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Physical and chemical properties of Indian silk fibres

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Abstract
Silk is the naturally occurring filament fibre which is an opulent gift of mother nature to mankind. Its unique qualities and exceptional glory make it distinct from other natural and man-made fibres. It is the only fibre which has variety of uses such as suiting, sarees, neckties, shawls, scarves, gowns, upholstery, carpets, parachutes, gas mantles, surgery and fishery. The knowledge of fibre properties is important as it determines the nature of resultant product. It can be classified as physical, mechanical, chemical, electrical and biological. Silk can be classified as mulberry and non-mulberry out of which four are commercially exploited *viz*., mulberry, tasar, eri and muga. It is composed of different amino acids and exhibit amphoteric nature and hence can be readily dyed with all class of dying agents. It is widely accepted for excellent strength as well as elastic recovery, sheen, drapability, pliability, high moisture regain capacity and resiliency which make it suitable for use as high-end textile apparel.

Keywords: Eri, muga, drapability, pliability, sheen, upholstery

1. Introduction

The history of fibre is as old as human civilization. A fibre is a unit of matter which is usually at least 100 times longer than its thickness (Gohl and Vilensky, 1987) [17]. The basic entity, either natural or manufactured, which is twisted into yarns and then used in the production of a fabric (Anon., 2019). For many thousand years, the usage of fibre was limited by natural fibres such as flax, cotton, silk, wool etc. Silk is rightly called the 'queen of textiles' for its lustre, sensuousness and glamour. Silk's natural beauty and properties of comfort in warm weather and warmth during colder months have made it use in high-fashion clothing (Reddy, 2009) [39]. Silk fibres have some outstanding properties that rival the most advanced synthetic polymers; however, the production does not require harsh processing conditions.

Silk is one of the oldest natural fibres utilized by man since time immemorial. The composition, structure and properties of silk vary depending on their specific source and function (Altman *et al*., 2003; Craig *et al*., 1999) [1, 13]. This filament is well known for its sheen, lustre, water absorbency, dyeing affinity, thermal tolerances along with insulation properties (Sheikh *et al*., 2016). In relation to fibre length, silk fibres are extremely long continuous filaments. It is the lightest among all-natural fibres and display and unusual combination of strength and toughness. Some of the textile properties such as finesse, strength, elasticity, dyebility, softness, flexibility, gloss, elegance made it suitable to use in the textile Industry (Khan *et al*., 2010; Ude *et al*., 2014) [24, 56]. The silk is mechanically robust biomaterial with environmental stability, biocompatibility and biodegradability and also offers wide range of practical properties for biomedical applications (Reddy and Prasad, 2011) [40]. Silkworms secrete silk fibres to build protective shell known as cocoons during the end of larval stage in their life cycle.

There are four types of natural silk which are commercially known and produced *viz*., mulberry, tasar, muga and eri silk produced by the silkworm *Bombyx mori*, *Antheraea mylitta*, *Antheraea assamensis* and *Samia ricini*, respectively. The tasar, muga and eri are non-mulberry silks also known as wild silk or *Vanya* silk in India. India enjoys the sole monopoly in the world for the fabulously famed golden yellow coloured muga silk which is produced only in the state of Assam and adjoining hills (Chowdhury, 1992).

1.1 Classification of fibres

On the basis of origin, the fibres may be divided in two categories: Natural and man-made (Singh, 2004) [47]. Natural fibres may be further classified into the following three groups:

1. **Vegetable Fibres:** It includes cotton, linen, jute, hemp, sisal, kapok, ramie, coir and pina.
2. **Animal Fibres:** It includes wool, silk and hair.
3. **Mineral Fibres:** Asbestos is the only naturally occurring mineral fibre.

1.1.1 Manmade Fibres are further classified into the following groups

1. Cellulosic Fibres: It includes rayon, acetate and triacetate.
2. Non-cellulosic polymers: It includes nylon, aramid, polyester, acrylic, modacrylic, spandex, olefin, vinyon, saran, novoloid, polycarbonate, alginate, anidex, graft etc.
3. Protein Fibre: Azlon is the only artificially manufactured protein fibre.
4. Rubber: It includes synthetic rubber.
5. Metallic Fibre: It includes metal made of aluminium, silver etc.
6. Mineral Fibre: It includes glass, ceramic and graphite.

