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REVIEW PAPER

Textile and Other Industrial Applications of Keratin Biomaterial

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ABSTRACT

Keratin is a fibrous protein available in hair, nails, horn, hoofs, wool, hair, feathers and epithelial cells in the outermost layers of skin. It is subdivided into alpha-keratins and beta-keratins, based on the structure of polypeptide chains. Keratin can be extracted by several methods viz., chemical hydrolysis, enzymatic and microbial treatment, dissolution in ionic liquids, microwave process, steam explosion, and thermal hydrolysis. It is a natural protein polymeric biomaterial and has been used in the fields of textile fibre, textile finishing & auxiliaries, film, hydrogel, sponges and scaffolds, and cosmetics. The underutilized coarser and waste wool, and other hair fibres can be used for extraction of keratin, while addressing the sustainable management of such bio-wastes. Keratin biomaterial has many advantages over the conventional biomolecules, namely unique chemistry due to its high sulphur content, notable biocompatibility, propensity for self-assembly, and intrinsic cellular recognition. Keratin polymer-based biofibres are strong and elastic, and have requisite moisture wicking properties, making them a new class of material for textile application. Substrates developed using keratin and blends show hypoallergenic and antimicrobial properties, making them a preferred a choice for clothing and other applications. Properties of paper produced from the feather fibre and wood pulp were compared with the hand-sheets, made of 100% wood pulp. This paper reviews the characteristic of keratin biomaterial, its extraction process and different end applications.

HIGHLIGHTS

- Value-added applications of keratin.
- Different sources of keratin.
- Keratin as a fibre and textile auxiliaries.
- Development of keratin-based bio-film and hydrogel.

Keywords: Wool, Fibre, Keratin, Biomaterial, Film, Textile application

Keratin is a fibrous protein polymer of hair, nails, horn, hoofs, wool & hair fibres, feathers and epithelial cells in the outermost layers of the skin. Keratin serves an important structural and protective functions, particularly in the epithelium. Keratin polymer can be subdivided into alpha-keratins and beta-keratins, on the basis of their polymeric structure i.e., the geometry of the polypeptide chains. Alpha-keratins found in wool fibre, hair and skin are primarily attributed for their fibrous as well as helical structure. In

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different, beta-keratins occurred in horns, birds and reptiles consists of aligned and parallel sheets of polypeptide chain (www.britannica.com/science/keratin). Keratin biomaterials are exceptionally biocompatible and have cellular proliferation efficacy, making them a preferred choice for drug delivery and tissue engineering (Idrees *et al.* 2020). Potential of such polymeric material is also found in energy sectors, agricultural fields, pharmaceutical & cosmetic, leather, and textile (Donato and Miza, 2020). With the exception of good quality wool that is mostly used in clothing and technical textile (rugs and carpet), there are challenges associated with the disposal and management of coarser and underutilized wool and other hair fibres. Unlike the fine and medium fineness wool, the coarser and kempy wool fibres as well as spinning waste fibres are dumped, landfilled and incinerated throughout the world, resulting generation of environmental pollution. There is a need of sustainable solution for efficient management of such wool and hair waste, while addressing the environment pollution. The present review focusses on the extraction of keratin from the wool fibre, hair and other potential sources, their properties, and different industrial applications in the area of textile fibre, textile auxiliaries & finishing agent, film, sponges, scaffolds, hydrogel and cosmetics.

