



## Potential Applications of Textile Wastes and By-products in Preparation of Textile Auxiliaries

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### Abstract

Ever since the Stone Age, humans have preferred natural products and materials for better health and comfortability. Wool and natural silk have been used in the textile clothing thousands of years ago. The performance and appearance attributes of wool and silk make them superior for many applications. On the other hand, the textile industries are technically, economically, socially, and environmentally related to some of the sustainable development goals (SDGs) of the United Nations Agenda 2030. For instance, the item number 12 in the SDGs aims to ensure sustainable consumption and production pattern. This necessitates proper utilization of all natural products as well as recycling and utilization of any waste thereof.

This article review deals with retrieval of wastes or by-products during wet processing of proteinic fibres; namely wool and silk. Different ways of proper utilization of the retrieved materials will be proposed. Specifically, this review article will focus mainly on three main by-products; namely keratinous materials, wool wax, and sericin. State of the art and future prospects for the utilization of these materials in the production of textile auxiliaries; Viz. softeners, binders, and flame-retardants, were discussed.

**Keywords:** Wool, natural silk, keratin, lanolin, sericin, waste, recycling, auxiliary.

### Introduction

The environmental benefits of recycling of waste are well-known, which comprise conservation of natural resource and synthetic ones, minimization of energy and water consumption and pollution prevention. Moreover, recycling of wastes has momentous economic positive impacts. All economic and scientific entities realized that recovery and utilization of wastes have both environmental and economic senses.

The textile industry is considered as a major source of water and air pollution in many countries as it adopts gigantic polluting technologies. A feasible greener approach towards ecologically acceptable textile wet processes is *“to evade release of pollutants instead of developing policies and strategies to get rid them of”*.

The textile wet processing usually comprise pretreatments, coloration, and functional finishing operations. About a quarter of chemicals produced globally are used in the textile industry [1]. The carbon

footprint in textile products can be lessened by adopting zero-waste technologies .

Wool is the most commonly used proteinic natural fibres that used in the field of textile and clothing. The wastes and by-products during processing of wool are categorized into two classes according to the recyclability. The first one comprises the recyclable wastes such as wool wax discharged from scouring of wool fleece and short fibres waste produced during the carding and combing process. The second category represents the non-recyclable wastes such as the ash and crushed cellulosic matters produced from carbonization of wool.

Natural silk is the most luxurious fibres among all fibres used regularly in textile and clothing industry. The most common by-product during processing of natural silk is the gummy material (sericin) produced from the degumming process.

Energy, water, and chemicals can be considered also as by-products from the textile industries and the minimization of their consumption as well as their reuse in the same or another textile wet

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process would be of prime importance from the economic and ecologic points of views.

This paper reviews and criticizes our studies as well as other investigations in the field which have positive impact towards achieving one of the SDGs goals. This includes retrieval and exploitation of solid and liquid wastes and by-products released during wet processing of wool and natural silk. We will through the light on the possibility of utilization of some waste materials as starting materials for preparation of textile auxiliaries such as flame-retardant, softener, binder, and water-repellent.

## 1. Wool

Wool is a nifty textile material that meets the comfort, performance, and appearance attributes for the wearers [2-4]. The most important factors that influence the quality of woollen products include fibre diameter, fibre curvature, and staple length and strength [5].

Processing of wool fibres are classified into dry and wet processes. The dry process includes

preparatory processes such as combing, carding, burling, spinning, and weaving as well as finishing operations; Viz. singeing, pressing, decatizing, and steaming. Wet processing of wool includes, among others, all or some of the following operations depending on the customer demand: scouring, carbonization, milling, shrink-proofing, bleaching, coloration, moth-proofing, anti-pilling, anti-microbial, flame-proofing, and UV protection [6]. Many investigations have been conducted to improve the efficiency of these processes with cost-effective operations [7-20].

The nature and amounts of waste or by-products from some of the aforementioned dry and wet processes are summarized in Table 1.

The two major materials which are worth to be retrieved are wool wax and short fibres. The former can be utilized to make lanolin which is used in many applications, and the latter can be recycled or dissolved to obtain soluble keratin.

