9 Mohair, cashmere and other animal hair fibres

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Abstract: Although luxury animal fibres, excluding silk, represent far less than 0.1% of global fibre production, they play a very significant role in the luxury, high-value-added end of the market, notably the apparel market, being renowned for their special and mostly unique features, such as comfort and softness. This chapter covers the production, properties, processing and end-uses of the various luxury animal fibres, with the exclusion of silk, with the main focus on the down (undercoat) fibres of those animals with two fibre coats.

Key words: luxury animal fibres, mohair, camel, yak, musk-ox, cashmere, Angora rabbit hair, alpaca, guanaco, vicuña, llama.

9.1 Introduction

This chapter covers the various animal hair fibres that are generally referred to as luxury fibres, excluding the wool from sheep and also silk (which are described in Chapter 7, volume 1: Silk fibres, and Chapter 8, volume 1: Wool fibres). These luxury fibres have been discussed in two previous books[1,2] to which the reader is referred for more information and a more detailed list of references. The fibres considered here represent considerably less than 0.1% of global fibre production. Therefore, in terms of production volumes, they are insignificant. Nevertheless, they are highly sought after and play a significant role in the luxury, high value-added end of the market, notably the apparel market. Most of these fibres are produced by animals which inhabit inhospitable mountainous regions, covering a range of altitudes and extreme climates, where a highly insulating and protective fibrous coat (mostly a double coat) is essential for survival. The hair and fibres tend to be medullated, which combines good insulation with lightness. Due to the extremes of temperature they encounter, most of these animals have developed two distinctly different coats: (i) an outer coat consisting of coarse medullated guard hairs, produced by the primary follicles, which offers protection from the sun, rain and dust, and (ii) a finer and shorter down hair or fibre (undercoat or inner coat), produced by the secondary follicles, which provides outstanding insulation against extremes in temperature. The only exceptions are the Angora goat, alpaca and vicuña which, like sheep, are essentially single coated,

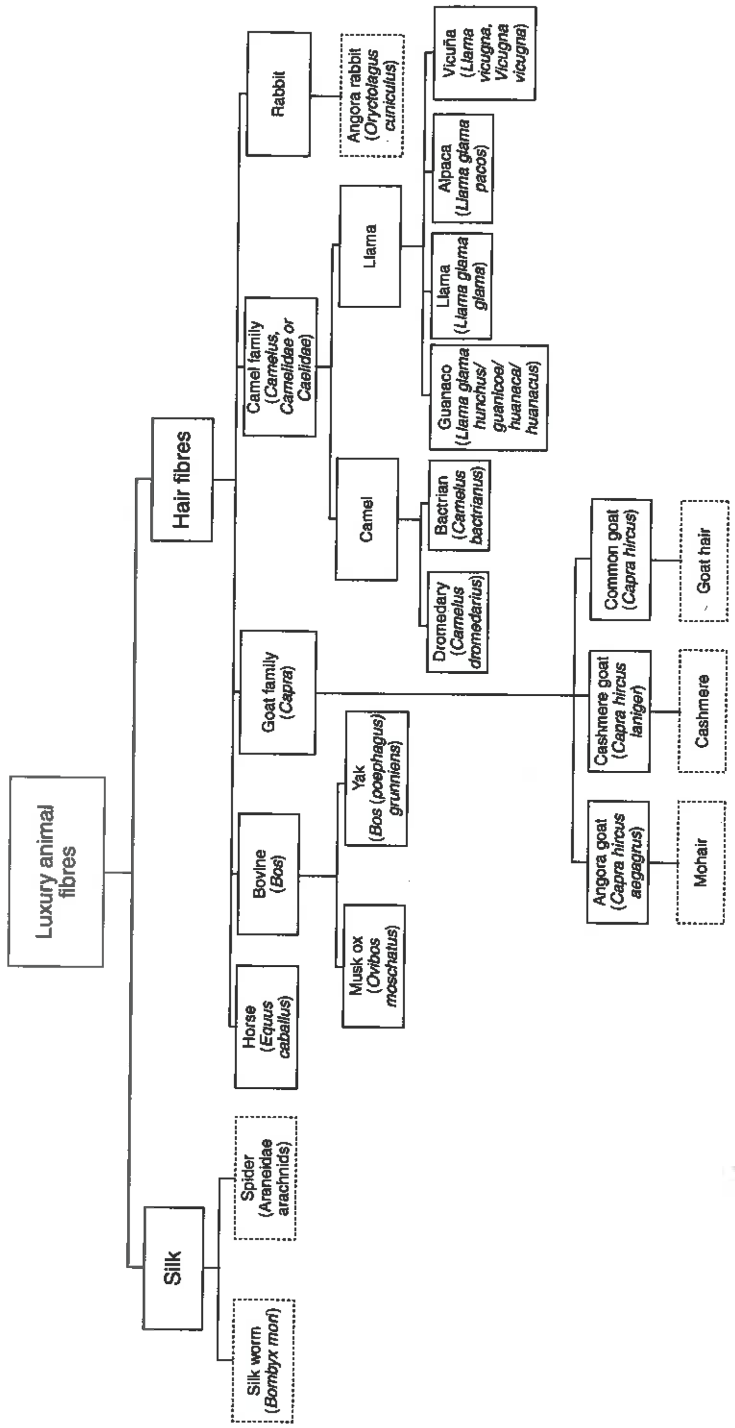
although still containing a combination of secondary and primary follicle fibres. In some cases, e.g. llama, there is also a group of intermediate fibres. For a given species, the younger the animal, the higher the altitude and the sparser the food the finer the fibre generally. The nature of their environment also largely determines the natural colour of animal fur,[3] for camouflage and other purposes; for example, the white winter fur of arctic animals, the grey-brown fur of forest and marshland animals and the yellowish fur of animals living in sandy areas.[3,4]

The fine undercoat (down) fibres, of two-coated animals, which are generally shed during spring, are the most valuable from a textile perspective, because of their combination of fineness, softness, lightness and good thermal insulation, and need to be separated from the undesirable coarse guard hair, either by hand or mechanically, a process called de-hairing. The finer the fibre and the lower the percentage of coarse fibres (guard hair) remaining in the fine component after de-hairing, the better the textile quality and value of the fibre. In this respect, successful de-hairing is largely dependent upon the differences between the two components in terms of fibre diameter/rigidity/linear density, friction and length and inter-fibre cohesion. Townend *et al.*[5] and Algaa and Mägel[6] have dealt with the de-hairing of luxury animal hair fibres.

This chapter focuses on the down fibres (fine undercoat) of those animals with two coats, the coarser guard hair (outer coat/hair) not being dealt with, except in a few isolated cases, and then only briefly. The ASTM D 2816 defines coarse hair as hair or fibres coarser than 30 μm, the criterion often used to differentiate between guard hair (outer coat) and down (undercoat).

Essentially, the main speciality animal hair fibres covered can be grouped into the following three main families or groups (see Fig. 9.1):

- Goat (*Capra hircus*)
  - Cashmere (*Capra hircus laniger*)
  - Angora (*Capra hircus aegagrus*)
  - Cashgora
- Camel (*Camelid/Camelus*)
  - Alpaca (*Lama pacos*)
  - Bactrian camel (*Camelus bactrianus*)
  - Guanaco (*Lama hunchus* or *Lama guanicoe*)
  - Llama (*Lama glama*)
  - Vicuña (*Vicugna vicugna*)
- Bovine (*Bos*)
  - Musk-ox (*Ovibos moschatus*)
  - Yak (*Bos (poephagus) grunniens*)



9.1 Main luxury animal fibre groups.

Angora rabbits (*Oryctolagus cuniculus*) do not belong to any of the above family groupings.

The South American Camelid (Camelidae) family consists of four species, three, namely llama (*Lama glama*), guanaco (*Lama hunchus* or *Lama guanicoe*) and alpaca (*Lama pacos*), representing the genus *Lama* and the fourth, vicuña (*Vicugna vicugna*), being a separate species.[7] They are now largely found in the Southern Andes, centred mainly on Peru's Altiplano region, known as the 'puna', a flat and rather barren terrain some 4600 m above sea level. There are also hybrids of the llama and alpaca. According to Greaves and Rainsford[7] the origins of the Camelid family (alpaca, guanaco, llama and vicuña) are not very clear, it being generally agreed that the two domesticated breeds, namely alpaca and llama, descended from the guanaco. It is also fairly widely believed that the alpaca originated as a hybrid between the llama and guanaco,[7] occurring after the Spanish Conquest of Peru in the early 1530s. According to Peruvian Andes archaeological sites, evidence suggests that the domestication of Camelids occurred between 7500 and 12 000 years ago.[7]

Table 9.1 compares the fibre characteristics and production figures for the different fibre types. It should be noted, however, that figures quoted in

Table 9.1 Approximate commercial fibre properties and production*

Fibre	Mean fibre diameter range (μm)	Typical (average) mean fibre diameter (μm)	Processed mean fibre length range (mm)	Typical processed mean fibre length (mm)	Raw fibre production per animal (kg/year)	Global raw fibre production (tonnes/ year)
Alpaca	20–35	27	70–80	75	2–4	6500
Angora rabbit	10–18	13	30–60	45	0.8–1.2	4000
Camel	15–25	18	30–70	50	2–5	1000
Cashgora	18–23	20	30–60	55	1–2	
Cashmere	13–19	15.5	20–50	35	0.1–0.4	15 000†
Guanaco	13–18	15	20–50	35	0.3–0.9	10
Llama	20–32	28	50–80	65	1.5–3.5	1000
Mohair	22–42	30	50–110	80	2–6	5300
Musk-ox	12–20	16	40–80	60	2–3	3
Vicuña	11–14	12.5	20–40	30	0.2	5.5
Yak	15–25	20	25–50	35	0.3–1.3	7000

* Compiled from various sources, with inputs also from:
Alpha Tops SA, Incalpaca TPX (Textiles Peruanos de Exportación), Seal International, Dr B. McGregor: Deakin University.
† ≈ 5 million kg dehaired.

Table 9.2 The composition of raw whole fleeces[8]

Fibre	Moisture (%)	Grease (%)	Water solubles (%)
Wool	11.0–11.7	9.5–27.0	3.9–7.1
Mohair	12.0–14.4	1.2–8.0	1.8–4.2
Australian cashmere	10.7–13.9	0.7–2.5	1.2–3.5
Chinese cashmere	11.1–12.9	5.0–7.2	2.3–3.0
Cashgora	13.2	1.2–2.8	0.6
Llama	12.0	2.8	–
Alpaca	10.9–14.4	2.8–3.9	0.6–2.4
Camel	9.9	0.5–1.1	–
Yak	10.4	12.3	–

the literature often do not specify whether they refer to greasy, raw, whole fleece or down fibres, or to staple or fibre length, etc. Tucker *et al.*[8] presented the composition of the whole greasy (raw) fleeces of various speciality fibres (see Table 9.2).

Most luxury or speciality animal fibres tend to be finer, less crimped and smoother than wool, their cuticular scales also being less pronounced (flatter or thinner), typically 0.4 μm thicker or even thinner, compared to wool which is generally 0.6 μm and thicker (typically about 0.8 μm).[9] The scales are also more widely spaced. Where crimp is present, it is generally not as pronounced or of as high a frequency as that of fine wools and in some cases is better described as a curling or waviness. Fibre cohesion and friction are consequently lower than for wool, requiring special conditions, or blending with other fibres, such as wool, for acceptable mechanical processing performance and yarn quality. After de-hairing, the down fibres are generally processed into yarn following either the worsted route for the longer fibres or the woollen route for the shorter fibres. Mechanical processing, although mostly done on machinery similar to that used for wool, needs to be adapted and optimised to suit the specific requirements of each of these fibres. Most of the expert knowledge to do so is held as a closely guarded secret by the various companies which process these speciality fibres. This also applies to the de-hairing process, which depends, amongst other things, on the differences in length and diameter of the respective fibre populations, as well as the percentage of down fibres present.

Chemically, these fibres belong to the same protein (keratin) family of fibres as wool, although their fine structures (morphological) and surface structures do differ, they also often being medullated. Table 9.3[10] gives the chemical (amino acid) compositions of some of these fibres. Because of their similarities in chemical composition, it is not easy to differentiate between them chemically. Ways in which they can be differentiated are covered in Chapter 11.

Table 9.3 Diameter and amino acid composition (mol.%) of speciality animal fibres[10]

Amino acid	Aust. cashmere*	Chinese cashmere	Aust. cashgora†	Mongolian yak	Camel	Wool	Guanaco	White alpaca	Black alpaca	Llama	Vicuña
Diameter (μm)	12.7–17.9	17.1±2.4	16.2±3.3	18.4±1.9	18.7±2.6	17.1	13.9±1.7	26.4±6.0	40.7±9.8	19.5±2.6	12.3±1.7
Amino acid											
Cysteic acid	0.1–0.2	0.1	0.1	0.4	0.3	–	0.5	0.2	0.6	0.4	0.5
Aspartic acid	6.6–7.1	6.7	7.1	6.6	8.1	6.9	7.2	7.3	6.9	7.2	7.1
Threonine	6.6–7.3	7.0	6.9	6.5	6.6	6.8	6.5	6.3	6.2	7.0	6.4
Serine	10.7–12.7	10.9	11.5	10.3	10.4	12.0	11.1	9.6	10.3	11.3	10.6
Glutamic acid	11.2–13.0	13.0	13.5	12.5	13.6	12.8	13.7	14.6	14.0	16.0	14.3
Proline	8.1–9.0	7.7	7.5	7.5	7.2	8.1	7.9	7.6	7.8	8.4	7.9
Glycine	9.0–10.2	8.8	8.4	9.3	7.8	9.5	8.1	7.9	7.9	5.9	8.1
Alanine	5.8–6.2	5.5	5.7	5.8	5.9	5.8	5.5	5.6	5.4	6.8	5.5
Cystine	4.2–5.6	5.5	4.8	5.4	4.6	4.6	6.0	6.0	7.6	6.3	5.9
Valine	5.0–5.7	5.7	6.0	5.9	5.9	5.2	5.8	6.0	5.9	6.3	6.1
Methionine	0.3–0.5	0.4	0.4	0.5	0.7	0.5	0.5	0.4	0.5	0.5	0.4
Isoleucine	2.6–3.0	3.1	3.2	3.4	3.3	2.8	3.0	3.2	3.0	3.3	3.0
Leucine	7.4–8.4	7.4	7.7	8.0	7.7	7.9	7.2	7.8	7.2	8.3	7.5
Tyrosine	3.4–4.1	4.1	3.5	3.5	3.3	4.0	2.9	2.8	2.6	2.8	2.6
Phenylalanine	2.6–3.0	2.9	2.8	3.2	3.0	2.7	3.1	3.0	2.5	3.2	2.6
Lysine	2.5–3.0	2.8	2.8	3.0	2.7	2.9	2.5	2.8	2.6	2.9	2.7
Histidine	0.6–0.8	0.8	0.6	1.0	0.8	0.9	0.8	0.9	1.0	1.0	1.0
Arginine	6.4–7.2	7.5	7.4	7.5	8.0	6.7	7.7	7.9	8.2	8.7	7.7

* 10 samples from individual goats.
† Sample from one goat.