Wool fibre, keratin and structural properties

Wool and other animal-based wool/hair fibres are one of the oldest fibres, mostly derived from sheep and small ruminants, but also from the alpacas, camels and goats. Australia, Eastern Europe, New Zealand, India and China are major wool and wool-like fibres producing countries. Such fibre is characterised due to unique attribute of warmth, bulky structure and presence of crimps. Fine quality wool possesses tentatively 10 crimps/cm, whereas the coarse wool possesses <0.4 crimps/cm. Number of crimps per unit length decreases with the increase in wool diameter. Sometimes, it is considered as a parameter to define a fibre diameter/fineness. Length of fibre generally ranges from 5 cm for the finest to 35 cm for the coarser wool, for their corresponding diameter in the ranges of 14 - 45 μ, and length (l) to diameter (d) ratio (l/d) of 2500:1 in case of finer to 7500:1 in case of coarse and longer wool. Microscopic longitudinal view of wool illustrates the overlapping surface epithelial cell structure, commonly known as scales, projected towards the tip of the fibre. Cross-sectional analysis of the fibre profoundly illustrate oval like shape. Wool fibre has also distinguished property like felting, i.e., irreversible shrinkage of the length, breadth and thickness under certain environment like heat, acid or alkali. Felting occurs due to serrated surface of fibres that is formed due to overlapping of epithelial cells/scales. Wool fibre also has unique property like directional-frictional-effect (DFE) i.e., different co-efficient of friction from bottom to tip and vice versa direction. A typical wool fibre consists of 33% keratin, 26% dirt, 18% suint, 12% fatty matters and 1% mineral water. Coarser fibres have a hollow internal space running along the fibre axis, known as medulla. Some of the important properties of wool fibre are as follows:

(i) **Specific gravity:** 1.31 g/cc

(ii) **Strength:** 1.35 g/den

(iii) **Elongation at break:** 25 – 35%

(iv) **Resiliency:** Excellent due to presence of crimp

(v) **Colour:** White, near white, brown and black

(vi) **Moisture regain:** 13-16%, very absorbent

(vii) **Washing stability:** Shrink upon washing.

(viii) **Stability in contact of alkali:** Wool keratin sensitive to alkaline solution and gets dissolved in caustic soda solutions.

(ix) **Stability in contact of acids:** Generally resistant to mineral acids, even at high temperature; nitric acid causes damage by oxidation.

(x) **Effect of organic solvent:** Does not get affected in organic solvents

(xi) **Effects of insects:** Affected by insects.

As far as fibre structural composition is concerned, it consists of 50% carbon, 12% hydrogen, 10% oxygen, 25% nitrogen and 3% sulphur. Cuticle is the layer of overlapping epithelial cell's surrounding the wool fibre, which is consists of Epicuticle, Exocuticle and Endocuticle. Cortex i.e., core covering almost 90% of the fibre volume, consists of countless, long, spindle shaped cells or cortical cells. It has two distinct regions namely, ortho cortex and para cortex, spiral

around one another. Ortho cortex could absorb more dye molecules than the para cortex. Fine wool possesses around 20 such cells, whereas coarse wool has around 50 cortical cells across diameter. Keratin is structural protein macromolecules mainly, composed of amino acid. They are formed by the long polypeptides chain (Chilakamarry *et al.* 2021). Its unique structure governs properties like elasticity and durability. It also acts as a shielding layer for the epidermal like hair, nails, horns, hooves and feather. Wool protein is classified into alpha-keratin (α-keratin) and beta-keratin (β-keratin). Alpha-keratin is found in vertebrates and forms the key structural material of scales, wool, hair, nails, feathers, horns, claws, and the outer layer of skin. It is mostly found in mammals and their structure are formed by hydrogen bond between carbonyl group of one amino acid and amino group of another amino acid. Diameter of the α helices is tentatively 7–10 nm and the molecular weight is in the ranges of 40-60 kDa (Wang *et al.* 2016; Alibardi *et al.* 2006). On the other hand, beta-keratin (β-keratin), exclusive to sauropsids (reptiles and birds) contributes to the nails, scales, and claws of reptiles, as well as the feathers and beaks of birds. The β pleated sheet keratin found in reptilian tissues are formed by the intermolecular bond between the carbonyl group and amino group. Diameter of β pleated keratin is tentatively 3-4 nm and the molecular weight is in the range of 10-22 kDa (Chen, McKittrick and Meyers, 2012). Keratin molecule is insoluble in water and organic solvents, making them resistant for dissolution in diluted acids, alkaline solution, solvents, or water. Keratin molecules assemble into bundles forming intermediate filaments that are tough and unmineralized. Such filaments underwrite the strength of the epidermal appendages found in reptiles, birds, amphibians and mammals. Intramolecular and intermolecular disulfide crosslinks, hydrogen bonding and crystallinity contribute towards the structural stability of keratins.

