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# 12

## Saponin-Based Surfactants

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### 12.1 Introduction

Saponins belong to a diverse group of naturally occurring surface-active compounds. They occur in different tissues of a large number of plant species belonging to nearly 100 families. Although predominant in angiosperms, saponins also occur in some ferns (species of *Polypodium* and *Cyclamen*) and possibly algae, and in certain lower marine organisms. They can be found in different plant parts including roots, shoots, flowers and seeds. Their common feature is the formation of a soapy lather when shaken in water solution. This property has for a long time been used in the identification of saponin-containing plant species as well as for their quantification. The height of the froth when shaken in a glass tube and the time of its disappearance was a semiquantitative test. Since some other plant components may also form froth when shaken, a number of species were misclassified as saponin-containing plants, but in general most literature concerning saponin distribution in nature was based on this test.

In the Orient plants rich in saponins were used as a soap substitute in folk medicine. Thus, in many cases the common names of saponin-rich plant species were derived from this feature, e.g. soaproot (*Chlorogalum pomeidianum*), soapbark (*Quillaya saponaria*), soapwort (*Saponaria officinalis*), soapberry (*Sapindus saponaria*), soapnut (*Sapindus mukurossi*), soapjacob or ra-ra Ayoub – ‘bring back youth and health’ (*Glinus lotoides*), which is based on the folklore belief that the Prophet Jacob (Arabic = Ayoub), having dermal disease, cured himself by rubbing his skin with this plant. For these reasons saponins found some industrial interest mainly as surface-active or foaming agents. When occurring in food, saponins were for a long time considered as antinutritional compounds

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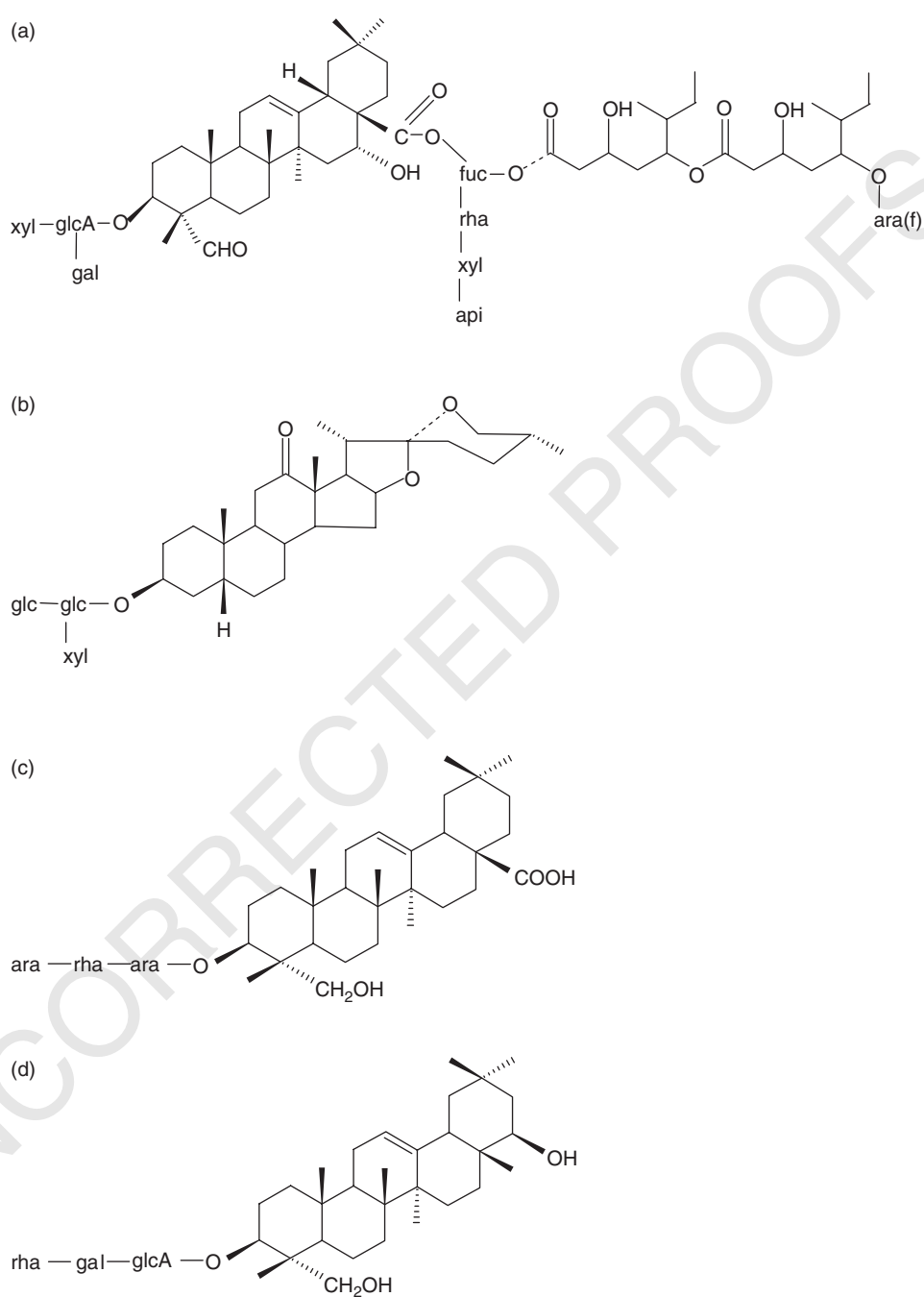
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due to their throat irritating properties and some bitterness; therefore food processing was targeted to remove these undesirable chemicals from the diet. Also the goal of breeding programmes of cultivated species was directed into the removal of these compounds, e.g. low-saponin alfalfa varieties. Nowadays saponins are considered in some cases as health beneficial food components due to their cholesterol lowering and anticancer properties, e.g. soya bean, garlic and onion.