1.2 Microstructure and appearance

Silk comprises of two important proteins, fibroin (the silk filament) and sericin (the gum). Each raw silk strand in the cocoon is known as "bave"; it is composed of the fibroin filaments called "brin" that are held together by sericin gum. Microfibrils are minute protein strands composed of ordered amino acid chains. The microfibrils are held together in bundles and several such bundles constitute a single fibroin. The cross-sections of mulberry silk fibres are more or less triangular whereas non-mulberry fibres are near rectangular. Striations are observed on the surfaces of muga and tasar silk fibres (Gupta *et al*., 2000) [20].

1.3 Composition of silk cocoon shells

Silkworm cocoons are composed of proteins, which account for more than 95% of its content; other impurities, such as waxes, mineral salts, and ash, constitute about 4-5%. The wild silk cocoon shell has a lower sericin content and higher levels of wax, minerals wax, ash and other impurities. The raw silk fibre extracted from silk cocoon is subjected to degumming process to remove sericin from it. After degumming silk fibre contains fibroin protein (Padaki *et al*., 2014).

1.4 Composition of silk

The silk is almost a pure protein composed of two types of proteins *viz.*, fibroin (70-80%) and sericin (20-30%) and other components such as carbohydrates, waxes and ash (1-2%) (Takasu *et al.*, 2002). Sericin ($C_{15}H_{25}N_5O_8$) comprises of 18 amino acids, with strong polar side groups and high content of serine, aspartic acid and glycine resulting in hydrophilic protein (Kunz *et al*., 2016) [27]. The silk fibre after degumming contains fibroin protein which is composed of about 20 amino acids (Gupta *et al*., 2000) [20]. Fibroin ($C_{15}H_{23}N_5O_6$) is made up of two components *viz*., crystalline and amorphous. In crystalline component, amino acids are present in a definite manner with a definite space and the glycine residues repeats with other amino acids in the ratio of 3:2:1 (Strydom *et al*., 1977) [51]. Japanese scientists have revealed that fibroin is composed of major homogenous part called heavy chain or H-chain (350KD) and minor heterogenous part called light chain or L-chain (25 KD) connected to each other by disulphide linkages (Shimura, 1988 and Gopinathan, 1992) [46, 18].

In mulberry silk, glycine, alanine, and serine together constitute about 82%, of which serine constitute 10%. Tyrosine and valine may be considered next to these at about 5.5 and 2.5%, respectively. The dominance of acidic amino groups (i.e., aspartic and glutamic acids) in the mulberry variety is more than that of the basic amino acids. The ratio of basic to acidic amino acids is 0.65 for the bivoltine and 0.75 for the crossbreed variety. Similarly, the ratio of bulky to non-bulky amino acids in these two varieties is ranged from 0.17–0.18. The ratio of hydrophilic to hydrophobic groups in both varieties suggests that the fibres are basically hydrophilic in character, although the crossbreed variety has a slightly higher value at 0.29 (Sen and Babu, 2004) [42, 43].

Table 1: Amino acid composition of different varieties of silk fibres

Amino acid composition (mol %)					
Amino acid	**Mulberry(bi)**	**Mulberry (cross)**	**Tasar**	**Muga**	**Eri**
Aspartic acid	1.64	1.49	6.12	4.97	3.89
Glutamic acid	1.77	1.53	1.27	1.36	1.31
Serine	10.38	10.85	9.87	9.11	8.89
Glycine	43.45	43.73	27.65	28.41	29.35
Histidine	0.13	0.15	0.78	0.72	0.75
Arginine	1.13	1.16	4.99	4.72	4.12
Threonine	0.92	0.76	0.26	0.21	0.18
Alanine	27.56	28.36	34.12	34.72	36.33
Proline	0.79	0.76	2,21	2.18	2.07
Tyrosine	5.58	5.76	6.82	5.12	5.84
Valine	2.37	2.89	1.72	1.5	1.32
Methionine	0.19	0.11	0.28	0.32	0.34
Cystine	0.13	0.12	0.15	0.12	0.11
Isoleucine	0.75	0.78	0.61	0.51	0.45
Leucine	0.73	0.75	0.78	0.71	0.69
Phenylalanine	0.14	0.18	0.34	0.28	0.23
Tryptophan	0.73	0.75	1.26	2.18	1.68
Lysine	0.23	0.25	0.17	0.24	0.23

(Sen and Babu, 2004) [42, 43]

2. Physical properties of silk

2.1 Colour

Mulberry silk fibre is white or yellow or light green. Muga silk is golden yellow, tropical tasar is copperish yellow or fawn coloured, oak tasar is yellow grey and eri silk is white, dull white (Krishnaswami *et al*., 1988). White or colourless fibres are more preferred because they can be dyed or printed with any hue of colour.