Extraction of keratin

Keratin can be extracted by several methods viz., chemical hydrolysis, enzymatic and microbial route, dissolution in ionic liquids, microwave process, steam explosion, and thermal hydrolysis or superheated process. Biological degradation of keratin is considered to be effective over the physical and chemical methods, yielding useful by-products. The important process of keratin extraction is depicted in Fig. 1. Table 1 shows the extraction of keratin from the different biological sources, their key properties and possible end applications. As far as extraction of keratin is concerned, the acidic hydrolysis process seems to be more effective, but it leads to achievement of low nutritional value, due to loss of amino acids like tryptophan. On the other hand, the loss of amino acids is noticed to be less in case of alkaline hydrolysis. Alkali hydrolysis at 80 °C with 2% NaOH for 3 h resulted in 25% yield (Nayaka, Gireesh and Vidyasagar, 2013). In hydrolytic processes of keratin extraction, the yield is commonly governed by the process conditions viz., pH, temperature and reaction time, and the type and concentration of acid/base used. Chemical hydrolysis is often accompanied by heating to ensure higher yield. However, high temperature may also clause damage of amino acids (Chao *et al.* 2007). Many microorganisms also help in keratin extraction by secreting keratinolytic and proteolytic enzymes, popularly known as keratinases. Such microorganisms include mesophilic fungi, actinomycetes and some species of Bacillus. Keratinase is used for the bioconversion of keratin waste, and commonly used in the textile and leather industries. Savinase enzyme is used to extract keratin from wool and feather materials. Enzymatic hydrolysis involves low usage of energy; however, it's carried out in the presence of certain reducing agents, which destroy the disulphide bonds of keratin. Keratin degradation occurs by proteolysis, sulfitolysis and deamination. Like other methods of keratin extractions, in microwave irradiation technique, the activation energy required for extraction is reduced, while providing the uniform heating to the keratinous mass. It is an effective and clean process of keratin degradation, and extraction is homogeneous with the possibility of rapid heating. The molecules in microwave-assisted heating tend to adsorb energy homogeneously with the rise of temperature in the reactor. Zoccola *et al.* (2012) used microwave irradiation at a temperature of 150–180 °C for an hour with the yield of 60% (Zoccola *et al.* 2012a). Zhao *et al.* 2012 suggested the steam flash-explosion technique to extract wool keratin instead of conventional steam explosion (Zhao *et al.* 2012). Steam flash-explosion is an