## 12.2 Molecular Properties

Saponins occurring in plants are predominantly glycosides possessing one, two or three sugar chains attached to the aglycone, and the terms monodesmosides, bidesmosides or tridesmosides have been given to them, respectively (Greek *desmos* = chain). The aglycones, also called sapogenins, which are the nonpolar parts of the molecule, may have a steroidal or triterpene backbone (Figure 12.1). The monodesmosidic saponins have a sugar chain attached usually at C-3 of the aglycone. The bidesmosides have two sugar chains, most often with one attached through the ether linkage at C-3 and one attached through the ester linkage at C-28 in triterpene saponins or an ether linkage at C-26 in steroidal saponins. The tridesmosides may have a third sugar chain linked through an ether or ester link at one of the OH or COOH functional groups occurring on the aglycone. Some authors also include in the saponin family steroidal glycoalkaloids occurring predominantly in the Solanaceae family and cucurbitacines, the bitter principles of some Cucurbitaceae species. The most common monosaccharides appearing in the sugar chains include: D-glucose (glc), D-galactose (gal), D-glucuronic acid (glcA), L-rhamnose (rha), L-arabinose (ara), D-xylose (xyl), D-apiiose (api) and D-fucose (fuc). The steroidal skeletons have in most cases furostanol or spirostanol form; furostanol glycosides usually have a bidesmosidic and spirostanol monodesmosidic nature. Both steroidal and triterpene sapogenins may have a number of functional groups (–OH, –COOH, –CH<sub>3</sub>) causing great natural diversity only because of the aglycone nature. This diversity has been multiplied by the number and composition of sugar chains. Thus, in most cases when the term ‘saponins’ is used, this should be understood as a complex mixture of glycosides with the same sapogenin or with different sapogenins. Their composition and the concentration can be different in plant parts (roots, shoots, leaves, flowers, fruits) and can be strongly influenced by environmental factors and the state of development of the plant.

The complex structure of saponins may undergo chemical transformations during storage or processing, which in turn may modify their properties and biological activity. The glycosidic linkage (between the sugar chain and the aglycone) and the interglycosidic linkages between the sugar residues can undergo hydrolysis in the presence of acids/alkali, hydrothermolysis (heating in the presence of water) or enzymatic/microbial transformations, resulting in the formation of aglycones, prosapogenins (partially hydrolysed saponins), sugar residues or monosaccharides depending on the hydrolysis method and conditions [1]. Complete acid hydrolysis yields the constituent aglycone and monosaccharides, whereas under basic hydrolysis conditions, cleavage of ester-linked sugar chains results in the formation of prosapogenins [2]. The solubility behaviour of the parent aglycone can be markedly different from the saponin due to its lipophilic nature.