These hair fibres are mostly processed, dyed and finished using similar machinery to that for wool, but the settings and the conditions (e.g. dyeing and finishing recipes, etc.) are adjusted to suit the specific characteristics, notably length and fineness, of each fibre. Because of the smooth and medullated nature of many of these speciality fibres, which differs from that of most apparel wools, dyeing recipes need to be adjusted from those used for wool, if a specific dye shade is to be achieved. Great care is also taken in practice to select the dyeing and finishing conditions, such as treatment time, temperature and pH, so that the desirable characteristics of the fibres, for example lustre and softness, are not deleteriously affected.

9.2 Alpaca

9.2.1 Fibre production, harvesting and properties

The ancient Incas already treasured the alpacas for their fine and soft fleeces which were reserved for royalty. After the Spanish Conquest of the Incas in the sixteenth century, alpacas were banished from lowland pastures to the hostile highland terraces of Peru,[11] their numbers decreasing greatly. Alpaca (*Lama pacos* or *Lama glama pacos*) from the genus *Lama*, descended from the Guanaca, is a member of the Camelidae family and mainly inhabits the 'Altiplano', a vast high, arid plateau of southern Peru, Bolivia, Chile and Argentina (South American Andes) at altitudes around 4000–5000 m,[12] most (close on 90%) being found in Peru. Alpacas (Fig. 9.2) are also found in significant numbers in other countries, such as the USA, Australia and Europe.

Alpacas are ruminants (or pseudo-ruminants), the only member of the Camelid family bred specifically for their fibres, being smaller than llamas but larger than vicuñas. They thrive on ichu (ychu) grass and at high altitudes. Originally shearing (mainly hand shearing), took place biennially, but now annually during the summer rainy season, from November to April, which is also their breeding period. In the case of alpaca, there is a less distinct difference between the fibre diameter of the outer coat and the undercoat (down). There are, however, essentially two types of alpaca, namely the relatively rare Suri which has long (some 140–170 mm^2),[13] straight (or slightly wavy) and silky (lustrous) hair which tends to be finer, with fewer coarse fibres (coarser than 35 or 30 μm),[14] and more valuable than that of the second type, namely the bigger and heavier Huacaya (Wakaya/Wayko), which has some 90–110 hair/mm^2.[13] The coat of the latter consists of compact and highly crimped fibres, the Huacaya accounting for close to 90% of the alpaca population and fibre production.

The average length of alpaca fibre ranges broadly from about 125 to over 200 mm (it grows about 100–125 mm per year), and the individual fibre

9.2 Group of alpacas. (Source: IncaTops, SA, Arequipa, Peru.)

diameters range from about 10–75 μm. Alpaca fibres tend to be lustrous and are mostly medullated, elliptical in cross-section and pigmented. The alpaca fleece average diameter varies from about 17 to 35 μm (more typically 25–35 μm), with an overall average of around 26/27 μm[7] (CV from 25 to 35%). Alpaca fibres have become coarser over time, recently less than 10% being around 22.5 μm (20%, 20–22.5 μm),[5] 40% around 26.5 μm (35%, 24.5–26 μm),[15] 20% about 31 μm and more than 30% around 34 μm and coarser.[16] 45–50% coarser than 31 μm.[15] Some findings[7] on mummified remains indicate that 1000 years ago alpaca fibres may have been some 10 μm finer, and more even and less hairy than today, ranging from 14 to 21 μm, and mostly around 18 μm.[16] Nevertheless, according to Greaves and Rainsford[7] the fineness and related quality of alpaca fibres have not changed significantly from 1970 to 2005.

Alpaca has a variety of natural colours, including white, cream, light and dark fawns, piebald, greys and blacks, the lighter the colour the more valuable the fibre, grey being particularly popular. Most alpaca is either pure white or flecked with a few brown or black hairs,[17] the balance being sorted into more than 20 shades, ranging from light fawn to black,[17] sorting being by hand, also according to fineness.

Today alpaca fibre is mainly produced in Peru and also in significant quantities in Bolivia, Chile and Europe. It was estimated that in 2007 there were some 4.5 million alpacas in Peru, mainly being farmed by alpaca farmers (Alpagueros) in the Altiplano region bordering the city of Puno, 3871 m above sea level in the south of Peru,[11] Arequipa, being the centre of Peru's alpaca trade and processing centre.[11] Covered shelters built in Peru for alpacas significantly reduced the mortality rate of baby alpacas, which can be around 40% due to respiratory and digestive illnesses under normal cold conditions, increasing to 80 or even 100% under severe cold conditions.[18] Alpacas have a productive life of up to 20 years, adults weighing between about 55 and 70 kg, and measuring about 1–1.1 m in height (up to the shoulder).[19] Peru, in around 2007, embarked on an important alpaca genetic improvement project (including DNA markers, artificial insemination and embryo transplants), recognising that 95% of alpaca farmers are small breeders, without an awareness of, or access to, modern technology and genetic improvement technologies.[16]

Huarizo, which resembles llama and produces coarser hair than the alpaca, is the term used in Peru for the hybrid produced by crossing a male llama with a female alpaca, the reverse crossing (i.e. female llama with a male alpaca) being referred to as Misti,[7] whose fleeces are not of the same quality as those from alpaca. When referring to the fibre *per se*, the term Huarizo is applied to alpaca fibre ranging from 29.1 to 31.5 µm, this quality tending to have a relatively broad medulla.[7] Crossing an alpaca male with a vicuña female produces the paco-vicuña, and the reverse cross the vicuña-paco.

Indications are that alpaca grown at high altitudes suffer considerable weathering damage, particularly to their tips, partly due to higher UV irradiation at such levels,[20] and the damage is more severe when the animals are only shorn every second year. The UV range from 290 to 310 nm causes the most damage by far to the wool fibre, the intensity of UV radiation increasing with increasing altitude.

Alpacas are now shorn, usually by hand, rarely by machine, annually (less often only every 18–24 months for combing, producing a staple length of over 200 mm), producing some 3 kg of fibre. Australian alpacas reportedly produce 6–8 kg of greasy fleece annually.[21] The lack of grease (lanolin) on the fleece necessitates oiling of the shears. The fibre yield of a fleece is around 85–90%, the raw 'white' alpaca fleece tending to be greyish in colour due to contaminants, such as dust, suint and grease;[22] some typical values are given in Table 9.4.[20,22]

According to Valbonesi[14] (quoting various references), both alpaca and llama fibre diameter (fineness) is affected by the age, sex, fleece colour and position on the body of the animal, nutritional conditions, period of the year, herd and/or origin. The diameter of alpaca fibres increases with age (up to an age of about 4 years[23]), for example from 21 µm at 10 months of age to 25 µm at 4 years of age,[24] the CV being around 28%. Finer fleeces have a lower CV (e.g. 18% for 22 µm) than coarser fleeces (e.g. 26% for 36 µm), the fibres from the upper part of the body tending to be finer

Table 9.4 Typical values for greasy alpaca fleeces[20–22]

Fibre	Grease (%)	Dust/vegetable matter (%)	Suint (%)	Yield (%)
Alpaca (Huacayo)	1–3	3–10	≈ 1	87–94
Wool (Med. Cross-bred)	15–30	5–20	4–7	43–57
Mohair (Cape)	1–8	5–10	2–4	78–92

than those from the lower part of the body,[20] with those from the rear part of the animal (britch area) invariably containing highly medullated, coarse and stiff fibres, similar to kemp fibres in cross-bred wool. Fibre length variation within a fleece is considerable (CV >40%). McGregor and Butler[25] found that, for Australian alpacas, the Suri produced fleeces (midside saddle fleece samples) 2 µm coarser than the Huacayas, with mean fibre diameter increasing with both the age (up to 7 years) and live weight of the animals, the CV of diameter ranging from 15% to 37% (average 24%), dropping from around 30% at 1 year of age to around 22% at 4 years of age.

Alpaca tends to have relatively more coarse fibres, e.g. coarser than 33 µm, than wool of the same mean diameter.[22] Alpaca fibres are generally medullated, the degree of medullation and non-circulatory (ellipticity ≈ 1.2) increasing with increasing fibre diameter,[22] the fibres becoming increasingly ovoid or kidney shaped as they become coarser. Fine alpaca has virtually no kemp, extra fine fibres (≈ 15–20 µm) being largely un-medullated, or have a fragmented medulla (≈ 20–30 µm), fine fibres (≈ 30 µm) having an interrupted medulla, medium fibres (≈ 40 µm) a continuous medulla and coarse fibres (≥ 60 µm) a broad medulla. Coarse alpaca, with a mean fibre diameter around 34 µm,[7] is strongly medullated, the medulla being slightly more than 50% of the fibre diameter.[7] Because of their medullae, the airflow method of fibre diameter measurement will underestimate the fibre diameter, the degree to which this happens depending upon the degree of medullation. More accurate results can be obtained by projection microscope, Laserscan and optical fibre diameter analyser (OFDA) based methods.

The ASTM standard specification (D2252-85, approved in 1991) for the fineness of different types of alpaca is given in Table 9.5.

Baby alpaca hair (≈ 22.5 µm) represents the finest hair from the first shearing, superfine alpaca (25.5/26 µm) forming a larger proportion of the production, also spanning the full range of more than 24 natural colours, coming from adult animals,[26] almost half of Peru's production being > 31 µm. The mean fibre diameter can range from as fine as 21 µm for Bolivian llama thampuls[27] to over 37 µm for Huacaya alpaca from Australia,[28] extra-fine (< 23.5 µm), fine (23.1–26.5 µm), coarse (> 31.5 µm) and inferior (> 30 µm) being some categories used.

Table 9.5 Fineness specifications for types of alpaca

Type	Description	Average diameter (μm)
T Extra	–	< 22.0
T	Tui, 12 months of age	22.00–24.99
X	Extra fine adult	22.00–24.99
AA	Medium adult	25.00–29.99
A	Coarse	30.00–35.99
SK	Skirtings	> 30.00
LP	Locks and pieces	> 30.00

Source: Standard specification for fineness of Types of Alpaca (ASTM-D2252-85, approved 1991).

In Peru, the Peruvian Technical Norm NTP 231:301 (Classified Alpaca Fibre), published in 2004,[7] defines the qualities of alpaca fibre as follows:

Baby alpaca: ≈ 23 μm
Superfine alpaca: 23.1 ≈ 26.5 μm
Huarizo alpaca: 29.1 ≈ 31 μm
Coarse alpaca: ≈ 31.5 μm

In Australia, alpaca fibre is classed into five diameter categories, five length categories and six colour categories (see Table 9.6[21]).

Pepper[29] has given the alpaca fibre classification shown in Table 9.7.

Other alpaca grades encountered include:

Inferior: > 39 μm
Super Fine: ≈ 26 μm
Baby: ≈ 22 μm

and

Coarse: > 31.5 μm
Fine: 23.1 – 26.5 μm
Extra Fine: ≤ 23.5 μm

Alpaca tops and yarn are classified as follows:

Baby (22.5 μm)
Fine Spinning
Adult (34 μm)
Suri (26/27 μm)
Superfine (26 μm)
Coarse alpaca (31–34 μm)

Table 9.6 Australian alpaca diameter, length and colour classing lines[21]

Fibre diameter	Length	Colour
Superfine (SF) < 20 μm	A: 120–150 mm	White (W)
Fine (F) 20–23 μm	B: 80–120 mm	Fawn (F)
Medium (M) 23–26 μm	C: 60–80 mm	Brown [light brown (BR), dark brown (DKBR)]
Strong (S) 26–30 μm	D: < 60 mm	Black (BLK)
Extra Strong (XS) >30 μm	O: (overgrown) > 150 mm	Rose grey/roan (RG), Grey (G)

Table 9.7 Alpaca fibre classification[29]

Type	Name	Average fineness (μm)	Minimum average length (mm)
Michell alpaca fibre classification			
BL	Baby	22.5	55
SU	Suri	26.5	68
FS	Fleece	26.5	66
AG	Coarse	32.0	68
LL	Llama	28.0	60
Inca Tops' classification			
BA	Baby	22–23	55
SU	Suri	25.5–26	68
SF	Super Fine	25.5–28	66
AD	Adults	28–30	68–60

Alpaca fibres are smoother and have a lower resistance to compression[30] than wool. The mean scale height of alpaca fibres coarser than 19 μm is about 0.4 μm compared to that of 0.8 μm for wool fibres of similar diameter.[31] It is therefore hardly surprising that the directional frictional effect (DFE) is much lower[20,32] for alpaca (around 0.20 for Huacaya alpaca and 0.16 for Suri alpaca[20]) than for wool which is around 0.40.[32] The with-scale and against-scale coefficients of friction (μ) of Suri fibres were found to be 0.29 and 0.40, respectively, the corresponding values for Huacaya being 0.28 and 0.42, respectively,[20] and wool 0.15 and 0.32, respectively. The differential frictional effect (DFE) is 0.16, 0.20 and 0.36 for the fibres in the above order. The initial modulus of alpaca is higher than that of wool.[33] According to Liu and Wang[34] Alpaca shrinks more in the Aachen felting test than wool of similar diameter, possibly due to the higher cuticular scale frequencies of alpaca, even though the higher scale thickness and DFE of wool should be expected to cause a higher felting shrinkage.

Cuticular scale frequency for alpaca varies from around 10 to 11 per 100 μm,[30,34–38] which is similar to that for llama. The difference between the scale lengths of wool and alpaca fibres decreases as the fibres becomes finer.[20] Because of the similarities of the cuticular and other surface structures of llama and alpaca (Camelid) fibres, it was considered well nigh impossible to differentiate between them, particularly between Suri, Huacaya and llama fibres.[30,39] Nevertheless, Valbonesi *et al.*[14] found that cuticular scale frequency, together with fibre diameter, enabled Suri fleeces (fibres) to be accurately and reliably differentiated from Huacaya and llama fleeces, and also to differentiate between llama and Huacaya fleeces, but less reliably so. Medium to coarse alpaca fibres (23–35 μm) have no distinct ortho-para-cortex differentiation.[20]

The breaking strength of Suri alpaca is lower than that of Huacaya alpaca, both wet and dry,[20] the dry tenacity of Suri being similar to that of wool but significantly lower than that of Huacaya, while its wet tenacity is lower than those of Huacaya and wool which are similar. The dry elastic moduli of the three types of fibre (Suri, Huacaya and wool) are similar. In one study,[40] the wet breaking tenacity and stress at 30% extension of Huacaya fibres were found to be double that of Suri fibres, the extension at break being similar for the two fibres. The greater strength of the Huacaya fibres was attributed to its more ordered structure (higher crystallinity) in the alpaca helices making up the micro-fibrils as revealed by X-ray diffraction. Australian alpaca was found to have much lower fibre curvatures (crimp frequencies) than wool (or cashmere[21]) of similar diameter, curvature decreasing with increasing fibre diameter[41] from about 50°/mm at 15 μm to about 15°/mm at 40 μm, the corresponding values for wool being 125°/mm and 58°/mm, respectively.[41] Fibre crimp (curvature) decreases gradually from the scoured state to the top.[41]

The complete amino acid composition of alpaca fibres has been determined. It varies widely between animals, due to factors such as nutrition, climate-induced stress and genetics.[22] Cystine plays an important role in the molecular architecture of a fibrous protein, the level affecting fibre and yarn properties.[22] Table 9.8 compares the levels of cystine for wool and alpaca.[22]

Table 9.8 A comparison of the cystine levels for wool and alpaca[22]

Fibre	Cystine content (mmol/kg)
Huacaya[20]	950
Suri[20]	1250
Wool[42]	900

The lipid component of the cell membrane complex (CMC) of different animal species differed, for example the CMC lipids of alpaca and llama fibres do not contain any sterols (e.g. cholesterol).[22,43] The amount of extractable CMC-lipid in alpaca fibre was found to be 2.6% by weight,[43] which was significantly higher than that of the other animal fibres examined.

