]. Therefore, substitution with natural surfactants may be viable and practical for the prevention of unwanted side effects. In this respect, monodesmosidic saponins (with one sugar unit) have been reported with great foaming characteristics rather than others [56]. Canto *et al.* [87] studied foam-forming properties of saponins extracted from mate fruits (*Ilex paraguariensis*) with the CMC of 0.15 mg/ml and surface tension of 52.8 mN/m, which showed abundant and persistent foamability over time *in vitro*. A similar trend, with high foaming ability of BSs extracted from *Sapindus mukorossi,* was also reported [83]. PdBSs, therefore, seem to be suitable ingredients to develop personal care products, particularly shampoo. Aghel *et al.* [88] attempted to replace hazardous surfactants and foaming agents in shampoo using saponins derived from the roots of the *Acanthophyllum squarrosum* plant. The physicochemical, rheological, and organoleptic behaviors of the formulation were assessed, which were favorable with excellent cleansing properties and stable foaming ability *in vitro*. In another study carried out by Moghimipour *et al.* [89], saponins derived from roots of *A. squarrosum* were used to formulate a surfactant-free herbal shampoo deemed suitable for usage with acceptable cleaning capabilities (the optimum formula contained 15% total saponins). Nizioł-Łukaszewska *et al.* [90] also explored the potential application of saponins derived from 3 plants (*Glycyrrhiza glabra*, *Viola tricolor*, and *Solanum dulcamara*) as natural antioxidants, washing, foaming, and emulsifying agents for increasing the efficacy and safety of body wash formulations *in vitro*. Accordingly, the addition of saponins would strongly decrease the irritation potential of bodywash gels, simultaneously increasing their cleansing properties. Rai *et al.* [67] evaluated saponins extracted from *Jatropha curcas* (leaves and stem bark). Accordingly, efficient surface properties and potential detergency were observed with an average CMC of 0.50 mg/mL and 0.75 mg/mL for saponins derived from leaf and stem bark, respectively. It was therefore suggested that *J. curcas* saponins can be used as environmentally friendly alternatives to synthetic surfactants for commercial applications.

4.1.2. Emulsification properties

BSs can also be used to increase the stability of colloidal formulations since they can effectively reduce the surface tension of water and decrease the possibility of the 'Ostwald ripening phenomenon' within an inhomogeneous mixture. Accordingly, smaller particles would merge, forming larger particles to reach a more stable thermodynamic state with a reduced surface-to-area ratio [84,91]. Smułek *et al.* [92] studied the impact of BS addition on agar hydrogels containing vitamins A and E *in vitro*. Accordingly, in the first step, saponins (0.1 mg/mL) derived from *Sapindus mukorossi* were used to stabilize vitamin-loaded aqueous emulsions. Then, the emulsion was introduced into a hydrogel matrix, while its mechanical and swelling properties, as well as color and transparency, were evaluated. They concluded that the addition of saponins can significantly stabilize emulsions while the droplet size is maintained without changing the other physicochemical properties. Because of their high emulsification properties, BSs are employed as emerging stabilizers in emulsion-based products for various industries such as food, pharmaceuticals, and cosmetics [22].

De Almeida *et al.* [93] studied the physicochemical properties of saponins extracted from *Genipa americana* L. (CMC of 0.65 mg/ml) and *Tamarindus indica* L (CMC of 0.87 mg/ml) fruits, which showed good emulsifying properties and superficial activities (reducing the surface tension of water to about 31.39 and 30.02 mN/m, respectively) for oil removal *in vitro*. In another study, Sabri *et al.* [94] extracted triterpene saponins (with the CMC of 0.05% w/v) from *Hedera algeriensis* and explored their physicochemical properties for the preparation of oil-in-water (O/W) emulsions. Since cosmetic products are frequently formulated as O/W emulsions, PdBSs show favorable properties for such purposes.

4.1.3. Self-assembling properties

Aside from cleansing properties, vesicular structures formed by the aggregation of BSs (micelles) can be used for drug delivery. In their hydrophobic core, PdBSs can encapsulate organic nonpolar compounds. As a result, the self-assembling properties of BSs can be used to entrap bioactive compounds and effectively distribute them. The micellization process of saponins generally differs from conventional synthetic counterparts. Scientifically, rather than the expected globular, ellipsoidal, and wormlike micelles, saponin molecules aggregate in complex hierarchical helical morphologies similar to bile salts [95].

Nakowitsch *et al.* [96] incorporated budesonide, a highly water-insoluble compound, using a micellar system comprising Escin (horse chestnut seed-derived saponins with CMC of 0.01%), propylene glycol, and dexpanthenol to increase its mucosal permeation *in vivo*. According to their results, this micellar formulation was well-tolerated in the nasal cavity of rabbits. Moreover, *ex vivo* permeation studies have also demonstrated a faster and more efficient absorption into porcine nasal mucosa. Therefore, such formulation presents an opportunity for faster onset of action and better therapeutic outcomes in products containing hardly soluble ingredients. In addition, BSs can interact through the self-assembly of proteins and enzymatic activity above the CMC [77,97]. However, these interactions are milder than their traditional counterparts, leading to modest effects on protein structure and their self-assembling properties. Moreover, the formation of such functional complexes with proteins inhibits the overall activity of enzymes such as β-glucosidase, which are responsible for catalyzing the degradation process of several biomolecules, initially by physical hindrance [77,98].