**Table 1:** Percentage of losses or by-products at each processing stage of wool [21].

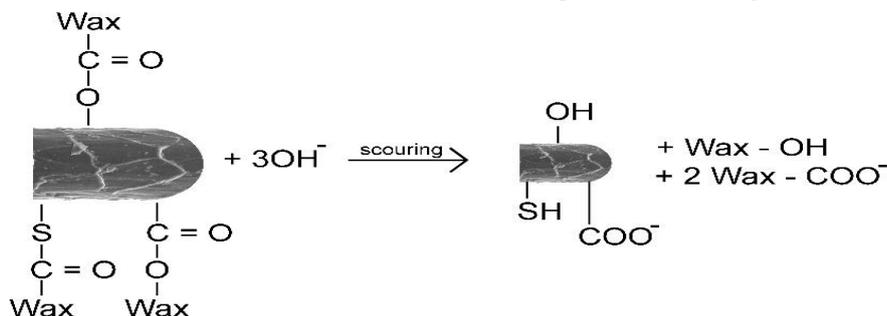
Process	Waste or by-product	Amount of waste (%)	Type of waste
Scouring	Wool grease (WAX)	2-25 (depending on sheep breed)	Recyclable
Carbonization	Vegetable matters/ash	2.5	Not recyclable
Carding	Short fibres	1.5	Recyclable
Combing	Short fibres	0.5	Recyclable
Spinning	Short fibres	2.0 – 3.0	Recyclable

### 1.1. Wool wax

Wool grease or wool wax is extracted from raw wool fleece during scouring process. The amount of wool wax that can be recovered from scouring effluent may be as low as 20- 50 % of the wax depending on the efficiency of extraction process and the type of wool being scoured. Usually finer wool fleece, such as merino wool has a higher amount of

wool grease than coarse wools; Viz. crossbred wool [21-23].

Wool wax is usually built-in wool surface by ester or theioester bond as shown in figure 1. Scouring of wool in alkaline medium would result in rupture of the said bond together with creation of carboxylic, hydroxyl, and thiol groups on wool surface. This process results in liberation of fatty acids and long-chain aliphatic alcohol (Figure 1).



**Figure 1: Mechanism of scouring of wool in alkaline medium**

#### 1.1.1. Wool wax recovery

The main constituents of wool scouring effluents are wool wax, cellulosic matters, dust, sand, pesticides, detergents, sodium carbonate, and sweat.

The amounts of wax, cellulosic matters, and soil particles found in the scouring effluent of raw wool fleece vary from wool breed to another. They also depend on the area where the sheep were grazed. Table 2 shows the results of an investigation carried out in

our laboratories to determine the amounts and chemical properties of wool wax extracted from different wool breeds.

Like most of other high molecular weight organic wastes, wool grease is not easily biodegraded. Together with suints and pesticides, it exists as an emulsion in the scouring effluent. Usually 20-50 per

cent of the wax may be recovered through multi-stage centrifugation, followed by bleaching and refining processes to obtain lanolin. The methods of recovery of wool wax from scouring effluent were reported elsewhere [24, 25].

**Table 2:** Amounts and chemical characteristics of wool wax extracted from scouring liquors of wool fleece from different sheep breeds

Wool breed	Amount of wool wax (%)	Iodine Value	Saponification value	Acid value	Hydroxyl value
Merino	26.1	16.4	72	5.5	19.6
South African	22.6	16.6	79	5.7	19.4
Argentinian	22.0	16.7	77	5.5	19.9
Peruvian	21.9	16.7	78	5.4	19.8
Egyptian	12.9	17.2	88	5.8	19.5

Based on the routine investigations of industrial samples of raw wool fleece in our laboratories, the maximum amount of recoverable wool wax from the scouring effluent of various wool sheep breeds is *ca.* 25% of the total discharged impurities; Results which are in harmony with the data obtained from the Agriculture and Resource Management Council of Australia and New Zealand.