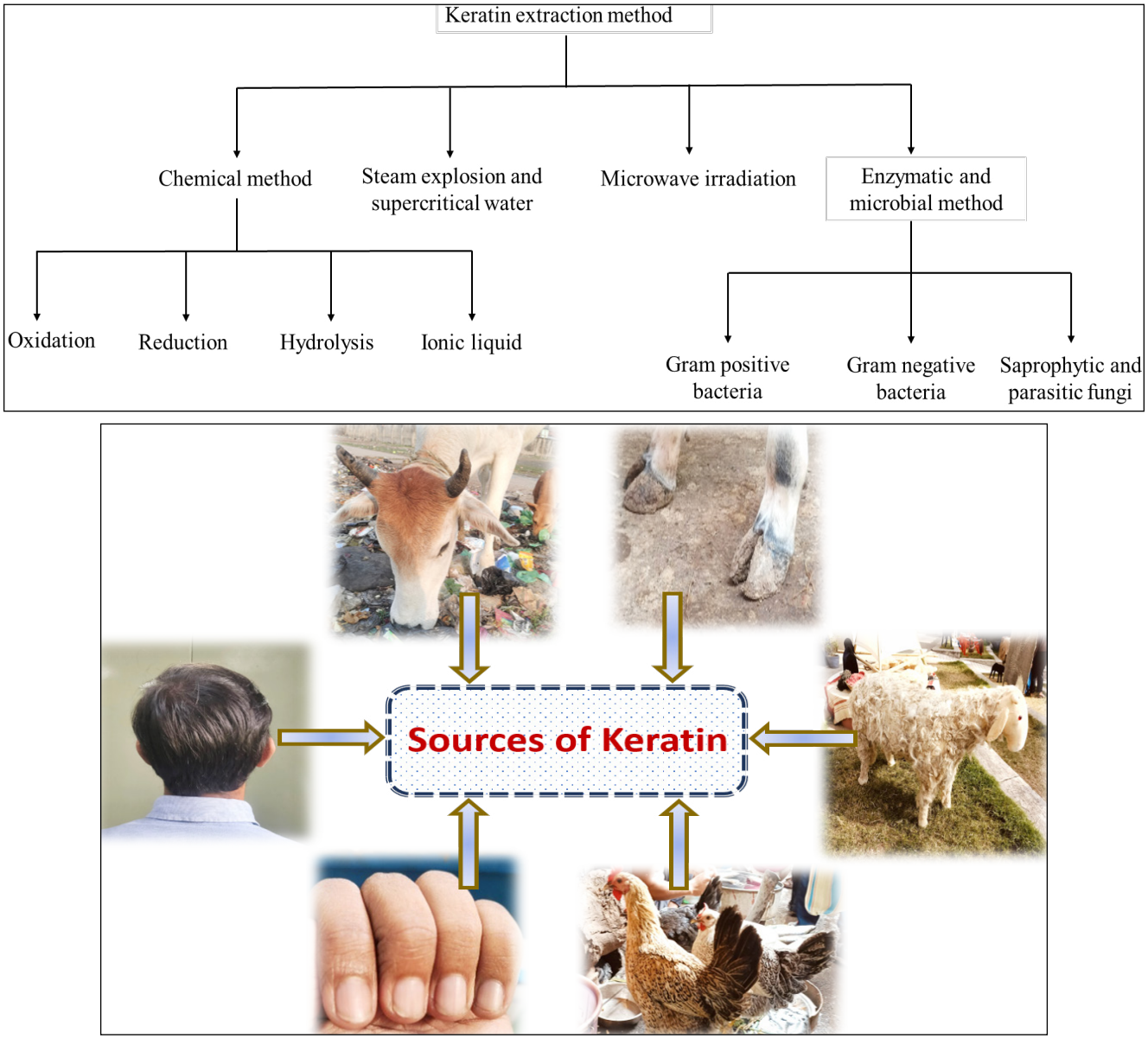

Fig. 1: Different resources for extraction of keratin

advanced form of steam explosion, developed as a pre-treatment technique to enhance the solubility of feathers in water and other solvents. Steam explosion is a hydrothermal process that utilizes high pressure saturated steam for shorter intervals of 1–10 min. Keratinous biomass is subjected to temperature of 180–230 °C in the reactor. At the end of the treatment, the pressure is rapidly dropped, causing explosive decompression and rupturing of the rigid biomass fibres. Factors related to temperature, time, particle size and moisture greatly influence the outcome. Miyamoto *et al.* 1982 mentioned this technique as a route of keratin extraction from the wool (Miyamoto *et al.* 1982). In other study with saturated steam at 164 °C for 2–8 min converts the wool (80%) to pepsin digestible material (Xu *et al.* 2003).

Applications of keratin

Keratin, an emerging biomaterial, finds its diversified applications in various domains due to its diverse properties of mechanical durability, biocompatible and ease biodegradable. It has inherent competence to simplify cell adhesion, proliferation and tissue regeneration, providing a biocompatible matrix for cell growth and regeneration (Shavandi *et al.* 2017). Keratin biomaterial can be used as substrates for nerve repair, haemostasis and wound healing

Table 1: Extraction of keratin from the different sources and key properties of the materials

Sources of keratin	Properties and application	References
Sheep wool/ Wool	◆ Thermal insulation of external walls, concrete slab floor, fibre-reinforcement-concrete, carbon fibre precursor ◆ Apparel, carpet industry ◆ Regenerative medicines, bioplastics, coatings or packaging ◆ Antipilling processing, biopolymer, hydrogel, nano-fibres, sponges and porous foams	Parlato and Porto, 2020; Gong *et al.* 2016; Fernández-d'Arlas, 2019; De Masi *et al.* 2019
Human hair	◆ Biomaterials, drug permeation films used in tissue engineering	De Masi *et al.* 2019
Chicken feather	◆ Bioplastic films, biofertilizers, bio-composites, cosmetics, composites in automobile and aero planes. Hydrogels thermoplastic films for food packaging, making thermoplastic films for food packaging, printed circuit boards and dielectric material. ◆ Used in paper production	Donato and Mija, 2020; Tesfaye *et al.* 2017
Bovine hoof	◆ Hoof bovine is compatible material used for promoting cellular attachment and used in biomedical and tissue engineering	Kakkar, Madhan and Shanmugam, 2014