2.2 Lustre

It is a subjective measure of the reflection of incident light from a fibre, filament or textile material. A uniform cross-sectional area of the silk fibre coupled with filament form imparts high lustre to the mulberry, muga and tasar silk yarns due to even reflection of incident light. Eri silk is also lustrous due to its higher translucency with a uniform cross-sectional area. As per birefringence data, the molecular arrangement in mulberry silk is highly oriented whereas three non-mulberry silk fibres have lower orientation with no significant variation (Gupta *et al.*, 2000) [20]. Birefringence is the difference between the refractive indices of fibre in two directions i.e., along fibre axis ($n\parallel$) and perpendicular to the fibre axis ($n\perp$).

2.3 Fibre length

Silk filaments are extremely long continuous filaments. Longer fibres are easier to process and more even yarns with high strength can be produced from them.

Silk	Total Filament Length (m)
Mulberry (Uni)	800-1500
Mulberry (Bi)	1000-1500
Mulberry (Multi)	300-700
Multi-bi hybrids	700-900
New hybrids	1000-1200
Tasar	650-1300
Oak Tasar	650-750
Muga	300-500

(Srivastav and Thangavelu, 2005) [49, 50]

2.4 Fibre fineness

The size of the bave, raw silk is expressed in terms of denier, which refers to the weight of a length of 450m in 0.05gm units or 9000 m weighs one gram. Filament denier is not uniform throughout the reelable length of filament. It plays an important role in determining the quality of resultant yarn and hence of the resultant fabrics. The lower the denier, the finer the silk and vice-versa. Mulberry silk is the finest, followed by eri, tasar and muga (Gupta *et al.*, 2000) [20]. Non-breakable filament length (NBFL) is the length of silk filament that is present continuously in the cocoon.

Table 2: Fibre fineness and non-breakable filament length of silk fibres

Type of silk	Fibre fineness(den)	NBFL(m)
Mulberry (Bi)	2-3	700-800
Mulberry (multi)	2-3	400-600
Tasar	8-12	100-250
Oak Tasar	3-5	300-450
Muga	4-7	150-250
Eri	3-4	0.05-2.0

(Padaki *et al.*, 2015) [37]

2.5 Linear density

Linear density is the amount of mass per unit length. The mulberry silk has relatively higher degree of order and more compact molecular packaging than non-mulberry varieties because of high glycine content and lower long chain/short chain ratio. The mulberry varieties do not exhibit pores or voids in their cross-sections whereas tasar, muga and eri silk show the presence of voids. Among the three non-mulberry silks, muga silk exhibits the highest density (Gupta *et al.*, 2000) [20].

2.6 X-Ray Diffraction

Silk fibroin have been studied extensively on X- ray diffraction of varieties of silk. The crystalline structure of the silk was first described in 1950s as an anti-parallel, hydrogen bonded β sheet based on the characterization of *B. mori* fibroin (Marsh, 1955) [32]. Physical parameters such as crystallinity, crystallite size, crystallite orientation is determined through X-ray diffraction. Crystalline regions in the mulberry silk yield 48%, tasar silk about 39%, while muga at about 40% and eri about 36%. It is observed from X-Ray diffractograms that mulberry silk varieties have similar distinct peaks, with better-ordered regions in comparison with the double peaks and distributed intensities as in non-mulberry silks (Sen and Babu, 2004) [42, 43].

2.6.1 Crystallinity and Crystallite size

Crystallinity is the indication of crystalline region in polymer with respect to polymer content. Silk is a semi-crystalline material. Earlier studies by X-ray diffraction analysis indicated 62%-65% crystallinity in cocoon silk fibroin from the silkworm, 50%-63% in wild-type silkworm cocoons, and lesser amounts in spider silk (Warwicker, 1956). According to Bhat and Nadiger (1980) [6], non-mulberry silk varieties show large crystallite size than mulberry silks attributed to higher alanine content (Ala-Ala links) in crystalline region. Three non-mulberry silks show large crystallite size and low crystallinity than mulberry silks which indicates high elongation. The presence of amino acids with bulky side groups offers lower crystallinity in non-mulberry silks with increase in crystallinity and crystallite size from outer layers to inner layers (Sen and Babu, 2004) [42, 43].