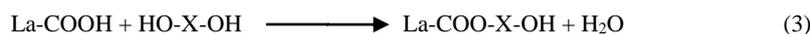
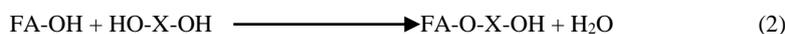
**1.1.2. Potential applications of wool wax**

Purified wool wax (lanolin) has its own place in the auction by virtue of its chemical composition which renders it some desirable properties in textile as well as non-textile applications. Lanolin is a group of esters which upon saponification gives out a hybrid of salts of fatty acids and long chain aliphatic alcohols [26-28]. We believe that the produced fatty acids would be suitable candidates for many industries such as soap, cosmetics, softeners, and water-repellents.

Lanolin has been already used to impart softness to polyester and polyamide 6 fabrics [26-29]. Recently, a condensate of fatty acids, derived from lanoline, and polyethylene glycol was prepared and

successfully utilized as a nonionic softener for wool fabric[30]. On the other hand, the hydrophobic nature of lanolin was utilized to impart super hydrophobicity to viscose fabrics [31]. Lanolin was also used successfully as a binder in pigment printing of wool, polyester, and their blend together [32]. However, most of these investigations are brought about on a lab-scale and need to be upgraded to pilot and industrial scales.

It is our opinion that the presence of fatty acids (e.g. palmetic acid) and sterols (e.g. cholesterol) within the product of hydrolysis of lanolin esters, makes it possible to use lanolin’s constituents for further reactions with other reagents to produce tailored textile auxiliaries. For instance, the constituents of lanolin may be reacted with bi- or poly-functional compounds containing solubilizing group(s) to form nonionic or ionic softeners which can be used as an auxiliary in textile finishing. Equations 1–5 show a suggested mechanism for the reaction between lanolin (La–COOH) or its fatty acids (FA–COOH or FA–OH) with a dihydric alcohol (HO–X–OH) to form ester or ether bond. Compounds with two labile amino groups are also possible choice for the same purpose.



**1.1.3. Non-textile applications of lanolin**

Lanolin is widely used in many industries other than the textile sector. These include personal care

products, lubrication, corrosion protection of metals, leather, varnishes, polishes, glues, and belt wax [26, 33-36].

The utilization of lanoline can be extended into new technologies. Ongoing research work is conducted in our laboratories to develop inorganic/organic hybrid fluorescent ink from lanthanide-doped photo-luminescent and lanoline extract. Lanolin will have the function of improving ink transfer, gloss and photo-stability. Fluorescent materials have various promising applications, such as chemical and biological sensors as well as bio-imaging.

## 1.2. Keratin

Keratin is the major protein which is naturally present in hard proteins; viz. wool, feather, hair, horn, nails, hooves, beaks, and claws. Keratin constitutes more than 90 % by weight of wool. Accordingly, most of the waste materials from wool as well as the other aforementioned materials are keratin. If properly recycled and utilized, it will be a source for profits. Technically, keratin is a potential candidate for many market applications such as hair cosmetics, feedstock, sponges, films, matrices for agent retention and transport, membranes, and removal of dyes and heavy metal ions from industrial wastewater [37-39].

### 1.2.1. Nature of keratin

Keratin is a versatile biomaterial by virtue of its chemical structure with different functional groups. The properties and functionalities of keratin is highly dependent on the hydrolytic conditions adopted during its extraction from its natural resources, especially whether the conditions causes disulphide bond breakage or restoral. Keratin exists in two molecular structure forms; namely  $\alpha$ -helix and  $\beta$ -sheets. Wool keratin and most of mammalian hairs exhibit the  $\alpha$ -helical form with its axis parallel to the fiber contour. Natural silk fibroin is an example of  $\beta$ -keratin [40]. Avian feathers and beaks exhibit some structural discrepancies in their molecular structures. They have  $\beta$ -keratin pleated sheets make it easier for flying and impart thermal insulation and hydrophobicity.

### 1.2.2. Methods of extraction of keratin

There are several reported methods for extraction of keratin from its natural resources. Most of them depend on dissolution of the keratin-rich natural resource followed by regeneration of solid keratin from its soluble form. In contrary to many other proteins, keratin is a highly cross-linked protein which makes it difficult to dissolve keratin without severe hydrolytic action and sharp reduction in its molecular weight. Figure 2 summarizes the classes of compounds usually used for dissolution of wool.