4.1.4 Biological properties

Saponins are also reported to have several therapeutic effects. Tmáková *et al.* [99] explored surface properties and antioxidant activity of saponins extracted from 5 plants: *Sapindus mukorossi*, *Verbascum densiflorum*, *Equisetum arvense*, *Betula pendula,* and *Bellis perennis*. According to their *in vitro* results, a good foaming ability was observed compared to common synthetic surfactants (SLS and Tween 80). As a saponin-rich plant, *Panax ginseng* contains more than 289 types of tricyclic triterpenoids, commonly known as “ginsenosides”. The latter is believed to be responsible for biological properties, including adaptogenic, anti-oxidative, antifatigue, anti-aging, hepatoprotective, antidiabetic, anti-cancer, and neuroprotective properties [100,101]. Ginsenosides are abundantly found in the root and categorized into dammarane, oleanene, and ocotillol according to their aglycone structure [33]. Among the dammarane type, according to the position and number of sugar substituents attached to the steroid backbone, there are two subtypes known as protopanaxadiol type (PPD) and protopanaxatriol type (PPT) [102]. Ginseng saponins are reported to decrease the surface tension of water to about 33 mN/m and the CMC value to 0.83 mg/mL [33,103]. Fundamentally, PPT ginsenosides are considered saponins, which show potential applications for anti-aging, immunoregulatory, and skin-whitening purposes [102,104].

To date, several types of PPT ginsenosides (such as Re, Rg_1, Rg_2, F_1, etc.) have been identified. Oh *et al.* [105] investigated the potential applications of ginsenoside Re toward skin barrier function using HaCaT keratinocytes *in vitro*. Based on their results, in a concentration-dependent manner, administration of such a compound would upregulate filaggrin protein and caspase-14 activity, which desirably improves the skin barrier function and results in potential anti-photoaging properties [102,105]. In another study, Shin *et al.* [106] studied the defensive properties of Ginsenoside Re derived from roots of *P. ginseng* C.A. Meyer, on skin damage caused by UVB radiation. Their results revealed that ginsenoside Re was significantly able to suppress UVB-induced damage and ROS formation. It was also capable of upregulating the total glutathione content and superoxide dismutase activity in HaCaT keratinocytes, enabling viable healing properties.

Shi *et al.* [107] assessed the therapeutic effects of ginsenoside Rg_1 against psoriasis-like dermatitis using the imiquimod-induced model. It was observed that lipid peroxidation, skin thickness, inflammatory cytokines (IL-23, 22, 17A, 1β, and TNF-α), and the psoriasis area severity index score were significantly reduced after ginsenoside Rg_1 treatment *in vitro*. Moreover, the expressions of pIκB and NF-κB p65 were also remarkably mitigated, indicating potential capacities of ginsenoside Rg_1 toward psoriasis-like dermatitis. Lou *et al.* [108] also demonstrated photoprotective and immunoregulatory properties of ginsenoside Rg_1 in UVB-irritated skin *in vivo*. Accordingly, ginsenoside Rg_1 could regulate the local expression of inflammatory markers (IFN-γ, IL-10, and TNF-α) and the UVB-induced p53 protein, which would protect the irradiated skin from UV radiation and provide immunoregulatory effects after topical application. As a metabolite, ginsenoside F1 is produced by the hydrolysis of ginsenoside Re and Rg_1 in *P. ginseng*. Kim *et al.* [109] studied potential properties of ginsenoside F_1 as a new anti-melanogenic agent suitable for skin whitening and as an anti-pigmentation effect using B16F10 cell culture media *in vitro*. Based on their results, melanin secretion by the α-melanocyte-stimulating hormone was reduced by 60%. Therefore, ginsenoside F_1 can be used as a reliable anti-melanogenesis ingredient in cosmetics, which is suitable for skin whitening purposes. Jiménez-Pérez *et al.* [110] noticed similar outcomes by ginsenoside Re with potential anti-pigmentation and anti-melanogenic properties.

Another example is soyasaponins, which are derived from soybeans (*Glycine max*). As oleanan-type triterpenoid glycosides, they are divided into three groups: A, B, and E according to their aglycon structure [111]. However, the mixture of saponins derived from soybean hypocotyl through hydroalcoholic extraction showed CMC values from 0.56 to 3.2 mg/mL, depending on the chemical structure [112]. Fenugreek (*Trigonella foenum-graecum*) extract contains saponins with steroidal aglycon that can exhibit potential properties in delaying skin aging after topical administration [113].