**Figure 12.1** Basic structures of saponins: (a) triterpene saponin QS-21 from *Quillaya saponaria*; (b) steroidal saponin from *Yucca schidigera*; (c) hederagenin glycoside from *Sapindus mukurossi*; (d) soyasaponin I from soyben (*Glycine max*).

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### 12.3 Sources of Saponins

The triterpene saponins are predominantly present in dicotyledons (Leguminosae, Araliaceae and Caryophyllaceae) while steroidal saponins occur predominantly in monocotyledons (Liliaceae, Dioscoreaceae and Agavaceae). The main dietary sources of saponins are leguminous plants, which include soya bean, chickpea, mungbean, peanuts, lentils and beans, but they are also present in some other edible plant species like oats, leek, garlic, asparagus, tea, spinach, sugar beet, sesame and yam. The concentrations of saponins in these products are not very high, ranging from 0.1 up to 2% in dry matter [3], but they are recognized as antinutritional factors, which should be eliminated by breeding or processing. Recent trends in nutrition showing the beneficial effect of some natural products on human health stimulated some research also on saponins. They were shown to express different kinds of activities including anticarcinogenic, antioxidant, hypcholesterolemic, hepatoprotective, antiviral, antifungal and antibacterial functions *in vitro* or *in vivo* animal tests. Once consumed they may increase the intestinal permeability and interact with bile acids. The largest number of nutritional experiments has been performed on soya bean saponins, but saponins from oat, quinoa, sunflower, garlic and tea have also been studied.

The main nonfood sources that have been commercially used in food and cosmetic industries include: soap bark tree (*Quillaya saponaria*), Mohave yucca (*Yucca schidigera*), fenugreek (*Trigonella foenum-graceum*), horse chestnut (*Aesculus hippocastanum*), licorice (*Glycyrrhiza glabra*), soapwort (*Saponaria officinalis*), gypsophylla (*Gypsophylla paniculata*), sarsaparilla (*Smilax regelli*) and some others (Table 12.1).

The concentration of saponins in some of these species is high. The best sources of these compounds seem to be *Yucca schidigera* and *Quillaya saponaria*, in which concentration of saponins reaches 10% of dry matter. Moreover, these two plants have been given by the Food and Drug Administration (FDA) a generally recognized as safe (GRAS) label, and are accepted as safe food, feedstuff and cosmetic ingredients in the United States. Since 1962 these species have been accepted as emulsifiers and foaming agents at a maximum concentration of 20 ppm in the UK and Japan. In Japan the saponins from two other sources, e.g. soya bean and Enju, have been accepted for food applications.

### 12.4 Saponins as Emulsifiers and Surfactants

The ability of a saponin to foam is caused by the combination of the nonpolar sapogenin and water-soluble side chain (see Figure 12.1(b) to (d)), which is similar to the structure of most synthetic surfactants having lipophilic and hydrophilic molecular parts. In synthetic surfactants lipophiles are usually similar from one surfactant to another (i.e. straight or branched alkyl chains) but hydrophiles show a range of chemical types. This has been the basis for surfactant classification as anionic, cationic, nonionic and amphoteric. In the case of saponins, hydrophiles are built of a sugar chain, which can differ in the length, branching, substitution and composition (glucose, galactose, rhamnose, arabinose, xylose, apiose and uronic acid), while the lipophiles may have a steroidal or triterpene structure. Hence, saponins of this composition are nonionic surfactants. Saponins with one sugar