**Fig. 2: Reagents used for dissolution of keratin**

Sando *et al.* dissolved wool using 2 % peracetic acid at relatively low temperature (37 °C) with continuous stirring. The disadvantage of this process is the fact that it is a time-consuming process and may continue for two days to obtain keratin therefrom [41]. However, this method for dissolution of wool keratin is not destructive and the used reagent attacks only the disulphide bonds in the keratin macromolecule without rupture of the polypeptide chains.

In another investigation, Shavandi *et al.* dissolved wool using 24% peracetic acid for 48 h, and the yield of water soluble keratin was 57 % plus another portion of insoluble keratin [42]. Rajabinejad *et al.* concluded that by oxidative extraction of keratin using organic peracids, all the cystine residues in wool are oxidized to cysteic acid resulting in its dissolution due to formation of water-soluble keratin [43]. The obtained biochemical material is labile for biodegradation in a relatively short time *in-vivo* compared to keratin obtained by other methods [44].

In a similar time-consuming process, sodium percarbonate is used for dissolution of wool keratin [45]. This process is akin to the dehairing process of leather reported earlier by other workers [46, 47].

An oxidative/reductive process for dissolution of hair keratin was proposed by Hatakeyama *et al.* using hydrogen peroxide/sodium thioglycolate mixture [48]. We believe that this solubilization process is not time-consuming and does not reduce the molecular mass of keratin macromolecules. Both oxidizing and reducing agents attack only the disulphide bonds between the polypeptide chains without adverse effect on the length of the biopolymeric chains.

Urea, a swelling denaturing agent for wool and feather, has been used in combination of some reagents for dissolution of keratinous substrates. Urea/thiourea/caustic soda solution was used to dissolve wool and feather at relatively low temperature [49]. However, this process results in decrease in the

molecular mass of keratin and formation of some oligomers of low molecular weights [50]. Urea/mercaptoethanol and urea/metabisulphite mixtures were used also for dissolution of keratinous materials [51-54].

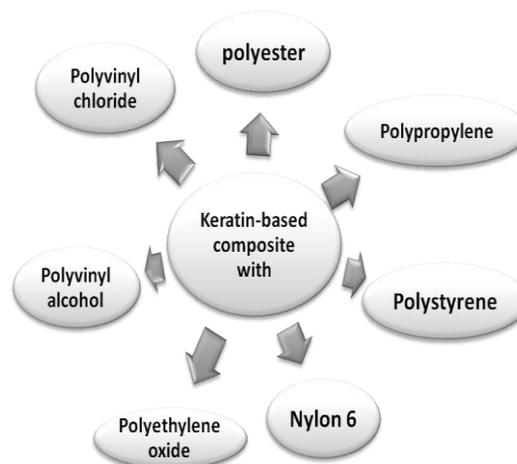
Feairheller *et al.* utilized sodium sulphide as a reducing agent followed by quick lime for dissolution of cattle hair and wool fibres in a time-consuming operation [55].

A number of ionic liquids (ILs) and deep eutectic mixtures (DEMs) were utilized as solvents for the dissolution of wool. The dissolution in DEMs is not satisfactory compared to the ILs. It seems that the ionic medium and the nature of some of the ions play an important role in this operation. Dissolution of wool in ionic liquids is taken place via rupture of inter and intra-molecular hydrogen bonds. 1-allyl-3-methylimidazolium dicyanamide ionic liquid at 130 °C achieved the highest solubilizing effect on wool fibres. Addition of mercapto ethanol as a reducing agent enhanced the dissolution of wool by the said reagent. The regenerated keratin retained the protein backbone, while the crystallinity was substantially lost. The dissolution also produced a breakdown of the polypeptide chains into lower molecular weight fragments, some of which became water soluble as observed by gel electrophoresis [56]. The use of ionic liquids in dissolution of wool and other keratinous materials is very limited due to the relatively high cost of ionic liquids.