Consequently, saponins address a broad spectrum of potential applications in the biomedical field, ranging from simple emulsifying agents to antioxidant and anti-inflammatory properties. Studies have also revealed their antimicrobial and immunomodulatory activities [22,114]. Accordingly, PdBSs can combat skin conditions and help maintain their healthy appearance. Table 2 represents some examples of saponins with potential applications in the cosmetics field.

Table 2. Examples of saponins and their potential applications in the cosmetic field.

Plant	Extracted BS	Potential applications	Ref.
Sapindus laurifolius	An anionic surfactant	Formation of stable foams	[115]
Glycyrrhiza glabra	Triterpenoid saponins	High emulsifying properties	[116]
	Whole extract containing Saponins	Potential anti-bacterial and antioxidant activities	[117]
	Triterpenoid saponins	Potential anti-inflammatory activity	[118]
Chenopodium quinoa	Saponins	Potential emulsifying and antibacterial activity	[57]
		Potential immunomodulatory activity	[119]
		Potential tyrosinase inhibitory properties and whitening activity	[120]
Ziziphus joazeiro	Triterpenoid saponins	Potential antifungal activity	[58]
Camellia sinensis (L) O. Kuntze	Saponins	Potential antioxidant and anti-inflammatory activity	[121]
Camellia oleifera	Saponins	Potential antioxidant properties	[114]
Bupleurum chinense	Saponins	Potential immunomodulatory activity	[122]
Bupleurum radix	Saikosaponin-d (triterpene saponins)	Potential anti-tumor activity	[123]
Panax ginseng	Ginsenoside Re	Anti-inflammatory, anti-photoaging and anti-melanogenic properties	[124]
	Ginsenoside Rg_1	Skin anti-aging and immunoregulatory properties	[125]
	Ginsenoside Rg_2	Anti-photoaging properties	[126]
	Ginsenoside F_1	Potential skin whitening properties	[127]
Glycine max	Soyasaponins	Potential antioxidant and anti-inflammatory activities	[128]
Trigonella foenum-graecum	Whole extract containing graecunins, fenugrin B, fenugreekine, and trigofoenosides A-G	Potential anti-aging and anti-inflammatory properties	[113]
Nigella sativa	Whole extract containing α-hederin	Potential anticancer and immunoregulatory properties	[129]
Aesculus hippocastanum	Escin and escinol	Inhibition of hyaluronidase	[130]
Allochrusa tadshikistanica	Whole extract containing Saponins	Potential wound-healing effect	[131]
Hedera helix	Whole extract containing α-hederin, hederasaponin-C, and hederacolchiside-F	Potential anti-inflammatory and wound healing properties	[132]
Betula pendula	Whole extract containing saponins	Potential antioxidant properties	[133]
Gypsophila paniculata	Triterpenoid saponins	High emulsifying and potential anticancer properties	[33]
Bellis perennis	Triterpenoid saponins	Potential activity for collagen synthesis-promoting	[134]
	Whole extract containing saponins	Potential photoprotective and immunomodulatory effects	[135]
Calendula officinalis	Whole extract containing saponins	Potential anti-inflammatory and wound healing properties	[136]
Beta vulgaris	Whole extract containing saponins	Potential anti-acne and anti-psoriasis properties	[137]
	Triterpenoid saponins	Foaming and detergent properties	[138]
Saponaria officinalis	Saponins	Emollient washing properties	[69]
	Saponins	Potential antifungal properties	[139]

4.2. Other PdBSs and their potential skincare applications

Apart from saponins, other classes of amphiphilic compounds are also produced by plants. Although their structure is fundamentally different from saponins, they have significant superficial properties that enable them to be considered as potential surface-active agents [49,140].

4.2.1. Proteins as BS

Since plant proteins contain amphiphilic monomers in their structures, they can exhibit different surface properties [141]. Sosa *et al.* [142] studied potential emulsifying applications of proteins derived from *Cajanus cajan* (named PPI8) on the formation of O/W emulsions as well as the influence of ionic strength (0.10 and 0.54) and different pH ranges (2.1, 3.9, 6.3, 8.3). Accordingly, the results revealed high emulsion stability at the ranges investigated, where the critical concentration range of proteins was between 1.5–2.0% (at ionic strength of 0.10) and 1.0–1.5% (at ionic strength of 0.54). Complexation of native wheat protein with conventional surfactants is a practical example of using exogenous proteins to improve cutaneous tolerability of detergent formulations [143]. In this respect, the concentration of free surfactant species that can cause skin protein denaturation would be lowered. The complex can also link to the skin keratin and provide a protective colloidal layer to reduce the skin irritation potential [143,144].