(Kelly, 2016). Keratin intervention in textile as well as other industrial sectors are summarized below:

1. Keratin fibre and film

Nowadays, research have been intensified for making electrospun polymeric micron-to-nano fibres for various end applications. Such biocompatible and biodegradable nanofibrous structure is becoming popular due its potential application in biomedical. In electrospinning process, a high voltage positive, negative or in combination of both the electric field is applied to create an electrically charged polymer, which is forcedly ejected in the form of a fine fibre, and finally get deposited on the collector plate or on a substate. Electrospun fibre exhibits diameters in the range of micro-to-nano meter scale, randomly deposited in the form a non-woven fibrous sheet. Such nanostructured nonwoven sheet facilitates cell adhesion and growth, that has been considered for the development of bandages for wound healing, and scaffolds for tissue engineering. Keratin, extracted from the hair and wool fibre, has been processed through an electrospinning technique. The produced sheet has meagre mechanical properties that was compensated by supplementation of suitable bio-and-synthetic polymer. In this line, the PEO/ keratin blended solution were prepared by adding 50:50 weight-by-weight ratio to a concentration of 10 to 7%. Spectroscopic and thermal analysis of the fibrous sample reveals the destabilization of natural self-assembly of keratin. In further work, keratin was blended with PEO in different proportions to corelate the physical, mechanical, and rheological properties of the solution with structural, mechanical and thermal properties of the fibrous sheet. Application of PEO/keratin mats is scanty due to its instability in water and poor mechanical performance. Wet spinning was attempted for extrusion of dope solution through the spinneret followed by passing through the coagulation bath, and subsequently drawn and stretched. Fibre forming efficacy of the aquas keratin was improved by addition of poly-(vinyl alcohol) PVA (Katoh *et al.* 2004a). Addition of PVA increases the viscosity of the spinning dope, allowing the fibre formability with addition of 13–46% keratin in spinning process. Up to 30% keratin is suitable to address fragile-nature of the fibre. Mixing of PVA with keratin solution underscore advantageous in terms of strength, water proofness and adsorption of toxic substances (Katoh *et al.* 2004a). Keratin–PVA fibers showed higher tenacity than that of wool. Keratin incorporated with cellulose shows high absorbency, higher hygroscopic properties, and lower wetting angle than the cellulose fibre itself. Cellulose-keratin fibres had better biodegradation attributes over a cellulosic fibre. Keratin fibre formed with polymers like poly (l-lactic acid)/ poly (hydroxybutyrate-co-hydroxyvalerate) are used in wound healing substrate (Azimi, Maleki and Zavagna, 2020). Such polymeric nano-fibre holds as ample scope in tissue engineering, drug delivery and wound healing, due to their ability to restore the natural extracellular matrix function.

Keratin fibre, prepared with polycaprolactam in the proportion of 7:3, is used in bone tissue engineering (Cho, Quan and Keng, 2020). Keratin-polyamide 6 composites prepared with 15% w/w using formic acid are widely used in bio-medical devices, as adsorbents for water purification (Yadav and Purwar, 2021).

Keratin as a film forming polymer has been reported since long. It is blended with glycerol to introduce transparency, strength, flexibility and biodegradability of the film. Mechanical properties of film were possible to enhance by addition of chitosan. Chitosan being a biomolecule with biological function for bacterial species, the antibacterial properties of the keratin/chitosan film was improved. Activity of keratin films was also increased by addition of a cell adhesion peptide, Arg-Gly-Asp-Ser (RGDS), at the free cysteine residues of reduced keratin extracts. The RGDS-carrying keratin films was observed to be excellent substrates for mammalian cell growth, underscoring versatility of keratin biomaterials (Yamauchi *et al.* 2003). Apart from the biomolecular characteristic, the bonding between the keratin and synthetic polymers has also been reported. Interaction between the keratin and polyethylene oxide (PEO) shows improved structural properties of the blended film (Tonin *et al.* 2007). Morphological, structural and thermal analysis were evaluated with the change of keratin level in the PEO blended films. The improvement in structural properties of PEO/keratin biomaterial is suitable for cell growth, wound healing and drug delivery (Tonnin *et al.* 2007). Relation between the keratin and polyamide (PA6) postulates a wide range of applications, ranging from biomedical devices to active water filtration and also as textile fibre (Zoccola *et al.* 2007). Compression molding of S-sulfo keratin powder is useful in order to produce pure keratin film, where mechanical properties of the film is governed by the temperature and water content within the film (Katoh *et al.* 2004b).