2.6.2 Moisture regain

Silk is a very hygroscopic textile fibre. Mulberry raw silk has a moisture regain of 11%, which reduces to about 9% after degumming (at standard atmospheric condition, 27 ºC and 65% RH) (Lee, 1999) [28]. Tasar silk shows highest moisture regain value followed by eri and muga for outer layers. The higher moisture regain of non-mulberry silk suggests that they may consist of higher ratio of hydrophilic and hydrophobic amino acid residues. Moisture regain of inner layers is less compared to outer layers because of compactness (Sen and Babu, 2004) [42, 43]. Silk fibres can absorb upto 30% moisture from the air without feeling damp and the fibres display 69J/g of heat of wetting from 0 ºC which indicate that coupled with high regain of about 10%, it offers sufficient time for the wearer to acclimatize to the change in weather (Gohl and Vilensky, 1987) [17]. Silk fibres swell about 30% of their volume under wet conditions: because of this, silk textile materials have a lower dimensional stability compared to other natural fibres. Due to this swelling action, silk fibres display partial loss of strength under wet condition.

3. Mechanical properties

3.1 Tenacity and elongation

The average tenacity of mulberry (bivoltine) and mulberry crossbreed was 3.75 g/d and 3.85 g/d respectively, while tenacity of tasar was highest i.e., 4.5 g/d among the three non-mulberry silks (Sen and Babu, 2004) [42, 43]. The tenacity of muga ranged between 3.2 and 4.95 g/d (Tsukada *et al.*, 1994). Eri silk showed lowest tenacity value, ranging between 2.3 and 4.0 g/d (Iijuka and Itoh, 1997) [21]. The variation in mulberry is not all that high, making eri the most non-uniform in terms of tenacity along the fibre. Wild silk possesses better elongation compared to mulberry silk. The mechanical properties of silk change substantially along the length and follow a definite trend.

3.2 Elastic-plastic nature

Silk is considered to be more plastic than elastic because of its very crystalline polymer system. Silk fibre may be stretched from 1/7 to 1/5 of its original length before breaking and returns to its original size with losing little elasticity (Singh, 2004) [47]. Stretching disorganizes the polymer system of silk which is seen as a distortion and wrinkling or creasing of the silk textile material (Gohl and Vilensky, 1987) [17]. There is a slow elastic recovery or creep after extension, but the silk does not regain its original length (Cook, 1984).

3.3 Breaking extension

Elongation is defined as the length to which a fibre may be stretched before breaking. Elongation-at-break showed a higher value for all the non-mulberry silks compared to mulberry varieties. The values range between 31% and 35% for tasar, 34%-35% for muga and 29%-34% for eri silks, respectively. The elongation values for mulberry varieties ranged between 19% and 24% (Babu, 2020) [4]. The relatively high degree of extension in the case of non-mulberry silks may be attributed to the following: (1) All the non-mulberry silks contain more amino acid residues with bulky side groups than the mulberry silk varieties (Iizuka, 1985) [23]. This enables molecular chains in non-crystalline regions in the fibre structure to slip easily when stretched and thus show higher elongation at break. (2) Unfolding of the long fibroin chains in the amorphous regions is a result of either less orientation or less crystallinity (Iizuka, 1997) [22].

3.4 Initial modulus

Another important tensile parameter is the initial modulus. The initial modulus values for different varieties changes along the filament length. The initial modulus values follow a similar trend as that of tenacity, showing higher values for the inner layers. The values ranged between 53.9 and 136.8 g/d for mulberry (bivoltine), 83.8 and 129.8 g/d for mulberry (crossbreed), 61.3 and 100.7 g/d for muga, 61.4 and 107 g/d for tasar, and 71.1 and 107 g/d for eri silk. This definitely indicates an increase in orientation in both the crystalline and the amorphous regions, as one moves from the outer to the inner layers (Sen and Babu, 2004) [42, 43].