9.2.2 Fibre processing

Alpaca hair is hand-sorted according to fineness and colour and then scoured on a scouring line similar to that used for wool (e.g. 5 bowls), the clean yield being around 85–90%.[2] Alpaca fleece contains up to 10% coarse fibres which need to be removed by de-hairing,[22] which takes place after scouring. Little information is available, i.e. public knowledge, concerning the processing, including de-hairing, of alpaca, since this is kept secret by the companies processing the fibre. The less distinct difference between the diameter of the outer coat and the undercoat makes effective de-hairing more difficult.[44] Wang *et al.*[21] investigated the technical feasibility of de-hairing alpaca using a prototype cashmere de-hairing machine, the de-hairing efficiency being assessed by the OFDA measured fibre diameter distribution, with changes in fibre length used to assess fibre damage during de-hairing. De-hairing of Alpaca is not as effective as that of cashmere, because of the smaller difference between the fine and coarse components in terms of diameter, stiffness and crimp.[21]

After de-hairing, mechanical processing, generally on the worsted system (rectilinear combing), sometimes on the woollen system, is similar to that for wool. Due to its smoothness and low fibre crimp, alpaca is difficult to process, as is the case with other speciality animal fibres, such as mohair. Blending with wool is common practice which improves cohesion and processing performance on modern wool processing machinery.[45] Wang *et al.*[45] found that blending alpaca with low crimp wool produced knitted fabrics which shrunk less than those produced from alpaca blended with high crimp wool, but the latter was softer. They concluded that high crimp wool may be preferable for blending with alpaca, particularly in terms of processing performance. Knitting yarns from 100% alpaca are typically around 16 Nm (≈ 60 tex) and weaving yarns around 28 Nm (≈ 35 tex),[46] or even 2/16 Nm (i.e. ≈ R120/2 tex resultant).

9.2.3 End-uses

Alpaca fabrics, particularly those containing the fine fibres, are generally considered to be soft, warm, light and luxurious. The medullated nature of the fibres suggests that these fibres will, on a weight for weight basis, provide better thermal insulation than unmedullated wool, although the relative amount of air trapped within the fabric structure will also play a significant role. Alpaca is popularly used in knitted and woven apparel, primarily in knitwear, often brushed or raised, finding application in products such as ladies coats and skirts, suits, sports jackets, upholstery, pile fabrics for rugs and simulated furs, hand-knitting yarn, blankets, pullovers, cardigans, stoles and scarves.[12] White alpaca tends to be utilised in the knitting sector, dyeing to fashion shades, while the natural colours tend to be used in woven fabrics, particularly coating fabrics, which are often raised (teaselled). Baby alpaca is particularly used in ladies' accessories, such as scarves, stoles, throws and capes.[47] Alpaca is frequently blended with other natural fibres, notably wool and silk, even cotton, since price is an important factor. In blends with wool and mohair it is often used in overcoats. Alpaca is considered an ideal fibre for fancy yarns, such as bouclé and frisé variations,[26] bouclé, in pure alpaca, or alpaca blended with silk, mohair or Angora rabbit hair, being popular for knitted garments. Poorer quality alpaca is also often used as filling in quilts, duvets and pillows,[21] often in blends with wool, polyester or cotton, since it is desirable to remove coarse fibres and contaminants to avoid discomfort.[21] Alpaca and camel hair reportedly felt at a slower rate than cashmere.[48]

The International Alpaca Association (IAA), based in Peru, runs Alpaca Marks,[49] such as gold, silver and white alpaca which relate to fibre fineness and blend percentages. The Gold Mark applies to 100% alpaca, not coarser than 28 μm.[49] There is a Huarizo Mark for alpaca coarser than 28 μm, 31–34 μm representing coarse qualities. Peru's Ministry of Agriculture's National Council for South American Camelids the Consejo Nacional de Camélidos Sudamericanos (CONACS) launched a registered 'Alpaca Peru' Mark for all alpaca products produced by artisan knitters and weavers.[50]

Chemical bleaching of pigmented alpaca typically involves treatment with an iron salt (mordant) under acidic conditions, followed by the removal of the mordant not bound to the pigment and then bleaching the pigment with hydrogen peroxide, now that improvements in the second step have been researched.[51] Alpaca is used either in its natural shade (colour), or dyed to the required shade. Alpaca generally requires more dye than wool in order to achieve the same depth of shade, probably due to the medullated nature of the fibre. For more information the reader is referred to the references for more information.[2,21,22,25]

9.3 Angora rabbit hair

9.3.1 Fibre production, harvesting and properties

Angora fibre, from the Angora rabbit (*Oryctolagus cuniculus*) (see Fig. 9.3), is one of the lightest natural fibres due to its highly medullated (largely

9.3 Angora rabbit. (Reproduced from Pier Giuseppe Alvigini, *The Fibres Nearest the Sky*, Mondadori Editore, Verona, by kind permission of Mr Pier Alvigini at Alvigini S.A.S., 13900 Biella Via Dante, 12 Casella Postale 430, Italy.)

hollow) nature, making it ideal for thermal insulation and for maintaining a steady skin temperature, while still allowing the skin to breath.[52]

The good qualities of the hair of the Angora rabbit have been appreciated for many centuries, and it is the only rabbit bred solely for its hair. The Angora rabbit essentially has two coats of hair, namely guard hair which is coarse (up to 60 μm), long (20–100 mm) and spike like (spiky), offering protection against the rain and elements, and a shorter (10–40 mm), fine (12–14 μm) down, offering thermal insulation. Angora rabbit hair occurs in various colours, mainly white, but also grey, black-and-white and camel brown, although the main strain (albino) bred for its fibres produces white fibres only.[2] Raising Angora rabbits successfully is very labour intensive and highly skilled work. They are fairly resistant to most illnesses, provided their metabolism is not disturbed and is 100% functional,[53] in which case their resistance to diseases is reduced, and it is important to keep them under highly hygienic conditions.

The Angora rabbit reportedly originated from Ankara in Turkey, having been raised for over 200 years in Europe, reportedly being sighted in England as far back as 1708.[54] In France the numbers increased to such an extent that it was estimated that around 1860 some 10 000 kg of 'Angora Silk' was produced annually.[53] The rabbits were referred to as 'Silk Rabbits' or sometimes 'Combing Rabbits'.[53] Intensive farming with Angora rabbits took place in Western and Central France, and in 1935 some 90 000 kg of rabbit hair was being produced.[53] French Angora rabbits were introduced in Germany during the second half of the twentieth century where breeding expanded rapidly, as well as selective breeding of improved animals.[53] The French bred larger animals with more hair (better suited for fashion articles), while the Germans bred for finer and softer hair, the German rabbit mostly being shorn and the French rabbit 'plucked' (epilated).

There are essentially four types (strains) of Angora rabbits, namely 'French', 'English', 'German' and 'Chinese'. The 'French' type generally contains more guard hair (up to 14%) and is 'spikier', longer and more difficult to dye than the 'German' type (maximum of 3% of guard hair), and is more suitable for the production of a brushed appearance and fashion type garments. The 'German' type produces a softer product, being very suitable for, and popularly used in, various types of underwear and medical wear. German breeders wanted as fine and low a level of coarse hair (spike hair) as possible because it facilitates the spinning of fine yarn used in underwear. The English Angora rabbit is smaller than the German and French types and has hair of different colours which are very popular in home industries, where the natural colours are desirable. English Angora rabbits are normally grey, with black heads. In the early 1900s, China imported Angora rabbits, breeding rabbits for both their hair and meat, and in the mid-1960s became a major producer of Angora rabbit hair, mainly obtained from young animals (8–12 weeks old). The Chinese strain, developed in the early 1950s, accounts for the bulk of the Chinese and South American production of hair, the fibres produced generally being shorter and finer than those of the French and German Angora rabbits,[53] the Tanghang representing an improved strain.[53] Over time, many other countries introduced Angora rabbit farming. Today, most Angora rabbit hair is produced in China; China produced 70% of the global production of some 8 million kg towards the end of the 1980s.[53] In China, the rabbits are farmed on a highly intensive small-scale factory farm system by individual farmers. Significant quantities of hair are also produced in South America (e.g. Chile and Argentina), Europe (e.g. France) and in India.

The hair from Angora rabbits can be harvested by pulling/plucking, or combing by hand, or by shearing using either hand shears or electrical clippers. The animal is generally brushed prior to this so as to facilitate fibre harvesting and classing and the removal of any contaminants. When shearing in winter, it is necessary to leave a short length of fibre to protect the rabbit from severe cold. Animals are shorn (clipped) for the first time around 6–8 weeks of age to remove their 'nest' hair, and plucked for the first time around 100 days and then every 100 days thereafter. The fibre from the first shearing is not as valuable as that from the subsequent shearing,[53] but shearing at an early age encourages subsequent hair growth. In China the hair is mostly removed by hand plucking; the ripe or mature fibres (after 3 months of growth) which easily come out are mainly removed by this method. The French mainly use a method called 'epilation' (plucking or 'combing'), which involves the use of a type of 'comb' with a serrated edge to pluck the fibres four times annually (every 90 or so days). This produces a greater variation in fibre length than the hand plucking method. Plucking generally takes place when the hair is most easily removed (i.e. is 'ripe' or 'mature'), and tends to produce more 'spiky' hair than shearing. Both methods of

plucking encourage the growth of coarse hair, but slowly reduce the total hair production.[53] The Angora rabbit has around 180–200 hairs per mm^2 of skin, which can drop to between 100 and 120 after 4–5 pluckings. Shearing is popular in Germany. This method tends to produce 'double cut' waste and bits of cut skin which can cause problems during spinning and dyeing, but has advantages in that it subjects the rabbits to less pain and stress, only taking 10–20 min when using an electric clipper. This method produces hair with a greater proportion of fine hair, with very little seasonal difference, and only a difference of less than 10% between the summer and winter clip, compared to 20% with the combing method. The rabbits are generally shorn every 3 months, before the hair starts falling (shedding) which can cause felting (matting). Hand plucked hair, which contains only the 'ripe mature fibres', is considered a better quality than shorn hair, it also leaves the animal with a coat 25–35 mm long as a protection against the cold. The different methods of harvesting Angora rabbit hair and the comparative qualities have been described in detail.[53]

A healthy, good quality Angora rabbit produces about 1 kg of first grade hair per year. Shorn hair production can be as high as 1.5 kg per year (i.e. ≈ 380 g four times per year). Commercial yields of down hair vary between about 420 and 820 g a year in China and up to 1000 g in France and 1200 g in Germany,[2] the yield being affected by nutrition and the quality of the rabbit.

The Angora rabbit can be considered to produce essentially three kinds of hair,[2] the lengths referring to staple length:

- *Guide hairs*: 100–110 mm long; they guide and cover the growth of the other hair.
- *Guard hairs*: 80 mm long; these have rough points that lock together, lie over the down and seal it off.
- *Down*: 60 mm long, with a diameter of about 14 μm, very smooth, with few cuticle scales.

Hair classification schemes

Angora rabbit hair is essentially graded according to its staple length and cleanliness, its appearance being of paramount importance. In certain cases the quality of the hair is specified quite independent of the source of the hair (e.g. whether from German or French Angora rabbits).

In Germany, the official classification and trading scheme, based upon DIN-60407, is as follows:[53]

1st Grade: Pure white, very clean, at least 6 cm long and not entangled (matted), without any double cuts.

2nd Grade: As for 1st Grade, but shorter than 6 cm, and longer than 3 cm.
3rd Grade: As for the above two grades but shorter than 3 cm.
Felted 1: Pure white, very clean but felted and matted.
Felted 2: White, felted and matted and dirty or with plant residues.

In France, the third grade is omitted, all hair with a staple length greater than 4 cm being included in the first grade. This allows for shorter intervals between harvesting.[53]

The following grades, into which Angora rabbit hair is sorted after grooming and where fleeces or part fleeces with lower quality fibre have been removed, have been given:[2]

Grade 1: Clean, free of felting, over 6 cm long (70% of the coat).
Grade 2: Clean, free of felting, under 6 cm but over 3 cm (15% of the coat).
Grade 3: Clean, felted, second cut.
Grade 4: All dirty, discoloured fibres.

The guard hair ranges from between about 20 and 100 μm, while the mean fibre diameter of the fine down ranges from about 9 to 14 μm, typically 12–14 μm, with the diameter of single fibres ranging from about 5–30 μm, 60% being in the range of 10–15 μm.[55] The fibre diameter distribution of French Angora rabbit hair is stated to be better described by a log-normal rather than a normal distribution,[56] the geometric mean, as opposed to the arithmetic mean, therefore being a more satisfactory representation of the 'true' mean fibre diameter, as determined by the evaluation of fibre cross-sections.[56] Stephanie and Wortmann[57] concluded that nutrition and climatic conditions, rather than differences in origin and quality, determined differences between the specimens they tested.

Mean fibre length of good grade Angora rabbit hair is around 45 mm, with a CV of around 50% and a mean fibre diameter of around 13 μm (CV = 25%). Number based mean fibre length, based upon the Zweigle Staple Sorting instrument, varies from around 16 mm for the poorer quality fibres to almost 53 mm for the top quality (super, pure white, unfelted 6 cm), the CV ranging from about 65%–90%, depending upon the source and quality of the hair. The number based short fibre content (≤ 10 mm) ranged from about 15%–45%, and for fibres ≤ 20 mm from about 25%–80%, the corresponding weight based values being 2–15% and 6–48%, respectively.[58] In some countries, such as South Africa, the percentage of hair with an average staple length shorter than 30 mm cannot exceed 10% in the better grades.

The cross-section of Angora rabbit hair is generally not circular,[59] occurring mostly as elliptical (ellipticity ≈ 4)[56], rectangular, square or bilobal.

Only a small percentage of the hair has a broken medulla or no medulla, the vast majority having one, or some even two or more medullae (channels).[59] The density of Angora rabbit hair can vary fairly widely, from about 0.95 to 1.3 (average between about 1.15 and 1.25 g/cm^3), depending upon the type and degree of medullation.[60] Blankenburg and Philippen[59] reported that the density of the hair they studied varied from about 1.1 to 1.2 g/cm^3, with an overall average density of 1.2 g/cm^3, with between 5 and 17% of the fibres they studied having no medulla, 83–89% having one medulla and 1–7% having two or more medullae (kemp), the corresponding values for fibre diameter being 9–11 μm, 12–14 μm, 13–37 μm, respectively, when measured on a projection microscope. In general, the hair from the female rabbit (doe) is stronger (30 kgf/mm^2) than that from the ram (buck), with that from the young rabbit being weaker than that from the adult,[53] winter hair tending to be weaker than summer hair. The extension at break of the hair lies between about 30 and 40%.[53] Angora rabbit hair scale height is of the order of 0.4 μm on average,[61] as is the case for other luxury animal fibres, such as cashmere and mohair. Angora hair felts less than wool in the felt ball density test.