2. Textile finishing and auxiliaries

Antimicrobial finishing of keratin-based materials, including woollen cloth and regenerated cellulose/ keratin composite films and nanofibers was accomplished by a facile chlorination process. It converts the nitrogen-bearing moieties of keratin into halamine compounds. Halamine-charged wool cloth exhibited rapid and potent bactericidal activity against different types of bacteria, with exhibition up to 99.99% in terms of colony forming units (CFU) against Bacillus thuringiensis spores. Regenerated cellulose/ keratin material chlorinated to display halamines was also found to be effective in inhibiting growth of *E. Coli* and *S. aureus* bacteria. Electrospun core/shell nanofibers with maximize keratin Cl exposed area display higher efficacy against S. Aureus than the film made of same material (Matthew *et al.* 2013). Environmentally friendly flame-retardant chemicals are being evolving in the present decade, keeping in mind the demand for sustainable textile production, in the present day's stringent environment law (Samanta, Basak and Chattopadhyay, 2015; Kambli *et al.* 2018; Basak *et al.* 2016; Samanta, Basak and Chattopadhyay, 2017). Keratin biomaterial was also attempted as an environmentally flame retardant with nitrogen/ phosphorus containing group on cotton fabric. Here, melamine and sodium pyrophosphate were considered as nitrogen and phosphorus doner, respectively along with glyoxal as a cross-linking agent. Due to the synergistic impact of nitrogen and phosphorous compounds, the modified wool waste keratin leads to formation of a continuous and intact layer of char, which contribute towards the improvement in flame retardancy in the cotton fabric. Limiting-oxygen-index of the cotton fabric after application of keratin witnesses nearly 66.7% increase in flame retardancy property, then that of untreated cotton (Patankar *et al.* 2021).

Keratin hydrolysate (KH) is used to improve the exhaustion reactive dye in the cotton fabric. It crosslinks with cotton fabric at neutral pH and temperature of 100 °C. During the esterification process, primary hydroxyl group reacts with hydroxyl group of keratins, in which water get condensed as by product, and the reaction was assured by the presence of water. Reactive dyeing of cotton fabric mainly consists two stages, exhaustion and fixation. Exhaustion of dye in a cotton fabric is achieved by addition of salt in the dye bath followed by fixation in the presence of alkali, leading to formation of covalent bond. Keratin hydrolysate (KH) is used to modify the surface of the cotton fabric, possesses thiol and amino groups, and exhibited good affinity towards reactive dyes. In the acidic pH, cationic nature of modified cotton fabric

occurs in the presence of auxiliaries. Protonation process of cotton helps the exhaustion of dye molecules without addition of salt. Colour strength (*K/S*) values of the fabrics, dyed with reactive dye without addition of salt, show very good results. Dye uptake by the fabric increases by increasing the amount of KH on weight of the fabric. It increases up to 91%, as compared to control cotton fabric, underscoring its efficacy as a dye exhausting agent, while addressing the high salinity effluent generation (Arivithamni *et al.* 2014).

Pilling is a one of the major issues in the textile substrates, where numerous tiny fibre balls are formed having very fuzzy appearance on the fabric surface. Such thing commonly occurs, due to slipping out fibres from the fabric surface, and gets entangled in the subsequent washing and wearing. Anti-pilling treatment of cashmere fabric is carried out with 8% (o.w.f.) keratin solution and 5% (o.w.f.) LKZ-610 at 50° for 50 min, keeping the material to liquid ratio of 1:20, followed by washing and drying. In the treatment a polymeric layer formed on the fabric surface decreases fabric surface frictional attributes, resulting improvement in anti-pilling properties (Jiru *et al.* 2016). The added layer acts as a sizing performance too, by protecting yarns surface to improve weaving efficiency (Parag *et al.* 2017; Yang and Reddy, 2013; Reddy *et al.* 2014). Alike to conventional sizing formulation, it could also enhance the tensile strength and abrasion resistance of the yarns.