3.5 Stress-strain curve

Silk is a visco-elastic material and exhibits the phenomenon of stress-strain. Creep and stress behaviour of silk has been reported by Das (1996) [15]. The extension, secondary creep is higher for tasar silk compared to those for mulberry silk and stress relaxation was also found to be more in non-mulberry silks. Non mulberry silk exhibits a high initial resistance followed by substantial yielding. The reasons are (1) fewer crystalline regions and (2) imperfect crystallites or entanglements, which initially offer resistance but later give way and allow easy deformation in the amorphous regions until strain hardening occur (Sen and Babu, 2004) [42, 43].

3.5.1 Cohesion and abrasion

Cohesion implies the force with which the composite filaments cohere to gather inside a strand. The measurement is done by degree of agglutination of filaments and sericin plays the role in it (Manna *et al.*, 1989) [31]. Abrasion is the rubbing or scrapping off the surface of a thread. Fibre crimp increases the cohesiveness, resilience and resistance to abrasion.

3.6 Resiliency

Resilience means that the fibre can be compressed or crushed and, on release of pressure, will tend to return to its original shape. This quality causes the fabric to be wrinkle-resistant. Silk fibres retain their shape and have moderate resistance to wrinkling. Fabrics that contain a large percentage of weighting or made from short-staple spun silk have less resilience (Singh, 2004) [47].

3.7 Drapability

The drapability of a fabric, or its ability to hang and fall into graceful shape and folds. Silk has excellent drapability because of its elastic and resilient properties (Singh, 2004) [47].

4. Dielectric and frictional properties

Silk fibres are insulators for electrical conduction. Therefore, under the action of friction, static electric charges tend to develop in the fibres. The moisture regain dissipates the static charges effectively; however, under low humidity conditions, static charges pose problems for silk fibre handling. Like most textile fibres, silk fibres get positive static charges.

The insulation resistance and dielectric strength of silk fibres give an indication of their dielectric constant, current leakages at certain voltages, moisture content, and stability under electric fields. Electrical and dielectric properties have gained importance with applications such as moisture measurement, evenness measurement, and the use of silk fibres in the form of fibre reinforced composites as insulating materials for special applications (Padaki *et al.*, 2015) [37]. The electrical resistance (R_s, Ώ kg/m2) of silk fibres is 9.8(log R_s value), which is much higher than cotton (about 7), wool (8.4), and polyester (8) fibres at 65% RH (Morton and Hearle, 2008) [33]. The electrical resistance decreases with rise in humidity and temperature.

The force that holds together the fibres in a spun yarn and the interlacing threads in a fabric is called as frictional force. If the friction is too low, the yarn strength will fall and dimensional stability of cloth will be reduced. Textile fibres have coefficient of friction (μ) values ranging from 0.1 to 0.8, the lower value indicating higher frictional resistance (Morton and Hearle., 2008) [33]. Typical μ values for silk fibre to fibre friction is 0.26 for crossed fibres and 0.53 for parallel fibres. The higher value is because of the smooth fibrous surface coupled with crystalline regions in the fibre while this fibrillar nature makes the silk fibres a poor resistant to abrasive wear (Padaki *et al.*, 2015) [37].

5. Thermal properties

Silk fibre is thermally stable below 100 ˚C. High degree of molecular orientation of silk fibroin helps the thermal stability of the silk fibre. Yellowing begins to occur in silk fibres at 110 ˚C after 15 minutes of exposure (Lee, 1999) [28]. From the peaks of Differential Scanning Calorimetry (DSC) curves of silk, Nakamura *et al.* (1994) predicted that the glass transition temperature of silk is about 175 ˚C and silk fibre degradation begins at 280 ˚C with an initial weight loss starting at about 250 ˚C. When silk fibre is subjected to heat, no significant changes occurs in the crystalline structure but the amorphous region becomes highly oriented (Tsukada., 1992) [55].

Silk is a good insulator of heat among the textile fibres; the specific heat of dry silk fibre is 1.38j/gK (Morton and Hearle, 2008) [33]. The thermal conductivity of mulberry silk fibre in longitudinal and transverse direction is 1.49 and 0.119 W/(mK), which indicates high orientation of fibroin molecules along the direction of fibre. Due to lower thermal conductivity and high moisture regain of silk fibres, the comfort level of wearing silken items is decreased in hot and humid areas. The heat of setting of twisted silk yarns is also carried out by utilizing the thermal behaviour of silk fibres, Steam heating of the twisted silk yarn increases the moisture level and temperature in the silk fibres (Padaki *et al*., 2015) [37].