Stephanie and Wortmann[62] gave values for the three different breeds of Angora rabbit hair which they tested (Tables 9.9 and 9.10).

Table 9.9 The percentage of medullated fibres in Angora rabbit hair from Germany, France and China[62]

	Percentage of fibres		
Fibre type	Germany	France	China
Unmedullated	33.1	22.3	12.2
Single medulla	66	74.7	85.1
Multiple medullae	0.9	2.9	2.9

Table 9.10 Average diameter (μm) of different types of Angora rabbit hair from Germany, France and China[62]

	Average fibre diameter (μm)		
Fibre type	Germany	France	China
All fibre types	13.4	18.7	12.2
Single medulla	14.1	19.0	12.2
Multiple medullae	31.3	42.5	31.5
Unmedullated	11.4	14.5	8.8

Table 9.11 Quality parameters for Angora rabbit hair from various origins[58]

Sample no.	Quality/grade	Source/origin	Fat/grease content (%)*	Vegetable matter content (%)†
1.	First grade, pure white, unfelted 6 cm	Czechoslovakia	0.8–1.0	< 0.1
2.	Second grade pure white, unfelted 3–6 cm	Czechoslovakia	0.8–1.0	< 0.1
3.	Third Grade, pure white, unfelted, 3 cm	Czechoslovakia	0.8–1.0	< 0.1
4.	Third grade, white, slightly felted and contaminated	Czechoslovakia	0.9–1.2	0.1–0.2
5.	Fourth grade, white, heavily felted and contaminated	Czechoslovakia	1.2–1.5	0.3–0.5
6.	Super choice	France	0.9–1.0	< 0.1
7.	Premium choice	France	0.9–1.0	< 0.1
8.	'tout Venant'	France	1.2–1.5	0.2–0.3
9.	Quality I	Argentina	0.6–0.7	< 0.1
10.	Quality II	Argentina	0.8–1.0	< 0.1
11.	Quality AB	Japan	1.1–1.2	< 0.1
12.	Quality B	Japan	1.1–1.2	< 0.1
13.	Quality 95%	China	1.2–1.3	0.4–0.6
14.	Quality I	Germany	0.6–0.7	< 0.1

* Methylene chloride extractable matter (IWTO-8-61).
† Boiled in 0.2N NaOH – solution for 15 min.

Fröhlich[58] listed the quality parameters for Angora rabbit hair (Table 9.11). He also gave average values for the chemical properties of the above fibres (Table 9.12).[58]

Gupta *et al.*[63] gave the properties of three Angora rabbit genotypes, German, British and Russian, as well as their crosses (Table 9.13). They also gave a comparative table for Angora rabbit hair and other fibres (Table 9.14).[63] Gupta *et al.*[64] gave the average values for the six genetic groups of rabbit hair which they tested (Table 9.15).

Table 9.16 compares the properties of Angora rabbit fibre (hair) with those of wool.[65] The comparative values (Table 9.17) for Angora rabbit hair and wool[66] have also been given for a selection of physical properties.

9.3.2 Fibre processing

Angora rabbit hair need not be scoured prior to processing, generally containing less than 1% of natural grease (generally 0.7–1.0%, sometimes even exceeding 1.2%, of fatty matter).[65] Dust and vegetable matter are often

Table 9.12 Average values for chemical and physical properties of Angora rabbit hair from various countries[58]

Property	Average value	CV (%)
Grease content (%)	1.0	–
Vegetable matter content (%)	<0.1	–
Cystine content (%)	13.6	1.5
Alkali solubility (%)	9.0	16
Acid solubility (%)	7.5	25
Urea bisulphite solubility (%)	65.3	4.2
Regain (65%RH)	13.7	1.2
Water retention (%)	52.9	8.4
Mean fibre diameter (µm)	12.8	5.7
Tenacity (kgf/mm²)		
Dry	19.9	12.4
Wet	17.8	10.8
Extension at break (%)		
Dry	33.1	5.0
Wet	45.9	2.0

RH, relative humidity; CV, coefficient of variation.

removed from the fleeces prior to sorting, by a process called grooming.[2] The fibre yield is some 97%, the hair containing very little contamination – only around 1–2% of hair scales and skin flakes. When hair is obtained from skin, blowing of the hair is the traditional way of cleaning it, i.e. removing skin pieces, etc. Due to its smooth fibre surface, relatively short length, lack of crimp and cohesion and greater propensity to generate static electricity, Angora rabbit hair presents more difficulty and waste during mechanical processing than wool; an antistatic lubricant (e.g. 0.3%), applied prior to carding, is essential if it is to be processed successfully.[65]

The properties and processing of Angora rabbit hair have been discussed,[65] it being stated that it was possible to process the hair on the worsted and woollen systems, economically and to the desired quality, provided special precautions and care were taken in terms of machinery fittings and adjustments. Spinning problems can arise due to the fibre surface characteristics, fineness, length and length distribution.[65] Because of the difficulties often experienced in spinning pure Angora hair, it is generally not spun in 100% form, being blended with wool (e.g. 50–90% of wool), and also nylon, with which it is highly compatible, a blend level of 15% rabbit hair, 75% wool and 10% nylon being popular. It is processed on either the woollen or worsted systems, depending on fibre length and blend. Blending with wool has a highly beneficial effect in terms of processing performance. Nevertheless, even then, special precautions, care and skill are required to successfully process the blends. Before mechanical processing, the fibre length variation (CV %) of Angora rabbit hair can vary from about 60 to 90%,[65] accompanied by a high short fibre content. The moisture content tends to be lower

Table 9.13 Properties of Angora rabbit hair[63]*

Genotype	Fibre fineness (μm)	Fibre length (mm)	Grease content (%)	Suint content (%)	UB† solubility (%)	Tenacity at break (gf/tex)	Elongation at break (%)
German Angora	13.5 ± 0.38 (50.6)	41.3 ± 0.45 (18.8)	0.58	2.65	59.0	14.8	39.7
British Angora	11.8 ± 0.33 (48.4)	45.5 ± 0.60 (25.2)	1.30	2.36	77.7	13.1	40.1
Russian Angora	11.8 ± 0.31 (45.3)	48.9 ± 0.74 (23.3)	0.79	2.57	64.1	14.9	39.2
German x British	11.6 ± 0.30 (44.9)	40.2 ± 0.51 (21.9)	0.62	2.18	66.0	14.7	40.6
German x Russian	12.5 ± 0.39 (54.1)	52.5 ± 0.85 (28.0)	0.61	–	61.1	13.2	38.8
German x (Russian x British)	11.6 ± 0.29	55.7 ± 0.82	0.79	2.15	68.5	14.0	36.2

*The CV values are given in brackets.
† UB - urea bisulphite.

Table 9.14 Physical and mechanical properties of various fibres[63]

				Dry			Wet		
Fibre	Fibre diameter (μm)	Linear density (tex)	Fibre length (mm)	Breaking load (gf)	Ext. (%)	Tenacity (gf/tex)	Breaking load (gf)	Ext. (%)	Tenacity (gf/tex)
Rabbit									
Fine hair	10.4	0.16	32.3	2.0	34.5	12.5	1.4	65.0	8.7
Guard hair	44.0	0.92	43.8	10.7	34.2	11.2	7.2	54.0	7.8
Cashmere									
Fine hair	10.9	0.26	30.5	3.2	32.5	12.3	2.7	59.6	10.4
Guard hair	48.4	1.67	50.7	19.4	34.0	11.6	13.6	58.0	8.1
Mohair	30.4	1.35	–	19.5	39.5	14.4	16.1	87.8	11.9
Rambouillet sheep wool	16.8	0.50	25.0	6.0	35.0	12.0	3.2	68.0	6.4
Avivastra sheep wool	21.5	0.87	45.1	9.0	29.7	10.3	5.2	54.0	6.0
Cotton (Coimbatore H-4)	12.0	0.17	28.0	5.0	5.2	29.0	6.6	6.3	37.0
Polyester	–	0.17	51.0	8.1	35.5	48.0	–	–	–
Acrylic	–	0.17	51.0	4.7	25.0	28.0	–	–	–

Table 9.15 Average values for six genetic groups of rabbit hair[84]

Property	Average value	Range
Fineness (tex)	0.18	0.14–0.23
Tenacity (gf/tex)	12.1	13.1–14.9
Extension at break (%)	39	36–40

Table 9.16 Mechanical and physical properties of Angora fibre and sheep's wool[65]

	Angora fibre	Sheep's wool
Fibre length (mm)	Approx. 15–60	20–250
Fibre fineness (μm)	12–17	16–40
Fibre cross-section (shape)	Rectangular	Circular
Fibre surface structure	Relatively smooth scales Very low crimp	Distinct scale sheath Good crimp
Relative density (g/cm³)	1.1	1.32
Fibre tensile strength (kg/mm²)	17–26	15–25
Wet fibre strength as % of dry	70–90	70–90
Breaking extension (%)	30–35	25–60
Wet fibre extension as % of dry	120–140	110–130
Regain at 21°C/6% RH (%)	13–15	15–17
Moisture retention (%)	45–55	40–45

Table 9.17 Comparative physical characteristics of rabbit hair and wool[66]

Property	First grade rabbit hair	Wool
Crimp/cm	2.7*	5.5
Breaking strength (gf)	2.8	10
Breaking elongation (%)	37	40
Coefficient of friction (μ)	*With scale*	*Against scale*
Rabbit hair on rabbit hair	0.21	0.49
Rabbit hair on wool	0.21	0.62
Wool on wool	0.5	0.80

(≤12%) and more variable than that of wool. A blend of Angora rabbit hair and wool generally produces more hairy yarns than pure wool.

On the woollen system, it is advisable for the fibre to have a moisture content (regain) of at least 14–15%, and a fatty matter content of around 0.6–0.8%[65] prior to carding, adequate time for conditioning being important. It is advisable to use, for blending, relatively fine wool (≈ 21 μm) with good crimp and not too long when processing on the woollen system.[65] Nm12 woollen spun yarn is fairly common, and it is advised[65] that the yarn should preferably have between 140 and 160 fibres in their cross-section. The use

of carbonised wool in the blend has some advantages because of the lack of contaminants in such fibres. The relatively high Angora fibre waste produced necessitates that at least 10% more Angora fibre be incorporated in the blend than that which has been specified. Excessive drafts during ring spinning need to be avoided, with a relatively high twist factor ($\alpha > 80$) being advisable. For the worsted system, it is advisable to use Angora with a staple length of at least 45–50 mm, with fibre fineness and length even more critical than for the woollen system. Fine pinning during gilling or drafting, precise drafting zone (nip) settings, low drafts and delivery speeds are important.[65] Mixing (blending) with wool generally takes place in sliver form. It is maintained[65] that provided all the necessary precautions are taken and processing settings and conditions optimised, it is possible to produce Angora/wool blend yarns on both the woollen and worsted systems which are of the same quality as the corresponding pure wool yarns. It is important to inspect the Angora blend yarns using an inspection (wrap) board, since this gives an indication of the visual appearance of the ultimate knitted garment. Onal and Korkmaz[67] have reported on the effect of fibre blend, yarn twist and fabric relaxation on the abrasion and pilling resistance of Angora rabbit hair blended knitted fabrics.

Until the early 1990s it was not possible to spin Angora rabbit hair on the conventional cotton spinning system,[55] but in more recent years it has also been processed on the short staple (i.e. cotton) system, mostly in blends with cotton, and then either ring-spun or rotor-spun (OE). Because of its length, processing on the cotton system has its benefits. Krishnan *et al.*[55] describe the conditions required to process Angora rabbit hair (38 mm) in blends with other fibres, such as cotton, viscose, wool, silk and acrylic, on the cotton system, ending in rotor (OE) spinning of hosiery yarn destined for knitting.

The same dyes used for wool can be used for Angora rabbit hair. Acid milling and 1:2 metal complex dyes are popularly used and the Chinese varieties are found[68] to have a greater dye affinity than other varieties. Wortmann *et al.*[69] found that blank dyeing of Angora rabbit hair yarns caused changes in the morphological structure of the medullated fibres, a significant proportion of the medulla cells starting to collapse at temperatures around 70°C, where the extent of the collapse depends upon the stress on the fibre in the yarn that is released due to a softening process in the keratin. Fibres with a 'ladder' type medulla passed through an intermediate stage where their medullae appear to be continuous before collapsing completely.

9.3.3 End-uses

Angora rabbit hair is very popular in knitwear and is used in both knitted and woven outerwear, ladies underwear, hosiery, gloves and knitted millinery and felt hats, although fibre shedding can sometimes present problems.

It is very popular in medical and thermal underwear, under-blankets in hospitals, nightwear and blankets, etc., particularly the hair from the German Angora rabbit. The hair from the French type is very popular in fashion wear (e.g. shawls).

The German textile industry was the greatest user of Angora rabbit hair during the latter part of the twentieth century, with popular end-uses there being medical and other types of underwear. In medical underwear,[53] it is considered to reduce muscular and other pains, attributed to its electrostatic, thermal and moisture absorption properties, the medullated and fine structures of the fibre resulting in it having excellent thermal insulation properties.

Angora rabbit hair knitted products can present serious fibre shedding problems, due to their low fibre friction, length and strength, together with the fact that low yarn twists are generally employed to maximise the softness of the garments. Zhaogeng and Bo[66] concluded that Angora rabbit hair shedding during wear was largely due to the fibres breaking rather than slipping, resulting from the low breaking strength of the hair. The low strength also results in serious fibre damage and breaking during carding, which can reduce the average fibre length by as much as 10 mm.

Additional information in relation to Angora fibre can be found in the references.[2, 53,65,70 and 71]

9.4 Camel

9.4.1 Fibre production, harvesting and properties

General

Camels belong to the Camelidae family, which has two genera,[72] *Camelus* and *Lama*. The genus *Camelus*, which is part of the Camelidae grey family,[2] is made up of two species: the one-humped Dromedary camel (*Camelus dromedarius*) (see Fig. 9.4), also referred to as the Syrian, European or 'Arabian camel', mainly from Arabia, Northern India and the Mediterranean, and the two-humped Bactrian camel (*Camelus bactrianus*) (see Fig. 9.5), also referred to as the Asiatic or Central Asian camel, mainly found in Northern China and Mongolia, in areas bordering the Gobi desert, and to some extent in other parts of Asia.[72] The latter produces the best and softest fibres. The finest quality comes from China, from young animals. It is thought to have descended from the cross-breeding of the ancient pure Bactrian (Bactriana) camel and the Dromedary camel, which produced the Bokhara type of camel, also known as the Boghdi.[70]

According to Harizi *et al.*,[72] there were about 14 million Dromedaries and 4 million Bactrian camels world-wide in 2002, with the greasy hair

9.4 One-humped Dromedary camel.

9.5 Bactrian camel. (Reproduced from Pier Giuseppe Alvigini, *The Fibres Nearest the Sky* (2nd ed. 1984), Mondadori Editore, Verona, by kind permission of Mr Pier Alvigini at Alvigini S.A.S., 13900 Biella Via Dante, 12 Casella Postale 430, Italy.)

production at the time being estimated[2] at 3–3.5 million kg, the bulk being from China and Mongolia. In the 1980s India reportedly[73] had 1.5 million camels (half Bikaneri bred), representing some 10% of the world camel population.