**Table 12.1** Plant sources for industrially utilized saponins

Plant source	Common name	Use	Plant parts	Concentration (%)
<i>Aesculus hippocastanum</i>	Horse chestnut	Aescin source	Seeds	10
<i>Agave sisalana</i>	Sisal, henequen, hemp plant	Hecoginin source	Leaves	>12
<i>Balanites aegyptiaca</i>	Heglig, lalob, desert date	Diosgenin and yamogenin source	Fruits, seeds, bark	22–27
<i>Chlorogalum pomeridianum</i>	Soaproot, California soap plant	Amolonin source	Bulbs	19–22
<i>Costus speciosus</i>	Crape ginger, Malay ginger	Diosgenin source	Rhizomes	3.86
<i>Digitalis lanata</i>	Woolly foxglove, Grecian foxglove	Digoxigenin source	Leaves	–
<i>Digitalis purpurea</i>	Purple foxglove, lady's foxglove	Digoxigenin source	Leaves, seeds	1.25
<i>Discorea composite</i>	Yams, barbasco	Diosgenin source	Rhizomes, roots	4–6
<i>Glinus lotoides</i>	Soap Jacob, lotus sweetjuice	Hopane and oleanane source	Roots, leaves, seeds	16.5
<i>Glycine max</i>	Soya bean	Soyasaponin source	Sprouts, seeds	0.5
<i>Gypsophilla paniculata</i>	Baby's breath	Gypsogenin source	Roots	>10
<i>Quillaya saponaria</i>	Quaillaya, Murillo's-bark	Soaps, foaming agents	Bark	≥25
<i>Smilax</i> spp.	Sarsaparilla	Smilagegnin source	Rhizomes, roots	2
<i>Solanum</i> spp.	Bitter nightshade, black nightshade	Solasodine source	Fruits, stems	0.3–0.8
<i>Sapindus mukurossi</i>	Soapnut	Hedragenin source	Fruits and roots	20
<i>Sapindus saponaria</i>	Soapberry	Hedragenin source	Fruits	11
<i>Tribulus terrestris</i>	Puncturevine, yellow vine and goathead	Protodioscin source	Fruits	>20
<i>Trigonella faenum graecum</i>	Fenugreek	Diosgenin source	Seeds and leaves	8–10
<i>Yucca schidigera</i>	Mohave yucca, Joshua tree	Soaps, foaming agents	Stalk and roots	10

Adapted from W. Oleszek, Saponins, *Natural Food Antimicrobial Systems*, 2000, CRC Press.

chain have the best foaming characteristics. For saponins with two or three sugar chains the foaming ability decreases and in some saponins no foaming in water solution has been observed, but due to their chemical structure they are still considered as saponins. The emulsifying properties of saponins are due to the fact that they have a salt-free nature, making them less likely to be affected by alkaline or acid conditions.

In water solution saponins form micelle-like aggregates [4] and show a critical micelle concentration (CMC). Below this concentration, molecules remain unassociated. An abrupt change in physical properties appears when the concentration surpasses the CMC and the solute starts to form micelles. Soya bean saponins, the saponins from *Saponaria officinalis*, and *Quillaya saponaria*, form micelles in aqueous solutions, the size and structure of which are dependent on the type of saponin. Commercial 'saponin white' from *Saponaria officinalis* and soya bean saponins form small micelles consisting of only two molecules, while the aggregates of saponin of *Quillaya saponaria* consist of 50 molecules, and appear to be significantly less hydrated [5]. These differences are quite unexpected as aglycones of quillaya saponin differ from the aglycone of 'saponin white' only by one hydroxyl group. Presumably they aggregate by hydrophobic interaction of their aglycones (as for other surfactants), leaving the hydrophilic sugar groups exposed to the water. The micelle-forming properties and the aggregation number (number of monomers in a micelle) of *Quillaya* saponins were affected by temperature, salt concentration and pH of the aqueous phase. At 25 °C, the values of the CMC of *Quillaya* saponins were in the range of 0.5 to 0.8 g/l. The CMC increased with temperature and pH but decreased with increasing salt concentration [5]. The shape of the micelles depends also on the saponin structure. The micelles formed by 'saponin white' and *Quillaya* saponins appear as elongated and filamentous, while those formed by soya bean saponins appear spherical [5]. Probably the reason for these differences is in the aglycone structures. The soya bean aglycones, unlike the aglycones of *Saponaria officinalis* and *Quillaya saponaria* saponins, do not possess carboxylic functions and therefore they are more uniformly hydrophobic.