Liu *et al.* [145] noted emulsifying activities of faba bean protein extracts. In this context, they found that enzymatic treatments (either via hydrolysis or cross-linking) and chemical modifications (e.g., acetylation and Maillard reaction) would improve the interfacial activity of extracts. This can also help the physical and oxidative stability of emulsions, together with optimized droplet-size distribution and solubility. For instance, heating at pH 11.0 increases the solubility of fava bean protein isolates from 43% at pH 3.0 to over 90%, which consequently results in more stable emulsions with a smaller particle size. Glutelins are a class of proteins found in certain members of the grass family. Gao *et al.* [146] investigated potential applications of glutelin as an emulsifier of corn oil/water emulsions in acidic environments (pH 4.5). In another study, Ochiai *et al.* [147] revealed anti-tyrosinase activity of rice (*Oryza sativa*) bran protein as a potent source of anti-melanogenic peptides using mouse B16 melanoma cells *in vitro*. This was also marked with high antioxidant and wound healing activity as well as good emulsification properties (with an isoelectric point around pH 4) [148,149]. Researchers have also described other plant proteins with surface activity, including soy proteins, pea proteins, lupin proteins, and gum Arabic [150–152].

4.2.2. Polysaccharides as BS

The term polysaccharide refers to a chain of monosaccharide units that are linked by glycosidic groups. Therefore, they have amphiphilic properties according to the structure of their monomers [152,153]. Shao *et al.* [154] assessed physicochemical properties and the *in vitro* release profile of β-carotene emulsions stabilized by *Ulva fasciata* polysaccharide, gum Arabic, or beet pectin. It was found that through such an encapsulation approach, the chemical stability of the prepared formulation and bio-accessibility would be increased in acidic environments (pH 3.0, 4.0, 5.0) and extreme temperatures (80 °C, 90 °C, 100 °C), particularly after the addition of EDTA or a-tocopherol. Pectin is a soluble polysaccharide found in several plants and is commercially used as an emulsifier and thickener in cooking [155]. Beet and citrus pectin are composed of branched anionic polysaccharides, which show high surface-active properties. Therefore, pectin can be used in cosmetic products as an emulsion stabilizer ingredient and to increase viscosity [156,157]. In addition to its surface activity properties, interest in pectin as an antioxidant, anti-inflammatory, and skin protectant agent is increasing [158,159]. Dambuza *et al.* [160] reported a good *in vitro* radical scavenging ability by pectin extracted from lemon peel, even though it was lower than the IC_{50} of ascorbic acid, which is a standard antioxidant. Polysaccharides are therefore drawing interest to stabilize pharmaceutical formulations or as skin permeation-enhancing agents and antiaging components.

4.2.3. Phospholipids as BSs

Phospholipids are a class of amphiphilic lipids that are composed of two fatty acids, a glycerol unit, and a phosphate group, which are considered the major components of biological membranes. They can self-assemble into lipid bilayer aggregates in aqueous environments by forming a sheet composed of two layers of lipids. Therefore, phospholipid-based emulsifiers are abundantly used in the pharmaceutical industry. Lecithin is a naturally occurring mixture of biocompatible phospholipids derived from several green sources, particularly soybeans, sunflower, canola, and corn [152,161]. It can also be used to improve dermal delivery. Raut *et al.* [162] introduced lecithin organogel as an effective approach for cutaneous delivery of bioactive ingredients. Thus, such a vehicle can form an optically transparent and visco-elastic, heat-stable, and microbial-growth resistant micellar system to partition loaded compounds (both hydrophilic and lipophilic) into the skin. Lysolecithin is generated through the enzymatic treatment of lecithin, resulting in smaller molecules with a lower CMC value [163,164]. Cabezas *et al.* [165] assessed the emulsifying properties of modified (enzymatic and chemical) lecithin (0.1–2.0% w/w) derived from sunflowers, which act against the destabilization processes (creaming and coalescence).

Han *et al.* [166] investigated co-delivery of insulin (hydrophilic) and quercetin (hydrophobic) molecules using a self-assembled W/O/W double emulsion system-stabilized by emulsifying agents (pectin, lecithin, black bean protein, or Tween 80). Their results showed a higher encapsulation efficiency (95.7% for insulin and 93.4% for quercetin), better chemical stability, and solubility as well as bio-accessibility (2.6- and 4.56-fold increase for insulin and quercetin, respectively) with black bean protein-stabilized formulation. Yan *et al.* [167] studied potential applications of hydrolyzed rice glutelin, soybean lecithin, or their mixture to stabilize O/W emulsions. According to their results, better resistance against flocculation and facilitated *in vitro* digestibility were found with soybean lecithin-stabilized formulation.

Phospholipids, particularly lecithin, can provide antioxidant properties via different mechanisms (chelating metals, scavenging ROS, quenching photosensitizers, etc.) [168]. Nasab *et al.* [169] reported potential anti-oxidative and wound healing properties of soy lecithin liposomes. Togni *et al.* [170] also reported antioxidant and antiallergic properties of quercetin along with the reduction of basophil degranulation using a lecithin-based dermal delivery system. Therefore, plant-derived lipids can improve cutaneous permeation and provide better biological responses. Apart from that, plant oils (virgin coconut oil, grapeseed oil, jojoba oil, olive oil, sweet almond oil, argan oil, etc.) can also provide great moisturizing potential (as occlusive and emollient) and nourishing properties for skin health [171–173]. They can also strengthen skin-barrier function and help its regeneration [174].