Camel hair used in textile applications almost solely comes from the Central Asian or Bactrian camel, the hair of the one-humped Dromedary generally being not important for textile applications because of its relative coarseness and inadequate length and strength.[74] The Bactrian camel yields a light fawn (tan) lustrous fleece mixed with coarser brown hairs. It has a double coat of hair, with the coarse outer hair or guard hair, 30–120 μm in diameter and from 60 to 375 mm in length, and the fine down or undercoat, 10–30 μm, or even 40 μm (average about 18 μm)[75] in diameter (CV from about 25% to 35%[76]) and about 25–125 mm (typically 50 mm, CV ≈ 24%), in length,[74] and characteristically reddish brown (tan) in colour. Most camel hair is produced in China (including Tibet) and Mongolia, some also being produced in Afghanistan, Iran and Russia.

Bactrian camel

As already stated, the Bactrian camel is the main source of camel hair used in textiles. When the camel moults, it sheds its hair (fleece) in large tufts over a period of time (≈ 6–8 weeks). Starting during late spring, the neck hair falls off first, then the mane, and finally the body and belly covering,[77] the hair on the humps remaining. When the camels moult, the hair can obtained by combing, shearing (done more commonly today) and collecting of shed hair, resulting in a combination of coarse guard hair and fine down, referred to as raw (i.e. un-dehaired) camel hair. Raw camel hair contains approximately 75–85% fibre, 4–5% fat (grease) and 15–25% sand and dust.[78]

Today the camels are increasingly being shorn (clipped)[78] once a year, the hair on the back generally not being shorn, serving as a cushion for the pack or saddle. The hair is also not shorn too short, so as to leave sufficient fibre to protect the animal from excessive heat and cold.[78] The whole fleece weighs typically between 2.5 and 3.5 kg, while in cold regions, the hair yield can be as high as 5.5 kg, with the average annual yield being about 4 kg.[78] The Bikaneri camels (in India) produce some 700 g of hair per annum, with an average fibre diameter around 25 μm, some 15% of the fibres being completely medullated and 45% partially medullated.

Msahli *et al.*[79] (quoting Franck *et al.*) stated that the characteristics which determine the fibre quality of South American domestic camelids are mean fibre diameter, colour, type of fleece, fibre length and uniformity of diameter and length. The finest quality camel hair is a light, bright fawn while the lower qualities are deeper in colour.[80] There is a relationship between fibre diameter and fibre length.[81] Algaa and Mägel[81] review the properties of camel hair.

The surface of camel fibre is covered by a layer of fine and irregularly shaped scales, having diagonal edges which are not very prominent.[82] The fibres are circular to oval, the cortical layer exhibiting regular striations due to strings of pigment granules[82] which give the fibre its characteristic pale red-brown colour, and some fibres have a medulla which is often fragmented.[82]

Camel hair has a tensile strength of about 16 cN/tex and a moisture regain of 13%.[74] The finer fibres do not have a medulla, while the coarser fibres have a medulla which varies in character and size.[74] Table 9.18[82] compares the properties of camel hair with those of certain other fibres. Weng *et al.*[83] gave a table comparing camel hair fibre properties with those of 70s Australian wool (Table 9.19).

Table 9.18 Comparison of properties of camel hair and other fibres[82]

Properties	Camel hair	Silk	Wool	Cotton
Tenacity (gf/den)	2–2.5	1–1.5	1.5–2.0	2–5.5
Elongation (%)	39–40	25–40	25–45	6–10
Density (g/cm³)	1.32	1.34–1.38	1.33	1.50–1.54
Moisture regain (%)	13.0	11.0	14–16	9
Acid resistance	Excellent	Excellent	Excellent	Bad
Alkali resistance	Bad	Good	Bad	Excellent
Resistance to moth/fungus	Resistance to fungus but not to moth	Resistance to fungus but not to moth	Resistance to fungus but not to moth	Resistance to moth but not to fungus
UV resistance	Bad	Bad	Bad	Good

Table 9.19 The properties of camel hair and 70s Australian wool[83]*

Property	Camel hair	70s Australian wool
Average length (mm)	43	55
Average fineness (μm)	17.8	19.1
Fineness dispersion (%)	28.6	21.2
Absolute strength (cN)	4.9	5.7
Relative strength (cN/dtex)	1.47	1.53
Elongation at break	39.0	38.5
Initial modulus (cN/dtex)	20.4	15.3
Work of rupture (cN·mm)	13.8	16.2
Crimp factor (times/cm)	3–4	4–7
Crimp ratio (%)	5.7	7.8
Residual crimp ratio (%)	3.6	5.3
Crimp-elastic recovery percentage (%)	64.0	68.5
Compression elasticity (%)	60.0	57.4
Fast-elasticity (%)	33	33
Slow-elasticity (%)	27	23
Elasticity (%)	60	56
Milling ball density (g/cm³)	0.13	0.18
Mass resistivity (Ω)	2.3×10^{13}	3.3×10^{13}
Moisture content (%)	13.9	13.3
Oil (grease) content (%)	1.3	13.8
Handle	Good	Fine
Lustre	Good	Good

*Values rounded off. 70s refers to the wool count, a measure of quality.

Dromedary camel

In Tunisia there were some 100 000 one-humped Dromedaries in 2003[72] (quoting Sghair) producing more than 100 000 kg of hair annually, only a little of which is harvested and used by Bedouin people to make traditional clothing, such as 'bernous' and 'wazra' worn by men.

The Dromedary camel also has a two-layer coat of hair, a coarse outer coat or guard hair (outer hair) and a fine undercoat or down.[79] The raw fibre obtained from the camel has to be de-haired in order to separate and remove the more valuable undercoat from the coarse guard hair. In general, the efficiency with which the two components can be separated during the de-hairing process depends upon how much the two components differ, particularly in terms of fibre length, fineness (diameter) and rigidity, as well as in their surface characteristics and inter-fibre cohesion:[79] the greater the differences, the greater the de-hairing efficiency generally.

Harizi *et al.*[72] evaluated and reported on the physical and mechanical properties of the under-hair (down) of Tunisian dromedaries. They found the scale frequencies for the under-hair and guard hair to be between 6 and 8 and 13 and 15 per 100 μm, respectively, compared to 6 and 7 for cashmere[72] (quoting Phan *et al.*). The scales of the Dromedary fibres are, on average, extremely long and quite visible, but do not protrude much from the fibre surface, appearing almost convex.[72] The colour of the hair varies from beige to brown to almost black.[72] The average fibre diameter is around 17.7 μm (CV = 27%) for the undercoat and 90 μm (CV = 28.5%) for the guard hair,[72] with an average regain of 15%,[72] which is slightly less than that for wool.[72] The average Almeter (AL100) fibre length (weight based) of the de-haired under-hair of a one-year-old Dromedary was found to be about 53 mm (CV = 41%), with 7.7% short fibres (< 15 mm), the hair being shorter than that of Mongolian camel (> 70 mm),[72] but longer than cashmere (≈ 44 mm).[72] Harizi *et al.* obtained a tensile tenacity of 212 MPa, an elongation at break of 37% and an initial modulus of 3.87 GPa for the under-hair (≈ 20 μm), the corresponding values for the guard hair (≈ 105 μm) being 121 MPa, 49.7% and 2.02 GPa, respectively. The average values for the under-hair were as follows:

Mean fibre diameter: 21.2 μm (35.9% CV)
Mean fibre length (Hauteur): 18.1 mm (CV = 53.3%)
Tenacity: 11 cN/tex (CV = 12%)
Strain: 37% (CV = 21.6%)

The average stress and strain were higher, and the modulus lower, than those of Merino wool, camel hair and cashmere.

Harizi *et al.*[72] found that de-haired fibre taken from the neck, chest, shoulders, nape of the neck, throat, tail and back (area 1) had, on average, similar

mechanical properties to those of fibre taken from the belly, side and kidney areas (area 2), but generally showed different trends with the age of the camel in terms of diameter and length. The average diameter of the fibres from area 1 was greater, also increasing more with age, than that of fibres from area 2. Fibre length increased with age for area 1 and decreased with age for area 2. Fibre bundle tenacity first decreased, and then increased with age, showing a minimum at about 8 years of age.[72]

9.4.2 Fibre processing

Bactrian camel hair

The processing of camel hair essentially consists of sorting, willowing (to remove dirt, dust and plant material), washing (scouring), de-hairing, spinning, fabric formation (knitting and weaving), dyeing and finishing. Sorting involves grouping the hair according to the fibre colour and the age of the animal, and visually separating the coarse hair from the fine, soft hair, after which the fibres can be willowed and then washed to remove any dirt or debris, which is followed by the de-hairing process.[82]

Raw (i.e. un-dehaired) camel hair from Mongolia contains between 20 and 35% guard hair and that from Iran between 50 and 65%,[81] and as much of this guard hair as possible has to be removed prior to textile processing. Although camel hair was originally de-haired fairly satisfactorily by carding and combing operations (even by hand in the nineteenth century) a mechanical de-hairing process, involving specially developed machinery, is more commonly applied today,[75] which is more efficient, slower, gentler and more sophisticated. Details of the de-hairing process are generally a closely guarded secret, with relatively few firms able to do it. De-hairing removes not only the coarse hair but also extraneous matter (contamination), such as vegetable matter and bits of skin (dandruff).[82] When combing is involved, the fine short fibre (i.e. noil) removed can often be of a higher commercial value than the tops.

De-haired down fibre diameter ranges from 16 to 20 μm, intermediate hair from 20 to 29 μm and guard hair from 30 to 120 μm.[2] Baby camel hair, which is the softest, has a diameter of about 16–17 μm. The mean fibre length of the down typically ranges from about 30 to 40 mm, with the guard hair being up to 375 mm long,[2] while the length of baby camel hair is similar to that of the adults.[2] Fine camel hair tops typically have a length of 50 mm and a CV ≈ 25%.

After de-hairing, camel hair is processed on both the woollen and worsted systems, often in blends with wool, sometimes also with nylon for hosiery and knitted products.[83] Weng *et al.*[83] concluded that the low cohesion of camel hair relative to that of 70s Australian wool was mainly responsible for its relatively poor spinning performance, its low cohesion being mainly attributed to its relatively low crimp and friction and relatively high initial modulus. Its shorter fibre length and greater fibre diameter variability may also have contributed to its inferior spinning performance *vis-à-vis* that of the 70s Australian wool. The long and coarse guard or outer hair, such as from camel manes (Mongolia) and third grade Chinese camel, is carded, gilled and Noble combed (sometimes twice), the very long fibres often being reduced in length (broken) prior to combing.

Since, like most speciality animal fibres, camel hair occurs in nature in various shades of grey or brown, due to the presence of a natural pigment (melanin), a bleaching process is often employed to remove its natural colour. The camel hair undercoat is characteristically reddish brown, reacting to chemicals very much like mohair and cashmere.[75] For white or pastel shades, such fibres need to be bleached, ideally with minimal damage to the fibre. Bereck,[4] Khishigsuren *et al.*[84] and Kang and Park[85] have reviewed and reported on the bleaching of naturally melanin pigmented animal fibres. In practice, pigmented fibres are bleached using either oxidative or reductive processes or their combination, and commonly involves a treatment with ferrous salts (mordanting) followed by rinsing and bleaching with hydrogen peroxide.[84] Khishigsuren *et al.*[84,86] described an improved ferrous mordanting process for bleaching camel hair, which resolved serious problems of discoloration and excessive damage of bleached fibres associated with iron deposition during mordant bleaching, and there was no need for an after-treatment with a reducing agent. The process used a mixture of thiourea and hydrogen peroxide to produce thiourea dioxide. This is an effective reducing agent when applied during mordanting,[87] and lower mordanting temperatures are possible.

Dromedary camel hair

Msahli *et al.*[79] reported on the effect of various parameters on the laboratory de-hairing of Dromedary camel hair using a Shirley Analyser. They found that four passages through the Shirley Analyser were optimum for de-hairing, the hair being scoured prior to de-hairing, with an opening process prior to the Shirley Analyser being of benefit, particularly in terms of fibre length. After the fourth Shirley Analyser passage, the down still contained about 10% of coarse hairs (> 30 μm).[79] If an opening process was first carried out, the Shirley Analyser component had a mean fibre length of 35 mm (CV = 47%), that of the original raw fibre having been 48.3 mm (CV = 60.4%), and the diameter 22 μm (CV = 39%) compared to that of the raw hair which was 26.5 μm (CV = 64.4%). The Stelometer bundle tenacity for the down was 15 cN/tex and that of the raw hair 10 cN/tex.

9.4.3 End-uses

Camel hair (down) fabrics, both woven and knitted, are well known for their warmth, comfort and hard wearing properties. They also drape well[74,75] and are used in both ladies' and men's high-quality clothing (apparel). Good quality pure camel hair products are highly sought after, but expensive, resulting in the fibre often being blended with wool. It is used, particularly in blends with wool, for men's and women's coats, jackets and blazers, skirts, hosiery, sweaters, gloves, scarves, mufflers and caps, dressing gowns and robes,[82] as well as in high-quality blankets.[75] As an example, camel hair and noils are blended with fine wool and spun on the woollen system for use in fabrics for overcoats, knitwear and rugs.[80] Camel hair is also blended with nylon to produce hosiery and other knitted products.[82] Products containing Camel hair should be dry cleaned or hand washed.[82]

The long and coarse guard hair, after being combed into tops, is spun into yarn on the worsted system and used in good quality interlinings, ropes, industrial belting,[74] tent fabrics,[80] in carpets and warm waterproof coats[82] and even paint brushes.[75] The hair from the North African camel is used in carpets, being harsh and unsuitable for apparel.[75]

Further information on camel hair can be found in the references.[2 and 81]

9.5 Cashgora

9.5.1 Fibre production, harvesting, properties, processing and end-uses

Although Cashgora initially attracted much interest, this was not maintained and the production of de-haired fibre dropped from about 200 000 kg in 1990 to about 60 000 kg in 2000.[2] Today little Cashgora fibre appears to be produced commercially, particularly in New Zealand and Australia.

The name Cashgora was coined in Victoria, Australia, in the late 1970s.[88] It comes from the Cashgora goat (Fig. 9.6), and it has been labelled the first new natural textile fibre of the last 100 years. The name 'Cashgora' was accepted as a generic term by the International Wool Textile Organisation (IWTO) in 1988.