In our opinion, the dissolution of wool and other keratinous materials to regenerate keratin therefrom should be carried out using oxidizing, reducing, and/or swelling agents to avoid the severe reduction in the molecular mass of keratin during dissolution of keratinous materials using alkaline solutions. These reagents affect keratins specifically rather than selectively. They cause rupture of the disulphide and hydrogen bonds between keratin macromolecules. On the other hand, dissolution of keratinous substrates using alkali metal as well as alkaline earth metal hydroxides result in adverse attack on the polypeptide chains of keratin macromolecules converting them into small oligomers or even the individual amino acids at high temperature [57]; a reaction which can be categorized as hydrolysis rather than dissolution.

### 1.2.3. Keratin-based biocomposites

Proper utilization of millions of tons of keratinous waste materials is of prime importance from the economic and ecologic point of views. Figure 3 shows the main thermoplastic and non-thermoplastic synthetic polymers that have been utilized in keratin-based composites.



**Fig. 3: keratin-based bio-composites with synthetic polymers**

In a previous study, keratin from feather was chemically bound to rubber for special technical applications [58]. In another investigation, wool keratin was blended with different thermoplastic polymers; to form bio-composites for special applications [59]. Among others, polyester, polystyrene, polypropylene, polyethylene oxide, and polyvinyl chloride are the most widely used [59-61]. The properties of the formed bio-composites depend on the nature of the thermoplastic polymer, ratio, pressure, temperature and time of mixing, and the nature of interaction between keratin and the said polymers. The presence of other plasticizer, supporter, or coupling agent highly affects the mechanical properties and surface morphology of the formed composites [62-64]. On the other hand, aiming at maintaining sustainable and eco-friendly behavior, green keratin-based bio-composites were reinforced by surface-modified nano-cellulose crystals [65]. This reinforced bio-composite is an appropriate candidate in the fields of tissue engineering or drug delivery.

Due to their biocompatibility, biodegradability, capability of self-assembly, and support cellular proliferation, keratin-based biocomposites have been widely utilized in many biomedical applications including drug release and delivery, wound healing, and tissue engineering [66-69]. Further applications of keratin-based biomaterials comprise bone-morphogenic protein carrier [70], ocular surface reconstruction [71], urinary tract tissue engineering [72], nerve regeneration [73], and hydrogels [74]. Keratin-based composites were used in manufacture of analytical stripes for quantitative determination of iron III cations [75] and free chlorine in domestic tap water [76].

### 1.2.4. Electro-spun keratin nano-fibres

Aqueous solution of soluble keratin is hardly electro-spun into fibres or casted into films. Alternatively, keratin should be mixed with other

polymers to obtain electro-spun polymeric materials with certain rheological properties [49]. To obtain electro-spinnable material with appropriate viscosity and rheological properties, keratin is usually blended with polymers such as polyvinyl alcohol, polyethylene oxide, polyamide, or poly acrylonitrile [77-82]. It has been reported that electro-spinning of nano-fibres from aqueous medium has the advantage of being green and up-scalable. Based on this assumption, Varesano *et al.* electro-spun nano-fibres from aqueous solution of organic/inorganic system of keratin and nano-sols of silver and TiO<sub>2</sub> [83].

El-Sayed *et al.* have reported that electro-spinning is the proper method of spinning of keratin-based composites to produce nano-fibres or nano-fibrous mats [84]. About three decades ago, multi-jet electro-spinning systems were adopted to enhance both productivity and cover area of nano-fibres [85]. More recently, nozzle-less electro-spinneret was introduced commercially also to increase the productivity of electro-spun nano-fibres [86].

Functionalization of the keratin-based nano-fibres is usually used to impart certain desired properties for special applications. Nano-fibres from keratin/PEO/ TiO<sub>2</sub>/Ag hybrid exhibits photo-catalytic activities and antibacterial [83, 87]. Keratin/PA 6 electro-spun nano-fibres were used for adsorption of heavy metal ions from industrial waste water [52].