6. Chemical properties

Silk is a protein fibre; it is composed of different amino acids. The properties of proteins depend primarily on the properties of the reactive groups of their constituent amino acids combined with the properties associated with the size of the protein. Amino acids are bifunctional, i.e., they contain both acidic carboxyl (coo-) and amino group (NH3+) thereby acting as Zwitterion.

6.1 Action of water

Water does not permanently affect silk fibre. It decreases about 20% in strength when wet, but regains the original strength upon drying (Lee, 1999) [28]. The amorphous regions of silk are reported to be more accessible to deterioration by water (Crighton, 1993) [14]. When steeped in warm water, the fibre swells but does not dissolve. The water use for reeling should be clean to prevent the dissolved substances present in it.

6.1.1 Action of acids

Concentrated hydrochloric acid dissolves the silk in one or two minutes. Non-mulberry silks are less affected by the action of acids than mulberry silk (Krishnaswami *et al*., 1988). When silk is treated with dilute hydrochloric acid, it dissolves in 1-2 minutes without losing its strength. If silk is treated with strong sulphuric acid for few minutes, then rinsed and neutralized, contraction of fibres occurs from 30-50% in length and losses its lustre. This property is utilized to impart creep effects (Srivastav and Thangavelu, 2005) [49, 50]. Action of nitric acid produces a bright yellow colour on silk which can be removed by treatment with stannous chloride. Formic acid and acetic acid have no injurious effect on s silk. Exposure to weak acids results in the ‘scroop effect’, which is a famous finishing treatment that produces a crackling noise when such fibres are rubbed together (Sonwalkar, 1993) [48].

Shell weight loss and silk filament recovery is influenced on cooking the tasar cocoons with tartaric acid. Mechanical properties do not change with the process parameters (Gulrajani, 1988). Muga silk could be chemically modified and tensile properties can be changed. Methanol and phenol treated fibre show higher tensile strength whereas Formaldehyde degrades the molecular weight and hydrogen bonding (Talukdar *et al*., 2011) [53].

6.2 Action of alkali

Silk fibres have low resistance to alkali and are easily damaged by exposure to weak alkali at elevated temperatures. Alkali conditions hydrolyze the polypeptide bonds of fibroin from its molecular chain ends, thus degrading silk fibre rapidly. Alkali solutions cause the silk to swell, due to the partial separation of the silk polymers by the molecules of alkali. Salt linkages, hydrogen bonds, vander walls force are all hydrolysed by alkali so dissolution occurs readily (Gohl and Vilensky, 2005). Silk fibre dissolves on treatment with strong hot alkalies such as caustic soda or potash. Ammonia and alkaline soaps dissolve only the sericin layer of silk but have no effect on fibroin. Sericin or fibroin has no effect on treatment with borax. If raw silk is steeped in lime water, the fibre swells and sericin becomes soft. Continued treatment with lime water cause brittleness in silk (Srivastav and Thangavelu, 2005) [49, 50].

6.3 Action of metallic salts

Silk has great affinity for metallic salts. This characteristic is employed for the process of silk weighting, to improve draping properties. Stannic chloride is used for weighting unless the material is to be dyed black. Black silk is often dyed and weighted by using log-wood and iron salt. A moderately weighted silk contains 25-50% of salt (Cook, 1984).

6.4 Effect of organic solvents

6.4.1 Effect of different organic solvents on mulberry silk: While treatment of mulberry silk with ethanol, ethyl acetate, methanol there is change in the secondary structures of silk fibroin from random coil to high strength β sheet structure and thermal stability also increases (Prasong *et al*, 2010) [35]. Methanol is the best solvent to induce strength and thermal properties (Nuanchai *et al*., 2010) [35].

6.4.2 Treatment of muga silk with organic acids: Modifies the fibre chemically and increases the tensile strength. Treatment with Methanol and phenol shows higher tensile strength (Talukdar *et al*., 2011) [53].