The double coated Cashgora goat is the progeny of a cross between a male (ram or buck) Angora goat (*Capra hircus aegagrus*) and a female (doe) down-bearing (cashmere-bearing) feral or cashmere goat (*Capra hircus laniger*), the first crossing producing the finest fibres. These goats were originally predominantly reared in New Zealand[89] and Australia, and shorn twice a year, as is the case for Angora goats. It has been stated that Cashgora is normally produced in the first and second cross and can be regarded as fine mohair[90] or coarse cashmere.[91] In Australia, the first cross between a female

9.6 Cashgora goat. (Source: http://flyinggoatranch.blogspot.com.)

feral goat and a male Angora goat is called a Cashgora, the fibre having some of the characteristics of both cashmere and mohair. Nevertheless, crosses of the Angora goat with cashmere goats, the *Anglo-Nubian* and dairy goats have also been recorded[92] – goats similar to the Cashgora goat, and involving cross-breeding native Kirghis from the former USSR and Angora goats from Turkey were already being produced in 1820.[93] It has been stated[91] that Cashgora is a classification for coarse cashmere: the Cashmere and Camel Hair Manufacturers Institute classifies only fibre not exceeding 19 μm as cashmere and everything exceeding this as Cashgora and not entitled to be classified as cashmere.[91] Friedlin[93,94] reported on the production and characteristics of New Zealand Cashgora which was defined[95] as the down component from a two-coated fleece (down and guard hair) having a mean fibre diameter between 17.5 (sometimes it can be as fine as 17 μm) and 22 or 23 μm, a standard deviation below 6 μm, a CV of fibre diameter below 28% and less than 6% of fibres coarser than 30 μm. Three types of Cashgora have been defined, ranging from the top end (18.5 μm), marketed as 'Ligne Or', the medium range (20 μm) marketed as 'Ligne Emerande' and the lower range (just below 22 μm) marketed as 'Ligne Saphir'.[96] At René Friedlin the de-haired Cashgora was classified in three classes according to diameter, namely:[93] 17–18.5 μm, 19.5–21 μm and 22–23 μm.

Cashgora fibre (or hair) can therefore be taken as the 'down' (fine de-haired secondary fibre) component of the fleece of the two-coated Cashgora

goat, under 22 μm (in some cases as 18–22 or 23 μm) in mean fibre diameter, with a length generally between about 30 and 90 mm (usually between 40 and 60 mm, individual fibres even exceeding 100 mm). The mean fibre diameter of Cashgora can in fact range from about 19 to 24 μm and the CV from about 25 to 35%. Finer fibres are down to 12 μm, with the coarser end running up to 45 μm. The fibres are medullated in some cases, and the fleece has almost the same lustrous appearance of mohair, none of the fibres being crimped. It has to be de-haired (i.e. the down fibre has to be mechanically separated from the coarse, rather kempy hair or primary fibres). The down has a low to medium (gentle) lustre and is generally white, soft and delicate to the touch. Cashgora is de-haired using the same criteria as for cashmere, namely, fibres coarser than 30 μm are classified as guard hair, the fine inner down representing approximately 50% of the mass of the fleece.

Phan *et al.*[97] discussed the morphological features of Cashgora, showing that they differed sufficiently from those of cashmere to allow the two types of fibres to be distinguished. Phan *et al.*[98] stated that the scale structure of Cashgora is more similar to that of mohair than to that of cashmere. Nevertheless, Cashgora fibres are considered to possess either cashmere-like features (i.e. cylindrical and semi-cylindrical scales) or the characteristics of mohair, with 'splits', lance-shaped scales and subscales.[31] In the kid and young goat stage (up to 2 years of age) the fleece of the Cashgora contains fibres which are similar to cashmere and also fibres which are of the mohair type, both with lustre.[99,100] As the animal ages, the fine cashmere type fibres disappear and the fleece reverts to super-fine mohair in characteristics. A guard hair is always present.

Cashgora fibres range from a bilateral to non-bilateral structure, some resembling the bilateral structure of the cashmere, others resembling the non-bilateral structure of mohair, with the majority being intermediate.[10,101] It contains both ortho-cortex and para-cortex, with fewer fibres exhibiting a bilateral structure than is the case for cashmere. After de-hairing, Cashgora generally follows a similar processing route as wool and mohair. Cashgora can generally be woollen-spun and used in most articles of clothing (e.g. jackets, coats, scarves and stoles, with the exception of underwear) as well as in blankets. It is considered more suitable for the weaving trade for high grade lightweight suiting fabrics.[93] Albertin *et al.*[102] have compared the behaviour and properties of Cashgora during finishing operations.

Knitted Cashgora garments do felt and shrink during machine washing,[103] although they can safely be hand-washed. The pilling of the knitted garments was low (good). A chlorination shrink-resist treatment, involving sodium hypochlorite, reduced felting shrinkage during machine washing to acceptable levels, but caused some yellowing and scale modification, the latter assessed by means of the methylene blue test.[103]

9.6 Cashmere

9.6.1 Fibre production, harvesting and properties

Cashmere goats (*Capra hircus lasinger*) (see Fig. 9.7), also known as 'Shawl goats' or 'goats of Tibet',[104,105] have two fibrous coats (usually white): a coarse outer coat (guard hair) and fine down (undercoat).

The thick 'guard hair' provides physical protection while the fine undercoat provides thermal insulation,[106] an ideal combination for extreme climatic conditions, particularly extremely cold and wet conditions. Generally, the fine down hair grows during summer, preparing the animal to withstand the winter, and is then shed in spring when it can be harvested, the animal not requiring this highly insulating layer under warm, even hot, summer conditions. The outer hair of the ordinary goat is mostly too coarse for textile use, although raw goat hair (i.e. a mixture of the down and guard hair) was used in earlier times in fabric (e.g. tenting) and carpets.[106] Goat hair is still used to make brushes and interlinings, with the down removed to make felts.[106] Cashmere goats, found in extreme climatic mountainous regions, around the Himalayas and Central Asia, particularly in the regions around the Gobi desert,[52] are domesticated in various countries, such as China, Inner Mongolia, Iran (from the Passang or Iranian goat), and Afghanistan, and also bred in countries such as Australia and New Zealand. There is, however, no specific or distinct breed of cashmere goat,[107] although cashmere goats are generally white with spiral horns,[106] ranging between about 40 and 70 kg in weight and 0.6 and 0.8 m in height, with an average life span of about 7 years.[2]

9.7 Cashmere goat. (Reproduced from Pier Giuseppe Alvigini, *The Fibres Nearest the Sky*, Mondadore Editore, Verona, by kind permission of Mr Pier Alvigini at Alvigini S.A.S., 13900 Biella Via Dante, 12 Casella Postale 430, Italy.)

The fine down (undercoat) grown by the two-coated 'cashmere' goats is referred to as cashmere, being finest in the first year of the goat's life. The term cashmere, which originated from the Kashmir region (where in the 1700s Europeans first saw the fibre woven into shawls) and goats of Tibetan origin, is sometimes used interchangeably with the words Kashmir, pash and Pashmina[108] (the latter is the Persian term for cashmere,[109] and the local term for the cashmere or Pashmina goat and cashmere from the southern Himalayan region in India and Nepal; see also Section 9.13.8). Cashmere, also referred to as Tibet hair,[110] 'soft gold' and 'fibrous diamond',[111] can be defined,[112] according to the US Wool Products Labelling Act, as the 'fine (de-haired) undercoat fibres produced by a cashmere goat, with an average fibre diameter not exceeding 19 μm, and with no more than 3% of the fibres (by weight) having an average diameter that exceeds 30 μm, and a CV of diameter not exceeding 24%'. According to this definition, therefore, the coarse guard hair from the cashmere goat is not regarded as cashmere. Cashmere is generally taken as the fine (de-haired) undercoat (down) fibre from a two-coated goat.

The diameter of the down from cashmere goats is similar to that (≈14 μm) from 'ordinary' goats, although the former normally produces more down fibre than the latter. The AATCC definition of cashmere was coarsened in 2001,[113] with the ASTM not regarding fibres coarser than 30 μm as being cashmere.

Phan and Wortmann[114] proposed the following definition of cashmere:

- The de-haired, fine undercoat fibres produced by a double-coated species of goat.
- An upper limit of 19 μm for mean fibre diameter and 24% for the CV of 'diameter'; with the level of coarse hairs (> 25 μm) less than 3% by weight.
- Goat fibre samples with a mean fibre diameter (MFD) between 19 and 23 μm are classified as Cashgora.
- First class cashmere should have a MFD below 15.5 μm and a soft handle.
- Cashmere with an MFD higher than 15.5 μm is second class.

The bulk of the global cashmere production comes from China and Mongolia (combined over 90%), with the rest coming from Iran, Afghanistan, Russia, India, Pakistan, Turkey, Australia, New Zealand, Britain and the USA.[104] China's production of raw cashmere fibre (i.e. guard hair plus cashmere) was estimated[115] at some 15 million kg, in 2005, some 6.5 million kg being produced in Inner Mongolia.[116]

The guard hair (outer coat), of the cashmere goat is long (around 15 cm), coarse (from 30 to 150 μm, average about 60 μm) and medullated, and is produced by the primary follicles. The fine, short, unmedullated down or undercoat (with a prominent surface scale structure), termed cashmere, ranging in single fibre diameter from 4 to 30 μm,[117] is produced by the secondary follicles. Between 100 and 300 g of fine down is produced per goat, with an average diameter ranging from about 12 to 19 μm, and average length from about 20 to 50 mm. The finest cashmere generally comes from China and Mongolia, although the average diameter of Mongolian cashmere increased from about 16 μm to between 17 and 19 μm after the mandatory culling of older male goats was revoked, the fineness of cashmere from male goats increasing by up to 1.5 μm at the age of 2 years. Nevertheless, the introduction of the Liaoning breed in Inner Mongolia is bringing the diameter down to about 15.5 μm. The Arbas breed of cashmere goat in Inner Mongolia is considered to produce excellent quality cashmere, with a high yield of up to 400 g of fine down.

The cashmere goats moult over several weeks during spring, when the cashmere is harvested either by combing (e.g. in China), or shearing (e.g. Iran, Afghanistan and Australia),[118] the long, outer or guard hair often being shortened (clipped) prior to combing. The method of harvesting affects the fleece characteristics, such as the ratio of down fibre (cashmere) to guard hair, and the level of contaminants, these also being influenced by nutrition and goat quality.[118] It also affects de-hairing efficiencies, for example it is more difficult to de-hair shorn hair than combed hair.

The total hair removed from a cashmere goat can be about 800–900 g. Of this some 500 g is clipped guard hair. The balance of 300 g (raw cashmere) is hand sorted which removes ± 20% of residual guard hair. Willowing removes about 10% of sand and dirt and the remaining 200 g is then scoured, leading to a further 20% loss. De-hairing then decreases the yield by another 30% (due to guard hair removal, known as cashmere waste), leaving 50% fine de-haired cashmere down (i.e. ≈ 100 g).[119] The fleece of the cashmere goat typically contains between 50 and 75% of fine down (i.e. undercoat).

Australia's cashmere industry, based on their feral goats,[120] was launched in 1972.[104] Australian feral goats have a fine, 15 μm or less[121] (even down to 13 μm), and ≈ 60 mm long undercoat (down) and ≈ 60 μm hair fibres (≈ 55 mm). They are probably the progeny of the original domestic goats from various European and Asiatic areas, during the latter 1800s.[121] Only about one in ten of these feral goats produce cashmere type fibres, which are often pigmented, the average down production per feral goat being between 75 and 125 g per year in 1981.[122] In order to produce white Australian cashmere, white top quality Angora goat males (bucks) are crossed with female feral goats carrying coloured down fibres, producing mostly white soft down fibres, > 18 μm, which is called Cashgora in New Zealand.[121] Cashgora, 18–23 μm, has a CV 25–30%, whereas well de-haired cashmere usually has a CV less than 20%[121] (see Section 9.4). Australian cashmere, which is produced

Table 9.20 Cashmere produced in different countries[104]

Country	Average scouring yield (%)	Average dehairing yield (%)	Average diameter (μm)
China*	75	51	14–16
Mongolia*	75	51	16–17
Iran†	80	35	17–19
Australia‡	92	30	15.5–18.5

* Blackburn 1990.
† Ekhtiyari 2000.
‡ Australian Cashmere Marketing Corporation.

in both Australia and New Zealand, is shorn, is predominantly white in colour, and considered to be longer, stronger, cleaner, softer, less crimped (i.e. lower curvature) and more lustrous than that produced in other countries.[104] It is therefore considered suitable for processing on the worsted system. The average fine fibre yield is some 200 g per animal, with an objective of 500 g per animal ultimately. Singh *et al.*[104] gave a table containing comparative data of cashmere production in various regions.

Cashmere is not as lustrous as mohair, and ranges in colour from white to brown, even black. According to the surface structure as well as handle, cashmere can be differentiated into 'cross-bred cashmere' and 'classical Asian cashmere'.

Various 'cashmere fibre types', classified according to average fibre diameter, presence of guard hair and colour are produced commercially (white is the most valuable; even 5 fibres/g of coloured fibres in white cashmere impact negatively on quality). International markets generally evaluate (grade) raw cashmere quality according to fineness (fibre diameter), colour, length and level of contamination (e.g. bits of skin, vegetable matter, etc). Fibre diameter greatly influences the market price of cashmere: the finer the better the perceived quality and price. The colour of the fibre also has a great impact on its price, with white being the most expensive. Black cashmere generally has to be bleached, particularly if it is to be dyed to pastel shades. Price is also affected by the fibre length, level of guard (coarse) hair and level of contamination (e.g. bits of skin, vegetable matter, etc.).

Fibre diameter can be measured by projection microscope (IWTO-8-97), Airflow (IWTO-6-98), Sirolan-Laserscan (IWTO-12-98) and OFDA (IWTO-47-95), as well as by scanning electron microscopes (SEM) and cross-sectional (CS) methods.[123] Some differences between the different techniques having been observed, however.[117] Fibre length, for example, can be determined by the time consuming single fibre length test (IWTO-16-67), or using an Almeter (e.g. AL-100) according to IWTO-17, values of 40 mm being obtained on Mongolian cashmere, when using the latter method.[117]

Cashmere fibres generally have very little crimp. Work by McGregor[124] and McGregor and Postle[125] shows that cashmere from newer producing regions, such as Australia, New Zealand and the USA has an even lower fibre curvature (i.e. crimp) than cashmere from the traditional sources, such as China, Mongolia, Iran and Afghanistan, with cashmere fleeces not exhibiting the well-defined staple crimp structure (formation) found in Merino fleeces. Fibre curvature was, as in the case of wool, negatively related to fibre diameter and nutrition affected the curvature of Australian cashmere. For the Chinese cashmere, the age and sex of the goats affected the fibre curvature, as follows; bucks 52°/mm, does 65°/mm and kid bucks 78°/mm.[124] For Mongolian goats, crimp curvature varied from 55 to 66°/mm, decreasing with mean fibre diameter, and also varying between certain regions.[117] McGregor and Postle[125] gave two tables representing results obtained on commercial de-haired cashmere and cashmere tops from various origins (Tables 9.21 and 9.22).

Chinese cashmere is considered to be the best quality, with an MFD between about 13.0 and 16.5 μm. Iranian/Afghan cashmere is 1–2 μm coarser (around 17–19.5 μm) and that from Australia and New Zealand is around 16–18 μm. According to tests done in Germany on commercial cashmere samples from different origins, the MFD ranges between about 18 and 19 μm,[121] with less than 1% (even 0.2% for knitwear and 1% for wovens[126]) of coarse fibres (i.e. coarser than 30 μm). For good quality Chinese cashmere,

Table 9.21 Median, standard deviation (SD) and range of pooled data for attributes of de-haired cashmere[125]

Top attribute	Median	SD	Maximum	Minimum
Mean fibre diameter (MFD) (μm)	16.4	1.4	19.3	13.5
CV of MFD (%)	21.7	1.6	29.0	19.8
% Fibres >30 μm	0.5	0.5	2.1	0.1
Fibre curvature degree/mm	60.0	9.3	79.7	40.1
Resistance to compression (kPa)	5.6	0.6	7.7	4.5
Incidence of medullated fibre (%w/w)	0.43	2.4	8.8	0.0
Mean medullated fibre diameter (μm)	34.8	12.3	62.9	23.6
LAC* (mm)	22.8	7.8	36	15
CV (LAC)* (%)	67.0	5.7	75.6	52.1
LAC fibres <25 mm (%)	63.1	11.3	86.7	38.0
LAC longest 5% (mm)	53.6	10.6	77	32
Inferred 'Barbe' (mm)	33.6	7.1	50	19
Ratio LAC: MFD (mm/μm)	1.41	0.30	2.21	0.93
Bundle tenacity (cN/tex)	9.9	0.9	12.0	8.2
Bundle extension (%)	40.8	4.5	50.0	31.3
Lightness	61.1	3.6	65.4	44.8
Yellowness	–0.3	1.8	3.7	–4.3

*LAC: length after carding.