### 1.2.5. Utilization of keratin in textile wet processing

Keratin is rich in the hydrophilic functional groups which makes it an appropriate reagent for many applications. These groups include the carboxylic, amino, hydroxyl, thiol, and amide groups, which vary in their polarity. Regenerated keratin from wool and feather was successfully used in enhancing the dyeability of wool fabric with acid and reactive dyes [88], and in pigment printing paste prepared for printing of polyester and polyester cotton blends [89, 90]. It was also used in hydrophilization of saponified polyester fabric [91] and in imparting bactericidal effect to viscose fabric [92]. Encapsulation of the wool scales using keratin was utilized to impart felting resistance to wool [93].

We believe that keratin would be suitable for treatment of various synthetic fabrics; Viz. acrylic and nylon fabric, to improve their comfort attributes including enhanced moisture regain, lower electrostatic charges, and improved dyeability. Acid-dyeable synthetic and cellulosic fabrics can be prepared by treatment with keratin. To ensure durability of the modified synthetic fibres, treatment of the said synthetic fabrics would be preceded by partial hydrolysis to create the functional groups which are able to bind with keratin by covalent bond rather than physical interactions.

An ongoing research project in our laboratories concerns with the use of keratin as a starting material to prepare textile auxiliaries such as flame retardant. This will be carried out by linking keratin with series of phosphorous-containing compounds. Keratin-containing flame retardant will be easily bonded to the textile substrate by virtue of its functional groups.

## 2. Natural Silk

Production of natural silk comprises many stages starting from cultivation of mulberry, silkworm rearing, silk reeling, spinning, and finishing and coloration [94]. Silk is classified as a proteinic biopolymer spun into fibers by certain *Lepidoptera larvae*; Viz. silkworms, spiders, scorpions, mites and flies [95, 96]. The most extensively characterized natural silks are produced from the domesticated mulberry silkworm (*Bombyxmori*), which belongs to *Bombycidae* insects' family, and from spiders (*Nephilaclavipes* and *Araneusdiadematus*) [97, 98].

The two main components of proteins in natural silk are the silk fibroin (70–80 %) and the outer layer sericin (20–30 %) [99]. Sericin is removed from silk fibroin during a process called degumming [100]. Most of the produced sericin is discharged in the effluent causing loss of profits and environmental concerns. In the following part, we describe the state of the art in the degumming process and the textile and non-textile applications of sericin together with our vision for new utilization of sericin.

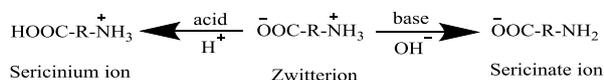
### 2.1. Degumming of silk and separation of sericin

A series of consecutive processes are brought about from cocoons to the finished clothing articles, including reeling, degumming, dyeing or printing, and finishing [101]. Sericin, which encapsulates the silk fibroin, diminishes its lustre and degree of whiteness. Moreover, sericin causes harsh feeling to silk and hinders its dyeability [102]. Thus, sericin is entirely removed to obtain a lustrous, soft handle, typical shiny aspects of the fibre and the elegant drape highly appreciated by consumers [103].

The principle of silk degumming is based on increasing the solubility of silk gum by rupture of peptide linkages of sericin structure into small oligomers. Several methods were reported for degumming processes including extraction with boiling water [104], soap [105], sodium carbonate [106], alkalis [107], organic and mineral acids [101], proteases [108-110], low temperature plasma [111], microwave irradiation [101, 112], and ultrasonication [113]. We highly recommend the microwave-assisted degumming of natural silk as it requires much lower consumption of water, energy, and utilization [101].

However, further technological work should be directed towards commercialization of this process.

There are many reported methods for recovery of sericin from the degumming effluents. Precipitation sericin was carried out by using ethanol [114], freeze-drying [115], and membrane filtration [116]. We believe that ethanol precipitation method has negative economic and environmental impact if applied on an industrial scale. The membrane filtration method, on the other hand, is more beneficiary from the technical point of view as it allows better separation of sericin from other impurities in the degumming effluent. Recently we succeeded to recover sericin from the degumming effluent by adjusting the pH of the bath at the isoelectric point and hence precipitation of sericin as a *Zwitter* ion (Scheme 1). The deviation in the pH of the degumming bath towards acidic or basic region results in formation of the soluble sericinium or sericinate ions, respectively [37].