The presence of carboxylic acid in the saponin molecule may strongly influence the surface activity, emulsion stability or zeta potential of the emulsion droplets. Not only the presence but also the location in the molecule has been extremely important. This can be shown by the comparison of surface activity of soyasaponin I, the dominant saponin of soya bean and monodesmosodic saponins of *Sapindus mukurossi* [6]. Soyasaponin I contains the carboxylic group in the hydrophilic sugar chain part of the molecule. The carboxylic groups dissociate in the aqueous phase and form free carboxyl anion, which increases the solubility of a molecule in water. In contrast, the saponins of *Sapindus* contain the carboxylic group attached to the aglycone part of the molecule, which is hydrophobic, and the dissociation of this carboxylic group is very low (Figure 12.1(c) and (d)). Due to these differences the surface activity, emulsion stability and foamability were higher and the surface and interfacial tensions were lower for *Sapindus* saponins as compared to soyasaponin I. However, the creaming stability of soyasaponin I was higher than that of *Sapindus* saponins.

Saponins can also form mixed 'sandwich-like' or 'pile of coins like' micelles with bile acids. These are much larger than the micelles of saponins alone and again they differ depending on the structure of the aglycone. Saponin white and *Quillaya* saponin

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form filamentous structures with bile acids, while the soya bean saponins have a loose, open structure with considerable penetration of water [5]. The ability of saponin to form these stable micelles with bile acids has very important nutritional consequences. The food and feedstuff containing saponins increase fecal excretion of bile acids, which in consequence leads to their reduced reabsorption and to lowering of the plasma cholesterol concentration.

Saponins also affect the permeability of intestinal cells by forming addition complexes with sterols (e.g. cholesterol) in mucosal cell membranes [7]. This leads to destabilization of the membranes and an increase in the permeability of intestinal mucosal cells, which inhibit active nutrient transport. Thus this facilitates the uptake of substances to which the gut would normally be impermeable, e.g. milk allergen  $\alpha$ -lactoglobulin.

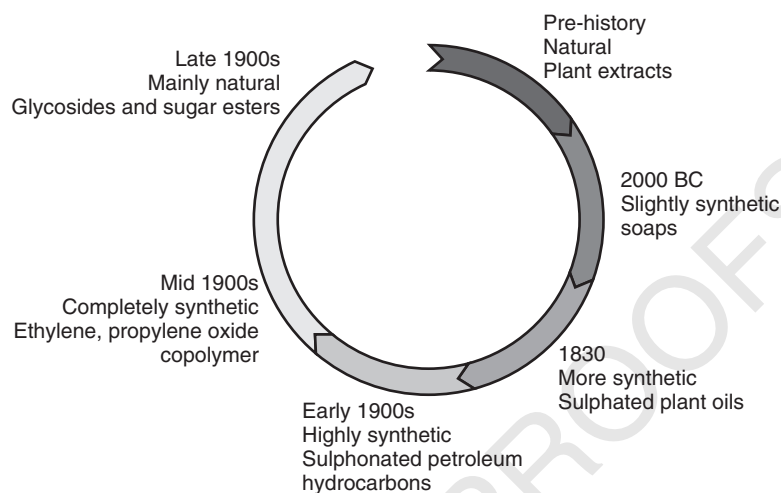
## 12.5 Application of Saponins as Surfactants and Emulsifiers

In the early days of mankind development of different plants and plant extracts were explored for personal hygiene purposes. However, this was not an efficient way to meet demands of a growing human population. Thus, the natural surfactants were replaced with different synthetic products. The synthetic chemicals that enter our environment have usually no 'ecological history' and have been very slowly degraded by microorganisms. Those synthetic chemicals may have detrimental effects on human health, being the main factor of so-called 'civilization diseases'. This includes also the common synthetic surfactants that can have a negative effect such a skin irritation. Thus, there has been an increasing interest in once again using natural products that could substitute for synthetic ones. Current pressure to move away from nonrenewable petroleum feedstocks and towards plants as a source of raw materials has led to much effort in developing surfactants from oleochemical feedstocks. Many recently developed surfactants are the result of an attempt to satisfy modern consumers' desire for products to be 'more natural'. Thus, the history of surfactant development has turned full circle, as demonstrated by soap production (Figure 12.2).