Table 9.22 Median, SD and range of pooled data for attributes of cashmere tops[125]

Top attribute	Median	SD	Maximum	Minimum
Mean fibre diameter (MFD) (μm)	17.5	1.2	19.3	15.2
CV of MFD (%)	21.2	1.2	23.8	19.8
Fibres >30 μm (%)	0.6	0.4	1.6	0.1
Fibre curvature (degree/mm)	58.0	5.5	68.6	48.9
Resistance to compression (kPa)	5.9	0.4	8.3	3.6
Incidence of medullated fibre* (% w/w)	0.3	0.4	1.5	0.1
Mean medullated fibre diameter* (μm)	29.8	9.2	51.7	23.6
Hauteur (mm)	41.1	4.9	50	28
CV of hauteur (%)	41.2	6.9	57.4	31.8
Hauteur fibres	16.8	11.6	51.1	6.9
< 25 mm (%)				59
Hauteur longest 5% (mm)	69.7	6.6	82	37
Barbe (mm)	46.7	4.9	57	31.2
CV of Barbe (%)	36.7	5.0	47.8	1.52
Ratio hauteur: MFD (mm/μm)	2.37	0.36	2.91	8.3
Bundle tenacity (cN/tex)	10.4	1.0	12.0	19.5
Bundle extension (%)	39.1	6.6	50.0	

* Adapted from McGregor and Postle, 2004.

the fineness of the individual fibres ranges from about 8 to 24/25 μm,[123] with fibres coarser than 22 or 23 μm rare in well de-haired cashmere; it is stated that fibres between 25 and 30 μm are morphologically conspicuous and in appearance more like the coarse guard hair.[121] The upper threshold of the mean fibre diameter of commercial cashmere is around 19 μm, being set at 16 (+ 0.5 μm) by the Chinese National Standard, at 18.5 to ±0.5μm by the CCMI (Cashmere and Camel Hair Manufacturers Institute) in the USA, and at 19 μm by the ASTM.[123]

Well de-haired cashmere samples typically have a CV of diameter of 20%[114] (even up to 25%),[76] compared to that of 25–30% for Cashgora. The mean fibre length of the fine undercoat fibre of Chinese raw cashmere typically varies from about 21 to 40 mm (super grade), the lengths of the individual fibres ranging from about 5 to 80/90 mm,[123] depending upon the quality of the sample. Cashmere from China and Mongolia, as well as from Iran and Afghanistan, has shades of white, light grey, dark grey and brown; that from Iran and Afghanistan is typically cream, fawn and dark brown. Chinese cashmere (de-haired) average fibre length ranges from about 24 mm for the poorer qualities (e.g. Brown, Second Grade) to 36 mm for the top qualities (e.g. Super Grade).[110,114,121] That of Asian and Australian cashmere is measured at between 21 and 40 mm,[110,114] the individual fibre lengths ranging from 10 to 90 mm. Super Class cashmere has a fibre length of 38 mm (CV ≈ 33%) and First Class 36 mm. On the basis of the IWTO 5-66 test method, values for mean fibre length between 21 and 40 mm were found for Asian as well as Australian cashmere.[121] Coarse fibre (>30 μm) contents for Chinese Super Grade, First Grade and Second Grade are less than 0.1%, 0.2% and 0.5%, respectively (National Criteria of China for Cashmere Analysis, practised by CCIB offices in China).

Mongolian cashmere mean fibre diameter tends to increase with goat age, on average by roughly 1 μm from the age of 1 year to the age of 5 years.[117,127] It was found that the mean fibre diameters of cashmere from different provinces of Mongolia ranged from about 15.5 to 18 μm (CV ≈ 20%), increasing with age,[117] and mean fibre curvature from about 62 to 70°/mm[127] (55 to 66[117]), with a mean of 68.4°/mm. The mean bundle tenacity was ≈ 12.5 cN/tex and the bundle extension 45%.[117] In all, 94% of the samples had a down yield of over 60%, the average down yield being 80.4%, ranging from about 65% to about 85%. Mean fibre length of the two best provinces exceeded 38 mm in most cases, with 50% exceeding 40 mm. Yak and camel hair are about 1–3 μm coarser than cashmere, yak having some 2 scales per 100 μm more than Mongolian cashmere.[127]

Scale height of speciality fibres, such as cashmere, is about 0.4 μm and that of wool about 0.8 μm.[114] Different strains of classical Asian cashmere exhibit similar fibre surface characteristics,[123] with typically regular cylindrical and semi-cylindrical scale shapes, i.e. each cuticle cell envelopes the entire or half of the fibre shaft, with a mean scale frequency of 6–8 per 100 μm fibre length, e.g. 6–7 per 100 μm and a scale height < 0.5 μm for Mongolian cashmere.[117] Cashmere from the relatively new sources exhibits quite different scale shapes than the Asian types, usually having a higher scale frequency (> 8 per 100 μm). It is visually more complex and less regular, with many scales arrowhead-shaped like mohair,[114,123] and tends to be more lustrous and smooth (slippery), with a harsher handle than its Asian counterparts. The cortex of cashmere consists mainly of ortho-cortical and meso-cortical cells.[128]

9.6.2 Fibre processing

Raw cashmere can have between 25% and 30% of sand and dust, 4–5% (8–10%) of grease and 65–70% of fibre (clean fibre yield). Typically, cashmere processing commences with sorting, willowing (to remove dirt, grass, etc.) and aqueous scouring, to remove natural oils (grease), etc. Scouring yield is about 70%,[126] followed by de-hairing.[118] The most important step in cashmere processing is that of de-hairing, the effectiveness of which has a major impact on the quality, price (value) and processing of the fibre. The residual grease after scouring should be around 0.5%. De-haired cashmere (down yield), based upon the raw fibre weight, can vary from around 30% to 70%, this being largely dependent upon the method of fibre harvesting, i.e. combing or shearing, and the type and quality of the goat. Originally

de-hairing was done by hand, when it took some two hours to de-hair less than 60 g of fibre.[106] A cashmere de-hairing process was developed by Joseph Dawson in the 1870s, with the first successful commercial de-hairing machine being invented by Joseph Dawson and Sons in the UK some 100 years ago[129] with many different patents and designs of de-hairing machines appearing subsequently. Mechanical de-hairing essentially consists of three phases: opening up (individualising) of the fibres, separation and removal of the guard hair and fibre mixing.[130] Commercial de-hairing production rates are around 3 kg/h/m width.

The mechanical de-hairing of various animal fibres, such as cashmere, camel and yak, have been discussed.[130] Fibre rigidity/stiffness (which is largely determined by the fibre diameter) as well as fibre length play an important role in efficient mechanical de-hairing. A diameter threshold of around 30 μm is often used to distinguish and separate the fine down from the coarse guard hair. The separation criterion used for de-hairing by the combing principle is fibre length;[130] it merely removes relatively short fibres, hence, it is only effective if the fibre lengths of the fine down and the coarse guard hair do not overlap. A roller carding principle of de-hairing has also been developed.[130] The carding stage is particularly important in producing good quality cashmere yarns, requiring appropriately fine card wire and sharp points, as well as a very level surface. The world standard for Super A grade cashmere is 38 mm, modified cotton combing machines providing a length of 40 mm.[131]

It is possible to use both a modified Shirley Analyser[132–134] and the Shirley Trash Separator[134] for the laboratory de-hairing of cashmere, and for determining the yield, although some caution is necessary in the interpretation and application of the results, particularly those pertaining to fibre length. Aspects relating to the objective measurement of cashmere have been dealt with by Stubbs and Marler.[135] The Australian Wool Testing Authority Ltd. (AWTA Ltd.) developed[135] (see also www.awta.com.au) standard procedures for cashmere fleece testing, as well as for yield and mean fibre diameter measurement of sale-lots. Glasbey *et al.*[136] in 1994 reported on the use of digital image processing of microscopically measured diameters of raw cashmere (i.e. un-dehaired) to determine the mean fibre diameter of the down and guard hair, respectively, as well as the cashmere yield, without the need for first de-hairing. Lupton *et al.*[137] reported on a method they developed for estimating cashmere down yield and average fibre diameter of raw (i.e. un-dehaired cashmere) using an optical Fibre Diameter Analyser (OFDA). The fibre diameter results, but not the yield, correlated well with Shirley Analyser de-haired sample results. The density of guard hair decreased with increasing fibre diameter, due to concomitant increases in fibre medullation[137] (Phan and Wortmann[138] have dealt with morphological aspects of cashmere). Singh[21] and co-workers[139] have reported on a prototype cashmere de-hairing machine purpose built for 'Australian' shorn cashmere, which contains 60–70% coarse hair.

McGregor and Butler[118] found that the following factors were associated with more efficient de-hairing and/or longer de-haired cashmere: white colour, longer raw cashmere (staple length), greater fibre curvature, lower vegetable matter, normal length guard hair, and the absence of visible cotting, with coarser diameters also de-hairing more efficiently. Generally, commercial cashmere samples have a coarse hair content below 1%.[114] The level of coarse (guard) hair (usually taken as the fibres > 30 μm) present in good quality de-haired cashmere should be below 1%, or less than 0.5% by weight, according to Wang *et al.*[21]

Because cashmere is so expensive, and for improved processing, performance and yarn and fabric quality, it is often blended with silk and fine wool, such as lambswool, sometimes with a small percentage of nylon to provide added stability and strength. Nevertheless, unless it is blended with an extremely fine fibre, its handle and softness can suffer.

Due to its length and other factors, de-haired cashmere has been mainly processed on the woollen system, often mule spun. If it is long enough, it is processed on the worsted system, but only very rarely on the semi-worsted system. Similar machinery to that used for fine wool is employed, but with settings, conditions, etc., which are most suitable for cashmere and generally kept secret. Until the mid-1970s most cashmere was processed in Europe, mainly Scotland and Italy, but since the late 1970s China has increasingly processed cashmere locally,[104] this also applying to Mongolia. It has been stated[140] that in Scotland, a down (i.e. de-haired) yield of some 120 g of fibre can reduce to about 66 g at the spinning (i.e. yarn) stage. Some work has even been done on processing cashmere (35 mm, 18.7 μm) on the cotton system, followed by rotor (open-end) spinning.[141] A good quality cashmere top typically has a mean fibre length of about 38 mm and a CV of 33%.

Cashmere is generally fairly sensitive to dyeing and finishing conditions and the severity of the conditions (e.g. temperature, time, pH, agitation, etc.) must be minimised. Soft water is recommended for producing the lather which is so important in the optimum washing (scouring) processing of cashmere knitwear. It is also more sensitive to alkali than wool.

Pigmented keratin fibres contain black melanin pigment granules[100] (0.9 μm × 0.3) which are inert to all solvents. Oxidative and reducing agents, except hydrogen peroxide,[142] are used in what is essentially a two-stage bleaching process, involving an initial fast solubilisation of the melanin, followed by a slow decoloration. Bleaching is often associated with severe fibre damage: iron mordanting improves whiteness but with the penalty of increased keratin damage.[142] The binding of the ferrous ions to melanin was far stronger than that to the keratin. Khishigsuren *et al.*[143] showed that an after-bleaching rinsing process, involving sodium bisulphite on cashmere,

produced a better whiteness and less fibre damage than the conventional bleaching process. Pigmented fibre bleaching generally involves three stages: mordanting with ferrous salts, rinsing and treatment with hydrogen peroxide in an alkaline medium.[143] 18-MEA is the major lipid bound to the surface of a cashmere fibre,[142] which is removed by the hydrogen peroxide bleaching.[142] After-Chrome dyeing of cashmere with SCA-Cr mordant decreased the level of hexavalent Cr (VI) in the residual dye-bath and damage to the fibre[144] was notably reduced in terms of surface oxidation damage to the fibres.

9.6.3 End-uses

The quality of cashmere, notably fineness and length, plays an important role in determining its specific end-use (i.e. product), with the higher quality fine cashmere preferred for knitwear, where softness is of primary importance, while the coarser (lower) qualities often go into weaving. It is considered desirable for very high quality knitting and weaving yarns that the cashmere should be 40 mm or even longer. Good quality cashmere, notably the finer qualities, is popularly used in knitwear (particularly fully fashioned), scarves, shawls, ladies' underwear, etc., Scottish manufacturers set an 'unofficial' standard for the upper limit of cashmere to be used in such knitwear as 15.5 μm.[114] Fully fashioned knitting of cashmere has always been popular since it reduces the amount of costly fibre waste, and produces superbly shaped quality garments. Because pure cashmere knitting yarns tend to be weak, optimum lubrication is important to ensure relatively trouble-free knitting; so too are proper machine settings, low yarn tensions, straight as possible yarn paths, low take-down tensions and relatively slow knitting speeds.

Because cashmere is such a sought after fibre and so expensive, together with the rather limited supplies, it is in some cases even reused (recycled or re-processed). Reused (recycled) cashmere should, however, be clearly labelled as 'recycled cashmere'. Fisher's discriminant analyses have been used to distinguish between new and recycled cashmere.[145]

Although machine washable cashmere garments have been produced, they are generally cleaned by dry-cleaning or gentle hand-washing, using water which is not very hot and a pure soap powder or liquid or detergent specifically recommended for cashmere. The garment must not be rubbed or wrung during washing and should be rinsed thoroughly in cool water without softener and dried flat, out of direct sunlight. Cashmere is said to become more quickly saturated with water than wool.[107] The measurement of pilling in cashmere knitted garments has been investigated.[146] For further information on cashmere see the references[2 and 100] and www.cashmere.org.

9.7 Guanaco

9.7.1 Fibre production, harvesting and properties

Some 2 million years ago, the guanaco (genus: *Lama hunchus* or more commonly *Lama guanicoe*), a wild (now semi-captive) member of the South American Camelid family, first appeared in the palaeontological record, evolving in South America from *Hemiauchenia*.[147] The guanaco (see Fig. 9.8) is larger than the alpaca and vicuña, but smaller than the llama, and is a very timid animal and was originally killed for its meat and fleece,[12] although today it is farmed in semi-captivity and shorn for its fleece.