**Scheme 1:** Chemical structure of sericin in neutral, acid, and basic media

## 2.2. Chemical and molecular structure of sericin

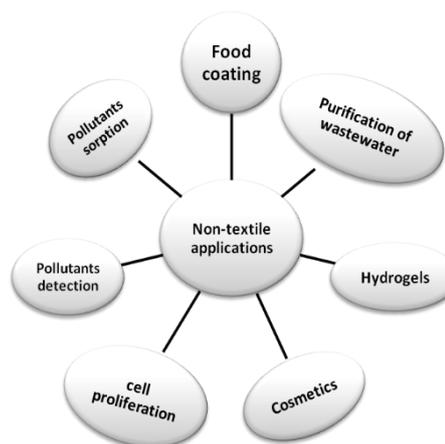
Sericin is a protein of an average molecular masses in the range 24–400 KDa depending on gene coding and post-translational modifications [117, 118]. The polypeptide chains of sericin consist of 18 amino acids. The hydrophilicity of sericin arises from the high content of serine and aspartic acid which constitute [119]. Sericin is characterized by high ration of serine (*ca.* 28%), aspartic acid (*ca.* 18%), and glycine (16%) [120].

Depending on the solubility in water, sericin consists of three layers or fractions: the outer layer (sericin A), the middle layer (sericin B) and the inner layer (sericin C). Sericin A is insoluble in hot water and it contains about 17.2% of nitrogen and some amino acids like serine, threonine, glycine and aspartic acid. Sericin B contains about 16.8% nitrogen and under acid hydrolysis it yields tryptophan and serine. Layer C contains sulphur and 16.6% of nitrogen, it is insoluble in hot water and under hydrolysis it yields proline, tryptophan and glycin [121, 122].

## 2.3. Utilization of sericin

### 2.3.1. Non-textile applications

Sericin is a biodegradable hydrophilic substance which makes it appropriate for various applications including medical biomaterials, functional bio-membranes, and hydrogels [123]. Figure 4 summarizes some of the non-textile applications of sericin.



**Fig. 4:** Non-textile applications of sericin

Sericin films can be used for food coatings to prevent water and oxygen permeation between food products and the atmosphere. Other uses of sericin include soil conditioner, and coagulant for purification of waste water [124]. It is used also as additives for health foods to prevent colon cancers, additives to rice cooking, light and sunscreen compositions and foam forming aerosol shaving gels.

Sericin alone or in combination with silk fibroin has been used in skin, hair, and nail cosmetics [125]. Sericin can naturally saturate human skin and refresh cells by virtue of its human-like configuration. Sericin can confine the functions of active-oxygen, which brings wrinkles and dark spots [126].

It forms a moisturizing, semi-occlusive, protective, long lasting anti-wrinkle film on the skin conveying a smooth and silky touch [127]. Sericin in sunscreen composition enhances the light screening effect of UV filter like triazines and cinnamic acid ester. Binding sericin to hair, in presence of olive oil, reduces damage of hair surface. Shampoo containing sericin and palarogenic acid of pH less than 6 are useful for the care and cleaning of hairs [98, 128].

Sericin can be used in cell culture because it promotes cell proliferation in a serum-free medium [129, 130]. It was reported that sericin with a molecular weight ranging from 5-100 KDa, effectively improved serum-free mammalian cell cultures [128, 130]. Blood exhibits anti-coagulant, fibrinolytic and anti-aggregation activity towards thrombocytes when adding a small concentration of copolymer formed by condensation of sericin, salicylic acid and formaldehyde [131].

In nutrition, sericin is used to relieve constipation, suppresses development of bowel cancer and accelerates the absorption of minerals [132, 133]. Oxygen permeable membranes made up of fibroin and sericin are used for contact lenses and artificial skin [128].

Sericin-based composites were successfully utilized in detection of some pollutants in domestic waste water. Low concentrations below to few parts

per million of  $\text{Fe}^{+3}$  cations and elemental chlorine in domestic water [86, 87].