Fundamentally, most available cosmetic formulations rely on conventional petrochemical surfactants. However, the high-value-added molecules present in plant by-products offer a wide range of possibilities for their applications [49]. Table 3 provides some examples of commercialized cosmetic products containing PdBSs in their formulation. Different kinds of PdBSs, however, are attracting interest due to their potential biomedical applications, especially skincare products. Since they could be used as pharmaceutical ingredients with a wide spectrum of activity, from solubilizing enhancers to hemostasis regulators [22,84]. Compared to synthetics, PdBSs have exhibited higher antioxidant activity as well as good surface-active properties and cleansing properties. They can also provide further biological properties, including anti-inflammatory effects, collagen stimulation, and skin-whitening properties [22,152].

Research on the biological functions of plant-derived BSs would provide a wealth of information for human and plant applications, and has encouraged manufacturers to develop more plant-based products [84,175]. Table 4 represents a list of skincare Patents containing PdBSs, which were gathered using Google Patents and Patentcloud search engines from different office databases such as WIPO (World Intellectual Property Organization), USPTO (United States Patent and Trademark Office), EPO (European Patent Office), and others.

Table 3. Examples of skincare products containing PdBSs in their formulation.

Product name	Brand	Containing BSs from plant origin	Properties	Ref.
Saponins Cream Cleanser	Sachi® Skincare	Saponins of Soapberry (*Shepherdia canadensis*)	A gentle, moisture-rich, and pH-balanced cleanser that helps maintain skin barrier integrity, especially stressed reactive skin.	[176]
Revive Eye Serum	Beauty of Joseon	Saponins derived from red Ginseng	A powerful eye serum that combats collagen and hyaluronic acid loss to increase skin elasticity and brightness while minimizing irritation.	[177]
Ginseng Essence Water	Beauty of Joseon	Saponins derived from red Ginseng	A nourishing and hydrating essence that helps to balance skin's moisture level and protect it from external stimuli.	[178]
Sanskrit Saponins	NIOD	Saponins derived from: *Sapindus mukurossi*, *Acacia concinna*, *Balanites aegyptiaca*, and *Gypsophila paniculata*	A viscous face balm and powerful cleanser for acne-prone skin, containing highly concentrated Ayurvedic surfactants.	[179]
Deep Cleansing Saponin Tea Gel; Forest Herbs	Fresheral®	Saponins derived from: *Camellia sinensis*, *Portulaca oleracea*, and Salvia *sclarea*	A natural cleansing formulation for sensitive skin.	[180]
Anti-wrinkle & Firm Moisturizing Eye Cream; Nordic Bloom	Lumene	Hydrolyzed rice bran protein	This eye cream can enhance skin moisturization, improve its firmness, reduce the appearance of wrinkles around the eye area, and help diminish the appearance of dark circles and puffiness.	[181]
Icelandic Relief Eye Cream	Skyn ICELAND®	Hydrolyzed rice bran protein	This cream is formulated to fight three major eye complaints: dark circles, puffiness, and wrinkles.	[182]
Total Repair Extreme Renewing Conditioner	L'Oréal Paris	Wheat protein	It is a conditioner for extremely damaged hair, which penetrates deep layers and repairs broken fibers.	[183]
Soybean Bouncy Protein Essence	Flaskin	Soybean Protein	This formulation combines the youthful skin biome with energy-rich proteins to address elastic and energized skin.	[184]
Satin Facial Scrub™; Mint	Young Living®	Pectin	This Scrub is made with apricot seed powder and peppermint premium essential oil to gently exfoliate and invigorate skin.	[185]
Black Cherry Collagen Peel	Savor Beauty®	Pectin	It is a cooling concoction containing active enzymes of cherry, pineapple, and papaya for exfoliation to gently remove dead skin cells.	[186]
Hydrating Mask	PCA Skin®	Pectin	It is a hydrating mask with an advanced blend of soothing ingredients and herbal ingredients that reduce irritation.	[187]
Brightening Serum; Glass Face	Auraïha	Lecithin	A plant-based emollient moisturizer suitable for sensitive and blemish-prone skin.	[188]
Tinted Moisturizer SPF 30; Bio Tint	Well People	Lecithin	Light to medium coverage tinted moisturizer with SPF 30 protection.	[189]
Nightly Renewal Cream	Furtuna Skin®	Lecithin	A light moisturizing night cream that boosts the skin's regenerative power to soothe wrinkles, resulting in a completely youthful appearance.	[190]
Opaleze Brightening Serum	Sonäge®	Lecithin	An effective face brightening serum that targets dark spots and skin discoloration.	[191]

Table 4. A list of skincare Patents containing surfactants of plant origin in their formulation.