Foam technology is a very effective and old process due to its larger volume per unit mass with high surface area. It is frequently applied to transfer chemical and dyes molecules on the different textile substrate. Low wet-pickup of about 20–40% in foam dyeing is found to be economic in terms of lower down the drying time, requirement of less water and energy, faster processing, and minimal effluents generation. In such process, a wide range of synthetic surfactants are used, as a foaming agent viz., sodium dodecyl benzenesulfonate, dodecyl amine hydrochloride, poly (ethylene oxides) and dodecyl belaine. Proteins are similar nature like amphiphilic synthetic surfactants, due to the presence of hydrophobic and hydrophilic, anionic and cationic amino acids in it, that provide them a certain degree of surface activity. In this direction, keratin as a foaming agent, alternative to synthetic surfactants, is not only beneficial in terms of biodegradability along with lower toxicity, but also in terms of textile waste water processing. Cotton fabric was coloured by foam dyeing technique using reactive dye, keratin hydrolysate 20 gpl as a foaming agent, urea 100 gpl for dissolution of dyes, sodium silicate 65 gpl for stability of dyes bath, sodium hydroxide 50 % ml/l for increasing the colour strength as well as fixation of dye. Complete process was carried out at ambient temperature for six hours in batch process with the provision of slow rotation. Sample was thus thoroughly washed with cold water, hot water, and finally with 2 gpl non-ionic soap solution. Foam dyed cotton fabric was compared with the dyed cotton fabric by conventional cold-pad-batch process. It is found that keratin hydrolysate shows a reduction in surface tension, good foam stability with dyeing auxiliaries and shows the bubble sizes of 0.02–0.1 mm (Parag *et al.* 2017).

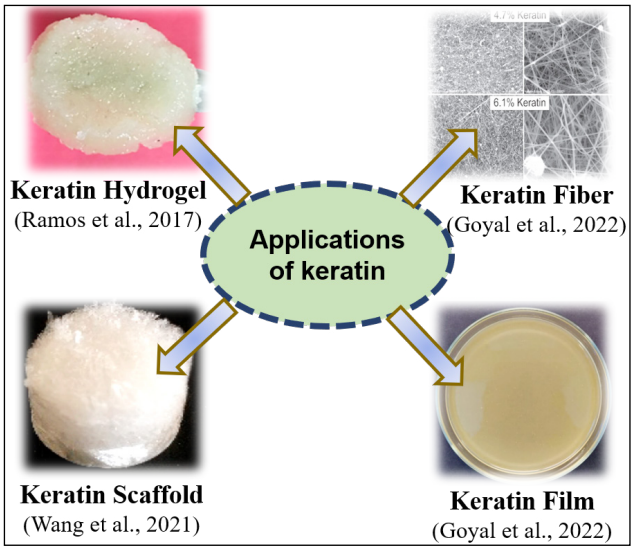

Fig. 2: Different end applications of keratin

3. Keratin hydrogel

Nowadays the use of biopolymer and synthetic polymer is very common for making film, gel, scaffold and nano particles. Such materials are used as a carrier for therapeutic agent for effective targeted areas for healing. Among the different important bio-polymers like alginates, chitosan and collagen, keratin is also gaining research interest due to its availability, bio-compatibility, low cost and biodegradability (Curcio *et al.* 2015). In order to prepare keratin hydrogel, water soluble keratin