Further applications of sericin include bio-absorption of pollutants and toxic substances from water [134], recovery of valuable substances from wastewater [135, 136], and manufacture of contact lenses [137]. Sericin-containing food relieves constipation, suppresses development of bowel cancer and accelerates the absorption of minerals. It elevates the apparent absorption of zinc, iron, magnesium, and calcium to different extents [132]. When taken orally, sericin causes a dose dependent decrease in the development of colonic aberrant crypt foci. The incidence and the number of colon tumours are suppressed by consumption of sericin [138].

In one of our recent research work, sericin was blended with polyamide 6 protic medium to form electro-spinnable composite which was electro-spun into nano-fibres using nozzle-less electro-spinneret [136]. The obtained electro-spun nano-fibres were successfully utilized in removal of some heavy metal ions as well as anionic and cationic dyes. The superior sorption power of these nanofibres is due to the high specific area and the functional groups able to capture the said pollutants.

An ongoing research project between the NRC in Egypt and the CNR in Italy, prepared an electro-spun sericin/gelatin/keratin bio-composite for utilization in tissue engineering trials. Results of cell growth test reveal that as the concentration of sericin in the prepared composite increases, the cell growth on the bio-composite increases.

### 2.3.2. Functional finishes of textiles

Treatment of polyester fabrics with sericin to improve its comfort attributes has been investigated by many researchers. In 2010, Bhat *et al.* cross-linked sericin into polyester fabric using formaldehyde and glutardialdehyde. The sericin-treated polyester fabrics exhibited improved hydrophilicity and reduced accumulated electrostatic charges [139]. In a cost-effective study, El-Newashy *et al.* utilized sericin-containing effluent directly in improving the comfort attributes of knitted polyester fabrics [140]. It has been reported that sericin-modified PET fabric shows significant reduction in the bacterial and fungal attack [141].

Rajendran *et al.* investigated the antimicrobial property of cotton fabric coated with sericin [142]. The sericin-coated fabric showed a high degree of bactericidal activity towards *E. coli* and *S. aureus*. Treatment of cotton fabric with sericin, in presence of dimethylol dihydroxy ethylene urea as a crosslinking agent, highly improved its moisture regain and water retention [143].

Sericin was used to improve the felting resistance of wool by coating and spot welding of the

tips of the surface scales [144]. The printability of wool fabrics with acid and reactive dyes was enhanced after being treated with sericin [145]. In another investigation, sericin was utilized in imparting antimicrobial properties and improved touch to wool fabrics [146].

El-Sayed *et al.* adopted a simple method to impart durable ultraviolet protection for polyamide 6 fabric using sericin. In this investigation, crosslinking of sericin into polyamide 6 fabrics was brought about using citric acid or epichlorohydrin by pad-dry-cure technique. The treated fabrics exhibited excellent UV protection without remarkable effect on their inherent physico-mechanical properties [147].

A number of textile auxiliaries are currently prepared based on sericin. These include textile softener, flame-retardant, and antimicrobial agent for synthetic textile substrates. The prepared textile auxiliaries will be compared with previously reported and commercially used ones [148-150].

### Conclusion

If properly recycled and utilized, wool wax, keratin, and sericin would be sources for high technical and economic profits together with positive impact on the environment. Although these materials are properly utilized in non-textile applications in industrial scale, however, we believe that these substances have not been effectively introduced into the textile sector.

Purified wool wax (lanolin) is rich in fatty acids and long chain aliphatic alcohols which could be starting materials for some textile auxiliaries such as softeners, and thickener. Keratin and sericin are biopolymers of neutral, acidic and basic functional groups which enable them to bind chemically to various untreated or modified textile substrates to impart certain desired properties; Viz. enhanced hydrophilicity, reduced accumulated electrostatic charge, improved dyeability, induced protection against ultraviolet radiation and microorganisms, and brought resistance to felting shrinkage for wool fabrics. Up to our knowledge, these biopolymers were not applied to some synthetic fibres, Viz. poly acrylonitrile fibres, viscose fibres, and the most difficult substrate polypropylene fibres.

Although recycling of wastes has been mandatory by law worldwide since decades, yet there are still some organizations that do not realize the importance of recycling. The costs associated with recycling should be also considered during our future investigations.

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