Patent number	Country of origin	Publication date	Status	Main type of PdBSs	Properties	Ref.
WO2011162954A2	USA	2011-12-29	PCT End - NP	Soy lecithin, as well as *Coffea arabica*, *Ilex paraguariensis*, and *Chrysanthemum parthenium* whole extract, along with some other plant-derived biomolecules and synthesized surfactants	A multi-active skin rejuvenating formulation that is beneficial for various types of skin aging, including wrinkles, redness, abnormal pigmentation, and brown spots.	[192]
CN103565679A	China	2014-02-12	PGPub - Granted	Fresh Ginseng extract containing saponins (ginsenosides: Rg_1 and Rg_2) and amino acids	It is a cosmetic formulation with potential tyrosinase inhibition and whitening effects, skin oxidation resistance, anti-aging properties, and moisturizing effects.	[193]
JP2006213649A	Japan	2006-08-17	Abandoned Appl. (Expired)	Soybean saponins	A cosmetic formulation with potential applications as a dermal cell activator, accelerator of collagen production, and topical antioxidant.	[194]
JPS6383017A	Japan	1988-04-13	Abandoned Appl. (Pending)	A mixture of *Senega officinalis* saponins and onjisaponins	A cosmetic formulation with anti-suntan effect that effectively protects skin from sunlight.	[195]
CN111135110B	South Korea	2014-04-24	Active	Ginsenoside Rg_3	It is a topical skin formulation that contains ginsenoside Rg3 with potential for anti-dandruff effects.	[196]
JP6233896B2	Japan	2017-11-22	Active	A mixture of Soybean polysaccharide, sugar Beet pectin, and other plant-derived biomolecules, along with some synthetized surface-active compounds	A cosmetic formulation with low irritation and excellent cleansing properties.	[197]
WO9962480A2	France	1999-12-09	PCT End - NP	Saponins or sapogenols derived from Soya or Medicago	A cosmetic formulation for increasing the amount of collagen IV synthesis as an anti-wrinkle treatment	[198]
EP2958630A1	France	2015-12-30	PGPub - Granted	A mixture of synthesized surfactants and plant-derived polysaccharides, such as amylopectin	A cosmetic gel formulation for makeup containing an aqueous phase and at least an oil phase	[199]
CN113230172B	China	2021-05-24	Active	A mixture of synthetized surfactants and triterpenoid saponin derived from *Centella asiatica* as well as ginsenoside derived from Ginseng	A cosmetic formulation with potential properties to resist skin aging, reduce wrinkles, inhibit acne and scar formation, cause skin whitening, and promote wound repair	[200]
US20130101662A1	USA	2013-04-25	PGPub - Granted	Hydrolyzed Wheat protein and hydrolytic Soyabean protein	A topical formulation with potential applications to treat skin, mucous membranes, and hair disorders	[201]
US9089504B2	South Korea	2012-08-20	Active	Green tea saponins	A topical cosmetic formulation with potential anti-aging properties	[202]
CN104688607A	China	2015-06-10	Abandoned Appl. (Pending)	Saponin derived from *Panax notoginseng*, *Angelica*, and *Salvia miltiorrhiza*	A night cream formulation suitable for all types of skins due to high moisturizing potential, skin tightening, nutrition supply, skin whitening, and nerve calming properties	[203]

5. Perspective and challenges

According to the United Nations, the world population will increase to 9.7 billion people by 2050 [204]. Undoubtedly, such a prospect raises concerns about the global consumption of fossil fuels, biomass, and annual waste generation, underscoring the necessity to move towards more sustainable resources. Moreover, unnecessary exploitation of natural resources, including carbon, water, and land, may also lead to waste overgeneration, greenhouse gas production, and excessive consumption of economic resources. Therefore, natural by-products are gaining international attention, not only for pollution-related issues, but also to achieve better outcomes in terms of safety and efficacy [49,205].

Thus, the development of commercial products completely based on natural raw materials is suggested. However, this has been a challenge for scientists, not only because they are limited, but also due to their costly isolation and/or extraction process compared with the chemicals [22]. In addition, finding materials that can be rationally justified, standardized, and formulated into commercial products is another challenge due to the biological differences among individuals of the same species. Therefore, the physicochemical and biological properties of materials obtained from natural sources must be meticulously analyzed before entering the commercial market [206,207]. Among the purification techniques, solvent-based methods such as liquid-liquid extraction are mainly used to obtain BS-rich extracts. The process may assist emerging techniques of ultra-centrifugation or ultra-homogenization, followed by residue filtration to concentrate the extracts [43,44]. However, the cost of extraction and processing of natural surfactants is relatively more expensive than synthetics [208]. As a result, these products do not enjoy market popularity despite their high safety and favorable properties. Therefore, the introduction of simple and cost-effective extraction processes is attractive in their commercialization prospects. In this essence, green extraction methods (supercritical CO2, pressurized liquid extraction, subcritical fluids, or enzyme-assisted extraction to protect sensitive compounds), orthogonal purification (solid-phase extraction, liquid-liquid extraction, and regulated crystallization for amphiphilic compounds), and process analysis (inline GC-MS, HPLC/UPLC, NMR, or Raman for real-time quality monitoring) may be useful to achieve higher extraction and purification efficiency [209–211].