Two major natural surfactants being used include lecithin, an emulsifier used in chocolate and ice cream manufacture, and plant saponins. However, the use of saponins has some limitations. First of all, these compounds are not as potent surfactants as the synthetic ones, and, second, the supply from plant sources has been quite limited, which makes these products less available and rather expensive.

One of the most important sources of saponins has been *Yucca schidigera*, which is native to the southwestern United States and Mexico. Native Americans used this plant to make soap. Currently, most commercial production of *Y. schidigera* products takes place in Mexico (DesertKing Int., ChulaVista, California, USA). The trunk of the plant is the part used. The logs are mechanically macerated and the macerated material is subjected to mechanical squeezing in a press, producing yucca juice. The juice is concentrated by evaporation, with the concentrated product referred to as an extract. The term 'yucca extract' is slightly misleading, in that the plant juice is removed by mechanical means, rather than by solvent extraction. Their antifungal and antibacterial properties are also important in cosmetic applications, in addition to their emollient effects.





**Figure 12.2** Soap development going full circle.

From T. Hargreaves, *Chem. Br.*, 2003, 39 (7), 38–41 (<http://www.rsc.org/chemistryworld/Issues/2003/July/amphiphiles.asp>). Reproduced by permission of The Royal Society of Chemistry.

The second saponin source of commercial value is *Quillaya saponaria*, found in the arid areas of Chile. The bark of the tree is the part used and has been used as shampoo in Chile for hundreds of years. *Yucca* and quillaya extracts are commonly used as foaming agents for beverages such as root beer (6–7 fluid ounces of yucca and 3.5 ounces of quillaya per 100 gallons of syrup). These have also been used in other soft drinks (1–2 fluid ounces per 100 gallons of syrup) and cocktail mixes. These phytochemicals have also commercial applications such as ore separation in industrial and mining operations, and are useful as components in products such as photographic emulsions, cosmetics and shampoos.

As a natural emulsifier *Quillaya* and *Yucca* saponins have been used in the following ways for products patented in Japan (Natural foaming agents quillaya and yucca, DK Int. commercial leaflet):

- to emulsify oil-based flavours for candy,
- to prevent precipitation in a protein containing liquid composition,
- to help prevent oil separation in mayonnaise,
- for use as a leavening agent in the bakery industry,
- to produce an oil in a water-type emulsion composition,
- to increase stability of cream when added to coffee,
- as a natural dispersing agent for waxes used in food coatings.

A unique organic toothpaste characterized by the use of *Quillaya* and *Yucca* saponins as the cleansing and foaming agent has been developed. The content of saponins may form up to 10% by weight of the toothpaste [9].

The crude saponin fraction from the pericarp of *Sapindus mucurossi* Gaertn., which grows in China and Japan, has been used as a natural detergent and as foam-stabilizing

agents in chemical fire extinguishers in Japan. The saponin extract from this plant has been listed in the Japanese Cosmetic Ingredient Codex, and is authorized as an ingredient in cosmetics by the Ministry of Health and Welfare of Japan. This saponin cannot be used as a food ingredient, as hederagenin glycosides and sesquiterpene oligoglycosides, which are components of 'crude saponins' from this plant, can be toxic. Due to their antidermatophytic activity they have been very promising as raw materials for ingredients to be used in cosmetics. Dermal toxicity tests did not show primary dermal irritation, sensitization, phytotoxicity or photosensitization effects [10].

Other sources of saponins that have been studied for possible commercial application include soapwort *Saponaria officianalis*, whose foliage yields a glycoside capable of wetting, foaming and grease dispersion – the very qualities that we recognize in a modern detergent. These natural glycosides have been used for specialized processes, such as washing delicate fabrics. A new quaternary ammonium compound, hydrolysed ginseng saponin quaternary (HGSQ), from Korean ginseng (*Panax ginseng*) saponin and 2,3-epoxypropyltrimethyl ammonium chloride, has been developed as a conditioning agent for hair care products. This structure has a hydrophobic group from the aglycone of ginseng saponin, which is biologically active and considered as the most important component of Korean ginseng [11].