6.5 Action of dyes

Dye-stuffs are absorbed by silk more readily and at lower temperature than any other normal fibre (Chowdhury, 1992). Silk was dyed with vegetable dyes extracted from stems, roots, stalks, foliage, barks etc of different plants in older times (Das, 1992 and Chowdhury, 1992) [16]. The selection of dye is very important as dyeing increases the value of silk (Chowdhury, 1982) [10]. Acid dyes produce brilliant shades with good light fastness but poor to moderate wash fastness which can be improved by treatment with cationic dye fixing agent at 40-50 ˚C for 20 min (Chakraborty, 2010). Dyeing of silk fabric with acid dyes improves good colour fastness and mechanical properties like count, cloth thickness and cloth weight (Mahale and Naikwadi, 2019) [30]. Reactive dyes have gained importance on account of brilliant colours, fastness properties and comparatively low cost. Treatment of muga silk fabric with acid and reactive dye results in decreased fabric weight, tensile strength, bending length but increased crease recovery of muga silk fabric (Arora, 2016) [3].

6.5.1 Dyeing of silk with natural dyes

Mulberry silk yarn dyed with mixture of bark of monkey jack and henna leaves produce different shades of brown colour, beige as well as green colour with satisfactory colour fastness properties and more denier (Boruah, 2016) [7]. The dye extracted from fruits of Ficus racemose have good affinity towards silk even without the use of mordants (Sudhakar and Ninge, 2011) [52]. *Camellia sinensis* (L.) kuntze (tea leaves), *Allium cepa* L. (onion peel), *Laccifer lacca* Kerr (lac insect) and iron ore were used as natural dyes in presence of different mordanting agents for dyeing of eri silk yarns. It improved the colour fastness to washing and light considerably which will motivate the weavers to use natural dyes with eco-friendly character (Banerjee *et al*., 2017).

6.6 Action with bleaching agents
Degumming followed by sequential oxidative and reductive bleaching on mulberry and tasar silk fabrics decreases fabric weight, thickness, tenacity, crease recovery, bending length whereas air permeability increases (Sharma *et al*., 1999) [44]. Hydrogen peroxide, performic acid, peracetic acid and potassium permanganate are some of the oxidising agents use for bleaching of silk. The reducing agents used are sulphur dioxide and sodium hydrosulphite. Treatment of natural colour silk with hydrogen peroxide doesn't change the structure, the degree of crystallinity decreases a little, the breaking tendency and the breaking elongation declines, the elastic modulus didn't change significantly (Li and Wang, 2013) [29].

6.7 Action of perspiration
Perspiration greatly tenders silk fibre. It becomes alkaline when deodorants containing aluminium chloride are used (Srivastav and Thangavelu, 2005) [49, 50].

7. Effect of sunlight
Sunlight disintegrates the silk. Raw silk is more resistant to light than degummed silk (Lee, 1999) [28]. The changes to mechanical strength on light ageing, with and without UV radiation has been analysed by Koremberg (2007) [25]. Yellowing has been attributed to the decomposition of tryptophan (Okamoto and Kimura, 1953) accelerated by the presence of tyrosine on light exposure (Yoshida and Kato, 1955) [57].

8. Biological and environmental properties
Under dry conditions, silk fibre exhibits excellent resistance to bacteria, fungi, mildews; however, some moths, silverfish and carpet beetles damage silk fibre. Under humid conditions, silk fibre is more susceptible to attack from bacteria, fungi and mildews (Padaki *et al*., 2015) [37].

9. Conclusion
The properties of any fibre determine the type of fabric produced from it. The finest among all is the mulberry silk, followed by eri and tasar silk. Muga is the coarser of all the varieties. They possess excellent tenacity as well as elastic recovery, lustre, soft feel and drapability. A high moisture regain, excellent pliability, and resilience offer superior comfort and make them appropriate for high fashion clothing. Silk requires careful processing so as not to affect its feel and appearance as it is worn as a symbol of royalty. Further research needs to be carried out to harness the other beneficial properties of silk.

10. Future prospects
Product development and diversification will be of greater importance to harness its inherent strength to meet market requirements. For e.g., Silk denim is a successful effort giving a new direction to both denim and silk. The improvements in the properties such as crease-resistant, dimensional stability, resistance to abrasion, photo-yellowing can increase the usability of new silk products. Biocompatibility has made silk a base material for construction of tissue walls, membranes, muscle ligaments, blood vessels etc. Targeting weak areas in the silk structure and properties can help to improve the durability of new textile products as well as those use in bioengineering.

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