From a technical point of view, genetic and metabolic engineering can be implemented to optimize BSs' function and composition (e.g., targeted expression of specific compounds) and to regulate biosynthetic pathways (either to reduce by-products or to adjust the desired hydrophilic-lipophilic balance). Furthermore, the optimization of bioprocesses should be carried out through: 1-Culture media modification (carbon/nitrogen (C/N) balance, trace elements, and precursors that improve yield and consistency); 2- feeding strategies (fed-batch, C/N ratios, and oxygen transfer to control molecular weight and micellization properties of BS); 3- process intensification (high-density cultures, continuous processing, and *in situ* product removal to reduce product inhibition); and 4) downstream processing (selective extraction, precipitation, or membrane-based purification to manage complexation of glycosidic moieties) should be carried out [209,212–215]. Despite plant breeding being able to help improve optimization results by selecting reliable genotypes (for greater access to precursors and compatible metabolite profiles), agricultural practices can minimize environmental variations (soil, irrigation, and climate-controlled cultivation). In other words, the goal is no longer just to maximize yield, but to optimize the process and maintain desired properties. Omics technologies are a set of tools used to study and analyze biological systems by looking at different molecular components. In the case of PdBSs, the key approaches include metabolomics (study of the metabolites) and genomics (studying the entire set of genes) [216–218].

Metabolomics profiles hundreds to thousands of small molecules (primary and secondary metabolites) in a single run using LC-MS/GC-MS techniques and provides a "fingerprint." The goal of the optimization process is to match this fingerprint to the desired profile, whereas genomics helps identify the biosynthetic pathways of the target compounds by selecting growth conditions or harvest time. Accordingly, after the objective is defined (extraction of the desired BS) and the design of experimental conditions and major parameters are completed (time, pH, pressure, solvent, temperature, etc.), the omics analysis can be conducted to generate a comprehensive data set and optimize the favorable profile (bioactivity, emulsification, self-assembly, etc.). In this context, key marker compounds (responsible for the effect) and optimal conditions (yielding the highest desired activity) would be identified. However, as a quality control metric, the use of an omics-defined fingerprint predicts optimal conditions and helps in validation recovery and scale-up [217,219,220]. However, omics-based optimization offers advantages over traditional methods, including robustness (adjusting processes to achieve critical compounds), discovery-driven (introducing new favourable compounds), comprehensive quality control (studying the active profile rather than a single marker), and data-driven logical models (reducing trial and error). Nonetheless, issues such as data complexity (management, processing, and interpretation of large datasets), cost and equipment demand, personnel expertise, and scale-up conversion from lab-scale to industrial-scale remain major challenges for holistic use [217,221–223].

The Quality by Design (QbD) process can also help achieve targeted purity, spectral fingerprint, functional activity (surface tension reduction, CMC, etc.), and thermal stability [43,211,215,224]. Alongside QbD, the use of Design of Experiment (DOE) to investigate promoter strength combinations, enzyme ratios, harvest time, and extraction parameters is prominent [224,225]. This is because DOE-based optimization can effectively enhance performance robustness under environmental conditions (temperature, light, and humidity) and ensure batch-to-batch consistency. Moreover, benchmarking to determine activity parameters (CMC, surface tension, and emulsification index) related to end-use specifications (cosmetics and detergents) must also be respected [43,210,215].

It is essential to note that some plant-based biomolecules are primarily produced as toxins against host invaders [42,208,226]. As a result, care should be taken to select non-toxic PdBSs when using these plant materials for commercial purposes [22,84]. Furthermore, many of these biomolecules also possess significant antimicrobial and anti-herbivore activity as well as anti-inflammatory, antifungal, anti-cancer, and antiviral properties. Growing consumer demand and restrictive environmental laws have further supported the substitution of synthetic products worldwide [227,228]. Therefore, in future research, researchers should focus on identifying some natural plant surfactants for such purposes [84]. In the case of saponins, there are over 100 families of plants, including some marine plants, that produce them. Therefore, there is a need for more studies that can identify reasonable sources, affordable extraction methods, and contribute positively to better utilization in the proposed fields. Accordingly, PdBSs could effectively replace synthetic counterparts and positively assist the global green program. Emphasizing their safety and efficacy, as well as educating consumers about the potentially dangerous consequences of chemically synthesized materials, would help change consumer attitudes and popularize natural surfactants [16,22].