The best hair loss shampoo formulations can also incorporate saponins, from soap bark, soapwort, sarsaparilla and ivy. These saponins make a very good lather but have low cleansing properties. To get appropriate detergency for washing hair, a high concentration of saponins is required, but a high concentration can be harsh to the hair fibre. Therefore, while formulating shampoo, these natural surfactants are generally combined with synthetic ones to ensure good cleansing and satisfactory cosmetic qualities.

The triterpene saponin has been patented in the USA as an effective component of fire-fighting foams [12]. Saponins were used in very early fire-fighting foams as foaming agents, but have long since been discontinued due to their high cost, which makes them unsuitable for use as foaming agents, given the existence of cheaper alternatives. It was invented under the patent that the use of low levels of a saponin (maximum 2%, by weight) gives a synergistic relationship between the saponins and surfactants present in the formulations, which provides a surprising and significant reduction in the amount of surfactants needed for effective fire-fighting performance. A considerable improvement in the heat resistance of the foam formulations is also observed.

Due to the foaming abilities saponins may also be used as emulsifiers helping in degradation of xenobiotics like polycyclic aromatic hydrocarbons (PAHs). The increased solubility of PAH in the presence of saponins make them easily available for degrading bacteria [13]. An aqueous preparation containing vitamin E, prepared by emulsifying or solubilizing vitamin E in an aqueous phase in the presence of a saponin, shows excellent transparency and thermal stability, and can be widely used in the fields of medicines, cosmetics, foodstuffs and animal nutrition [14]. The tea saponin paraffin emulsifier (TS-80 emulsifier) has been widely used in the building board industry. Because of its small oil droplet size, level of degree and good stability, the emulsion's character is much better than general emulsifier such as: alkyl sodium sulfonate, sodium oleate and ammonium oleate.

The addition of a small amount of a saponin in an aqueous enzyme-based composition containing a bacterial inhibiting stabilizer provides a product that is an effective water clarifier and solid surface cleanser. These compositions may be used to clean metals and metal-plated surfaces, such as stainless steel and chrome plating, plastics, plastic composites, ceramics, painted surfaces, wood, glass, textiles, carpeting, animal hair and skin, and the like, to remove a wide variety of food, animal and cosmetic induced stains, dirt and grime, oil, grease and the like. The composition provides superior deodorizing capabilities of such soiled surfaces [15].

The surfactant activity of saponins also finds some application in animal production. Feed grains such as barley, wheat and oats contain nonstarch polysaccharides (NSPs) such as  $\alpha$ -glucans, which are viscous gums that are poorly water soluble. They cause a 'plugging-up' of the intestinal mucosa in poultry because of their high viscosity. Saponins via their surfactant activity might be effective in improving the water solubility of NSP and in consequence the feeding value of barley, wheat and oats for poultry. However, this concept needs further study. Saponin-based surfactants may also influence starch characteristics and ruminal dry matter and starch degradability of steam-flaked grain. The mechanism by which the surfactant enhanced the degradability was not known. Ageing of the hot flakes results in a quadratic decrease in dry matter and starch ruminal degradability. The ageing process affects starch gelatinization enthalpy values of flaked grain in a manner opposite to that observed for ruminal dry matter and starch degradation. This phenomenon is most likely explained by increased starch intramolecular associations or crystallinity associated with starch annealing, or both. Because the rate of degradation was not affected by the surfactant, the increase in degradability was attributed mainly to increases in dry matter and starch solubility [16].

### Acknowledgement

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**Queries in Chapter 12**

- Q1. Please clarify if the abbreviation 'FDA' should be expanded as 'Food and Drug Administration' here. 1
  - Q2. The references 4 and 7 have not been listed in the reference list. Please provide the reference details 2
  - Q3. Please provide the author's names for references 9,12,14 and 15. 3
  - Q4. Please provide the year of publication for references 14 and 15. 4
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