(keratose) is used (Tonblyn *et al.* 2016; Ham *et al.* 2016). Application of ciprofloxacin in this keratin-based hydrogel shows the efficiency of 60% drug delivery in 10 days (Saul *et al.* 2011). Inhibition of postoperative adhesion after abdominal or peritoneal surgeries, keratin hydrogel played an important role (Peyton *et al.* 2012). Keratose hydrogel along with Halofuginone (HF), as a drug, is used and has been noticed that HF-keratin hydrogel reduced the density of adhesion in rodenticidal abrasion model. Keratose hydrogel with 9% of purity is used to reduce the burning progression, and skin regeneration, whereas 15% concentrated keratose hydrogel is proven to be useful in nerve treatment and recovery (Chen *et al.* 2020). A blend of 5% keratin hydrogel and 5% polyvinyl alcohol possesses wound healing properties (Reddy *et al.* 2021). Odontoblast cell behaviour has been improved by blending of 20% keratin and 3% glycerol, and also shows an effective in pulp dentine regeneration (Zafar *et al.* 2020). Keratin-allyl-thioether hydrogel has a controlled degradation behaviour and is a suitable matrix for encapsulation and cell delivery (Chen and Liu, 2016).

4. Keratin sponges and scaffolds

Keratin based scaffolds is widely used in biomedical application, due to its polymerizing ability and self-assembled 3D porous structure. Tachibana *et al.* in (2001), first reported the keratin scaffolds derived from wool for long term cell cultivation (Tachibana *et al.* 2005). In this process, freeze drying in a control process was carried out to obtain a homogeneous porous heat stable scaffold. A technique has been proposed in their research to hybridize keratin sponges with calcium phosphate. These ions were either react chemically within the sponges or by incorporating the hydroxyapatite particles within the keratin carboxy-sponges structure. Osteoblastic cultivation was supported by both the hybridized sponges positively. It is challenging to maintain a required pore size and porosity in a scaffold structure. A compression moulding technique was used to regulate the pore size of keratin scaffolds so as to allow cellular infiltration along with adequate delivery of nutrient (Tonnin *et al.* 2007). Composite made of pure keratin with inferior mechanical properties and brittleness was improved by the addition of synthetic biopolymers viz., PVA, PCL, PLLA, and PEO. Scaffold prepared from chitosan (2:1, v/v) are used to introduce anti-microbial activity (Sadeghi *et al.* 2020). Polylactic acid/ keratin chitosan composite helps in stimulation, proliferation and bones tissue engineering (Chakravarti *et al.* 2020). Mechanical strength of the composite made from carboxymethyl/ hydroxyapatite-keratin is improved for application in bone healing and drug release (Lago and Felisberti, 2020).

5. Application in cosmetic

Keratin hydrolysates are also used in cosmetic applications, like in hair and skin applications. Presence of keratin in the stratum corneum and hair cuticle helps in retaining moisture in skin by interacting with cosmetics. High molecular weight keratin is most apposite for skin care applications, due to their hydrophilic and film forming characteristics. A coating or film on the skin, formed by keratin molecule, provides smooth and soft sensation. Keratin, compatible with water, improves the mechanical and thermal properties of hair, supporting its usage as cosmetic products. Keratin peptides can reinforce the skin barrier function and reduce the trans epidermal moisture loss, allowing the skin to be firm and supple. Solubilised keratin proteins bond to the natural nail and strengthen the nail plate (Lusiana and Müller-Goymann, 2011). Hydrolysed keratins in a concentration of 0.2% are used in mascaras and about 0.028% in bath soaps and detergents.

CONCLUSION

Keratin is a fibrous protein polymer extracted from the hair, nails, horn, hoofs, wool & hair fibres, feathers and epithelial cells in the outermost layers of the skin. Keratin serves important structural and protective functions, particularly in the epithelium. There is a need of a sustainable solution for efficient management of coarser wool and hair waste, while addressing the environment pollution. Such material may be explored for extraction of keratin biomaterial. The present review focusses on the extraction of keratin from the wool fibre, hair and other potential sources, its properties, and different industrial applications in the area of textile fibre, textile auxiliaries & finishing agent, film, sponges, scaffolds, hydrogel and cosmetics. Research on

keratin biomaterial from several decades in the various fields like pharmaceuticals, cosmetics, biotech and textile shows it potential for different end applications. Keratin possess many distinct advantages over conventional biomolecules, namely a unique chemistry afforded by high sulfur content, remarkable biocompatibility, propensity for self-assembly, and intrinsic cellular recognition. Keratin based fibres are strong, elastic and having adequate moisture-wicking properties, suitable for textile application. Blend of keratin and polyvinyl alcohol possesses wound healing properties. A coating or film on the skin, formed by keratin molecule, provides smooth and soft sensation.

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