The concept of combining the biosynthetic capabilities of microbes with the metabolic diversity of plants could lead to the creation of novel hybrid BS systems. In other words, hybrid systems use microorganisms (usually engineered bacteria or yeasts) that can interact with plant hosts or plant-derived systems to produce, modify, or enhance the BS yield, which neither could achieve alone. This goal can be achieved through: 1- Symbiotic systems (engineering endophytic microbes to produce BS in the plant), where continuous and renewable feed is provided by the plant, reducing downstream processing costs and sterilization requirements; 2- plant-microbe co-culture (simultaneous cultivation of plant cell with BS-producing microorganisms in bioreactors) in which plant cells help provide specialized metabolites (BS precursors) needed for the production of by-products by microbes; and 3- enzyme-biological pathway integration (expressing the plant-derived enzymes in microbial hosts to modify BS production), which lead to increased biocompatibility, targeted bioactivity, and novel functional properties [229–233]. In this regard, Zaveri and Dasgupta [234] explored the BS-producing potential of bacterial endophytes isolated from *Wedelia urticifolia* and *Lantana camara*, indicating an untapped potential in fields of biotechnology. Moreover, such systems may struggle with some critical questions regarding safety, biocompatibility, cost-effectiveness, feasibility, and scale-up before commercial use. However, further studies would indicate research gaps as well as future directions in this field.

6. Conclusion

Surfactants are known for reducing the interfacial tensions of liquids and high detergency. Therefore, they are traditionally used as common ingredients in cleaning products, especially household detergents. However, their amphiphilic properties have drawn interest from different industrial fields, including paper processing, pharmaceuticals, personal care products, and cosmetics. Since surfactants are widely used in different industries, a wide variety of surfactants have been synthesized to meet specific consumer demands. Although these chemicals are obtained from relatively cheap petrochemical origins, they are mostly toxic, non-biodegradable, and are inclined to cause significant negative environmental damage, whereas surfactants of natural origins mostly have an eco-friendly nature with high potential for biocompatibility. Despite the high cost of net production, natural surfactants can be obtained from different biological origins, especially plants.

Compared to other BSs, particularly microbials, PdBSs could offer a better yield of extraction along with certain surface activities and biological effects. They are also available, as they are easily produced from widely cultivated crops, despite specific culture media. Moreover, due to their essentially green nature, fewer regulatory considerations and safety issues are required. These facts, combined with the fundamentally positive view toward plants and the increasing number of adverse effects with synthetic counterparts, demonstrate an irreplaceable position for PdBSs in the cosmetics industry over the next few years. In this review, a brief overview of PdBSs is provided, emphasizing their potential applications in cosmetics and skin-care products. Hence, new opportunities, prospects, and challenges associated with the development of plant-based cosmetics formulations were examined. However, there is an unlimited number of bioactive compounds produced by plants, and they are less toxic and harmful than chemically synthesized counterparts.

There is a need for further exploration processes for proper identification and extraction of new PdBSs. In this context, the difference in the amount and type of produced BSs may be controversial. As such, depending on the location of cultivation, the amount of irrigation, light reception, and nutrient consumption, the same plant can provide different byproducts. Although this fact does not pose a large impact on specific applications at individual scales, it can bring about important changes for standardization and optimization. However, the circular bioeconomy, as well as the demand for sustainable and "green" materials, not only presents BSs as an alternative to break free from dependence on petrochemicals but also considers them as potential major players with unique capabilities. Therefore, the synergy between plant-derived substances and biotechnological innovations is a key lever for progress.

Moreover, some issues may remain as major research gaps such as: 1- Discovery and characterization (structure-function relationships, biosynthesis, and genetic regulation); 2- limited understanding for the structural features that determine physicochemical properties (CMC, surface tension reduction, etc.) and biological activities (antimicrobial, immunomodulatory, etc.); and 3- introducing standardized extraction methods (to avoid variable results and inconsistent performance), as well as scalable cost-effective, and green purification techniques. On the other hand, bridging the gap between the lab and the market may also cause some industrial and logistical gaps, including: 1- The lack of a robust and year-round supply chain; 2- efficient pretreatment methods; 3- techno-economic analysis for process intensification at the lab scale; 4- compatibility studies of formulation (how BSs interact with other components): and 5- issues toward shelf-life stability. However, although biocompatibility is known, the lack of detailed understanding of the exact mechanism of their interaction with cell membranes and rigorous controlled clinical studies can lead to biomedical gaps.

In this context, the use of strategies such as: a) Stimuli-responsive drug delivery systems that release loaded components in response to specific environmental changes (pH or enzymes); b) structure-based toxicity reduction (to maintain therapeutic activity but reduce cytotoxicity); c) dedicated research on formulation science (to achieve better performance, stability, and cost-effectiveness goals); d) comprehensive techno-economic analysis (to identify real cost drivers and environmental needs); e) in-line process monitoring (to optimize real-time yields); f) pilot-scale bioreactors (to optimize biomass fermentation); and g) development of standardized methods for consistent extraction can help future directions (industrial/biomedical) move from potential to practical applications. Moreover, overcoming economic challenges and scaling up will determine the pace of their transition from a promising green alternative to a fundamental pillar of the post-petrochemical surfactant industry.

Use of AI tools declaration

The authors confirm that they did not utilize any Artificial Intelligence (AI) tools in producing this article.

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Conflict of 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.

Author contributions

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