The guanaco represented an important source of meat and fibre, the latter used in textiles for thousands of years by pre-Columbian cultures,[147] and reserved for the clothing of ruling families during the Inca Empire.[147] According to Rainsford,[147] there were an estimated 30–35 million guanacos roaming the South American continent prior to the Spanish conquest of eastern South America in the early 1530s, but their numbers decreased drastically due to excessive hunting, competition for pasture from European livestock and the introduction of fencing.[147] It is indigenous to Southern Patagonia, both in Argentina and Chile. It is estimated[147,148] that, in more recent times, there were well over 600 000 animals in the world, (including some 500 000 in Argentina, 90 000 in Peru and 70 000 in Chile), mainly in small herds in Patagonia and the island Tierra del Fuego,[148] about 1% being

9.8 A guanaco. (Source: IncaTops SA, Arequipa, Peru.)

bred in semi-captivity. Guanaco, also known as Huanaco in Peru, can survive at almost any altitude, from sea level at Tierra del Fuego to 4500 m above sea level along the Andes of Northern Chile, Peru and Argentina (also referred to as luan), and almost every climate from semi-tropical to extremely cold snow-capped glaciers.[147,149] They are both grazers and browsers, with areas of lush bog, known as 'bofadels', ideal for breeding males,[147] adult males weigh between 100 and 150 kg[147] and adult females between 100 and 120 kg and their height ranges from about 1 to 1.2 m.[147] Very young guanacos (chulengos) are hunted for their meat and valuable skins, and fibre is also shorn from their skins.[150]

In 1975 the guanaco was listed on the Convention on Trade in Endangered Species of Wild Flora and Fauna (CITES) list (regulations in Appendix II), meaning that, legally, guanaco fibre can only be shorn and processed into luxury goods in accordance with CITES regulations covering protected animal species.[147] Guanacos are now bred in semi-captivity, while wild adults are captured, shorn and released.[151] A challenge to guanaco fibre breeders is to achieve the critical fibre production of between 4000 and 4500 kg of raw fibre required for industrial processing.[151] In Argentina, growers were allowed (in 2000) to capture a maximum of 10% of their total wild guanaco population with a view to adapting the young 'chulengos' to a new life which requires high fencing, special baby feeding and separation of families to avoid adult male fights.[152] To raise guanacos in semi-captivity involves rounding-up pregnant wild females and keeping then in corrals until they give birth,[147] after which the mothers are kept with their young for three months to familiarise them with human contact, and then they are released back into the wild, making them easier to round up and recapture for shearing.[147] Attempts have also been made to raise the guanaco entirely in captivity, by capturing the very young, preferably week-old 'chulengos', bottle feeding them for 120 days, taking great care to avoid mortality,[148] and then releasing them into specially prepared paddocks with fences up to 2.1 m to graze on nutritional pastures, supplemented during the first winter.[148]

The guanaco fleece is shorter, coarser (≈ 18–24 μm) and lighter in colour than that of the vicuña,[12] weighing some 750 g[147] to 1 kg, and consists of two coats: a protective relatively coarse outer coat (≥ 50%) and a much finer (≈ 16.5 μm) undercoat (≤ 50%). The animal is honey (fawn) coloured with a white underbelly and legs, and greyish-colour head and ears and the colour of the fleece ranges from golden/beige for the younger animals (chulengos) to dark beige and reddish brown for the adult animals.[150] The guard hair is up to 45 μm (usually 23–35 μm) in diameter and up to 140 mm in length. The diameter of the undercoat ranges from about 13 to 19 μm, the fibre diameter varying according to feeding conditions. Good animals achieve a mean fibre diameter of 14 μm[154] while a young guanaco fleece can even be as fine as 13.3 μm, and 34 mm long,[153] with a weight of 450 g.[148] Commercial de-haired guanaco fibre ranges in diameter from about 13 to 17 μm,[7] with the bulk being 15–16 μm.

In an attempt to standardise the quality of fibre offered by the farmers (estancias), the Argentinian government has implemented regulations requiring its representatives to consult with the farmers concerning their fibre-harvesting systems (both from wild or semi-captive animals).[147] The price paid for guanaco fibres depends mainly upon fineness, length and clip preparation.[153]

9.7.2 Fibre processing

Hair harvested (shorn) from the guanaco needs to be de-haired to separate the coarse guard hair from the fine undercoat fibres. Guanaco fibre is mainly processed on the worsted system, although some fibre is also processed on the woollen system, scouring yields varying from about 85 to 95%,[150] with greasy to clean yield quoted[2] as 65–70%. In one case, some 400 high quality guanaco fleeces were processed into 14.97 μm tops, having a CV of 20.22%, Hauteur of 33 mm, a Barbé of 39.1 mm and a relatively low coefficient of variation of Hauteur (CVH) of 43%, having a fawn shade similar to camel.[153]

9.7.3 End-uses

Guanaco fibre end-uses are similar to those of vicuña, being mainly used in luxury woven fabrics, supplied to exclusive tailoring companies, the suits of which can retail for US$10 000.[147] It is less commonly used in knitwear, although up to 20% guanaco fibre blended with Merino wool is used in fine fashionable sweaters and other knitted garments.[148] Fine-count worsted yarns, in various blends with Merino wool and/or cashmere, are also supplied to exclusive tailoring businesses in London, Milan and Tokyo, where blazer cloth is popular, and where dress overcoats are made from a fabric containing guanaco, silk and cashmere,[147] each garment being individually certified. Woollen-spun guanaco yarns are used in suiting and over-coating fabrics for exclusive top-quality fashion brands.[147] Guanaco is also making inroads into markets for scarves and shawls. Pure (100%) guanaco is more common in accessories.

9.8 Llama

9.8.1 Fibre production, harvesting, properties, processing and end-uses

The llama (*Lama glama glama*), a ruminant or pseudo-ruminant living in the high altitudes of the Andes, has traditionally, and mainly, been a beast

9.9 Llamas. (Source: Inca Tops SA, Arequipa, Peru.)

of burden of the Andes,[12] from the time of the Incas. It is the largest of the South American branch of the camelids. It is smaller than the camel (see Fig. 9.9) measuring about 1.2 m at the shoulder, and weighs around 100–120 kg.[155] It has been domesticated since time immemorial.

The guanaco or huanaco (*Llama glama hunaca*), a ruminant (or pseudo-ruminant), is the common ancestor of the domesticated llama and alpaca.[156] The natural habitat of the llama is the 'Antiplano', the vast, high and arid plateau of Peru, Bolivia, Chile and Argentina, at altitudes between 4000 and 5000 m,[12] feeding mainly on ichu grass. It has been estimated[155] that in 2006 there were some 3.4 million domesticated llamas in the world, with some 2.0 million in Bolivia. Peru has some 1.1 million and there are also significant numbers in the USA.

The llama fleece has a similar mean fibre diameter as the alpaca but is a double coat. There are, however, essentially two main types of llama. One type, the Kara (K'cara, qara/carguera or light fleece), is mostly used as a beast of burden and is the typical double-coated animal (single fibre diameter of the fleece ranging from about 10 to 150 μm), which has predominantly coarse guard hair and relatively fewer fine undercoat fibres or down.[14,35] The second type, 'C'haku/chachu' (woolly or heavy fleece), which is the main source of llama hair used for textiles, has essentially a single coat of relatively fine and soft fibres, but with a relatively high level of medullated (kemp) fibres amongst the secondary unmedullated fibres.[35] Interbreeding between llamas and alpacas has resulted in many and varied types (hybrids) of animals and fleeces, the cross of llama male with an alpaca female producing the Huarizo, known in India as Huaro, the reverse cross producing the Paco-llama or Misti.

The fleece of the llama (typically 15–60 μm) is not as attractive as that of the alpaca. It contains both coarse, long, kempy hairs and fine undercoat hairs and it is not easy to separate[12] the coarse guard hair from the fine down, due also to the presence of 30–40 μm intermediate fibres. The coarse guard hair is typically 30–40 μm in diameter (these are also referred to as intermediate fibres), but can even be up to 150 μm, and ranges from about 250 to 300 mm in length (typically over 100 mm) and is kempy. The fine undercoat or down ranges from about 10 to 35 μm in diameter (average around 22 μm; and CV from 25% to 35%[76]) and 65 mm in length, with baby llama fibre diameter being 20–21.5 μm, which is slightly finer than baby alpaca. Wildman[156] suggested 35 μm as the limit (or criterion) for distinguishing between the woolly (undercoat) fibres and the coarse (outer coat) hair. According to tests done by Greaves and Rainsford,[7] the fineness and related quality of llama hair have not changed significantly from 1970 to 2005. The fleece of the llama contains less than 4% grease, less than 25% total impurities and average fibre yield is about 80% (85–90% greasy to clean,[2] quoting Rainsford).

The natural colours of the fleeces are similar to those of the alpaca and there are often different colours within a fleece. It is mostly brown (fawn) in colour, although greys and even white, used alone, are used in blends in knitwear and outerwear chiefly used by the locals in clothing (e.g. ponchos), carpets, rugs, etc., while the coarse llama guard hair is used in ropes, sacking, braids, carpets, etc. The llamas breed, and are also shorn (mainly by hand), during the rainy season, from November to March. A fleece grown over a 2-year period weighs approximately 2.5 kg and only about 1 million kg of normal quality llama fibre is produced annually.

Franck *et al.*[157] have objectively described the different fleece types, subjectively defined as styles, in terms of different fibre types, differentiated according to length, fineness, type of waves and the presence or absence of lustre. Llama fibres are nearly all medullated, only a few of the finest fibres being unmedullated. Cuticular scale frequency is around 10–11 per 100 μm.[35–38]

Llama is de-haired in Bolivia and other countries. Townend *et al.*[5] review the various de-hairing techniques which have been developed over time and report on experimental work on the variables affecting the de-hairing of llama when using a single swift woollen card. They refer to the problems created by the wide range of fibre diameters (10–80 μm) present in un-dehaired llama hair. They conclude that modifying and optimising the carding

arrangement, conditions and settings could lead to significant de-hairing, although probably not to the extent that is commercially desirable.

For more information on llama fibre see the references 2 and 158.

9.9 Mohair

9.9.1 Fibre production, harvesting and properties

Mohair, derived from the Arabic word Makhayar (Mukhayar or Mukhaya), is the fleece of the single coated Angora goat (*Capra hircus aegagrus*), named after the Turkish province of Ankara (Angora or Ancyra) (see Fig. 9.10). The Angora goat is thought to have originated in the Asian Himalayas (Asia Minor) or highlands of Tibet.

The Angora goat is regarded as unique amongst goats in that it is essentially single coated, with the fibres from the primary and secondary follicles not differing very widely, and it does not moult, its fibres growing continuously throughout the year. For centuries, mohair has been regarded as one of the most luxurious and best quality fibres available to man. It is generally a long, straight (uncrimped but often wavy), smooth and naturally lustrous fibre, and predominantly white in colour which can be dyed to deep, brilliant and fast colours. Mohair is characterised by, and renowned for, its high lustre, durability (hard wearing), elasticity, resilience, resistance to soiling, soil shedding, setting, strength, abrasion resistance, comfort (including moisture absorption) and pleasing handle, and by relatively low flammability, felting and pilling. Although mohair has proved extremely popular in many applications, it has some limitations in certain 'close to the skin' apparel applications because of

9.10 Angora goats. (Source: Mohair South Africa, Port Elizabeth, South Africa.)

its coarseness relative to certain other types of luxury animal fibres. Its outstanding properties, such as resilience and durability, also make it particularly suitable for household textiles, such as upholstery fabrics, curtains and carpets. The low flammability of mohair renders it useful in several applications. The Limiting Oxygen Index (LOI) of untreated mohair is about 24, with 27 generally regarded as the minimum required to pass the vertical flame test.

The mohair industry first developed in Ankara, Turkey which was also the first country to supply mohair as a raw material.[159] The first Angora goats to leave Turkey went to South Africa in 1838,[160,161] and Angora goats arrived in the USA around 1849.[162]

Angoras were also introduced into Australia during the 1850s and 1860s,[163] but attracted little interest until around 1970.[163] Angora goats were introduced to Britain in 1881.[163] Today, mohair is largely produced in South Africa (which presently accounts for over 50% of global production), and the USA (Texas), but also in Turkey, Argentina, Lesotho, Australia and New Zealand (Table 9.23).

Angora goats can survive extreme temperatures, but they are very sensitive to cold after shearing, particularly a combination of cold, wind and/or rain. Angora goats can thrive on widely different types of pasture, grazing from about 30 cm to 1.6 m above ground level. It appears that the Angora goat is very efficient in converting feed into fibre[164] and more effective than woolled sheep;[165,166] the latter are more effective in converting feed into body mass. Mohair grows about 20–25 mm in length per month (i.e. 240–300 mm per year), irrespective of age, and Angora goats are generally shorn six-monthly in South Africa and the USA and annually in Turkey and Lesotho. Mohair fibre is generally classified according to the age of the goats and when they are shorn.

According to Van Der Westhuysen *et al.*,[165] the age of the goat is probably the most important factor determining the quantity and quality of mohair produced, with fineness (i.e. diameter), independent of age, also very important. Kids have a birth coat of fibres that grow mainly from the primary follicles, those being the follicles which produce kemp and medullated fibres.[167] From about 3 to 6 months the goats shed their birth coat ('mother hair') as the fibres grow increasingly from the secondary follicles which produce the finer and unmedullated hairs.[167,168] Fibre production increases from birth, reaching a maximum fleece weight at an age of between approximately 3 and 4 years (see Fig. 9.11).

With age, the fibre diameter increases, reaching a maximum at approximately 5 years[165] (see Fig. 9.11). The mohair fibres are finer towards their tips, due to the fact that the fibres become coarser as the goat ages. Fibres from the neck and britch areas of the goat tend to be coarser than those from the other parts of the body.

In South Africa the first shearing takes place around 6 months after birth and the second shearing 6 months later, the goats producing more fibre in the

Table 9.23 World mohair production (million kg greasy)

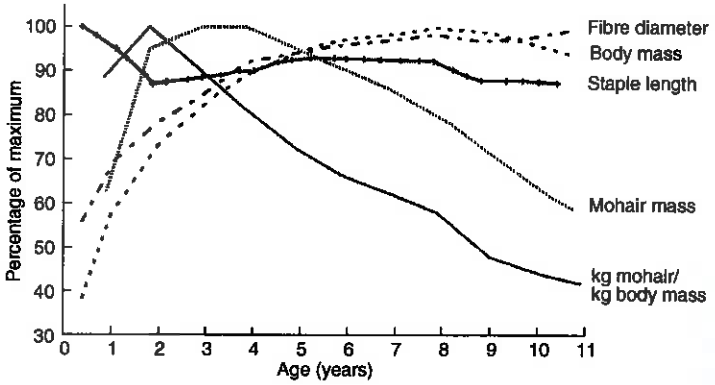
Year	South Africa	Turkey	USA	Argentina	Australia	New Zealand	Lesotho	Other	Total
1972	3.7	4.1	4.6	1.0	–	–	0.8	0.0	14.2
1973	3.4	4.1	4.5	1.0	–	–	0.6	0.0	13.6
1974	3.7	4.1	3.8	1.0	–	–	0.6	0.0	13.2
1975	3.8	3.9	3.9	1.0	–	–	0.6	0.0	13.2
1976	4.1	4.0	3.6	1.0	–	–	0.6	0.0	13.3
1977	4.6	4.1	3.6	1.0	–	–	0.4	0.0	13.7
1978	4.9	4.5	3.7	1.0	–	–	0.5	0.0	14.6
1979	5.4	4.5	4.2	1.0	–	–	0.5	0.0	15.6
1980	6.1	4.5	4.0	1.0	–	–	0.6	0.0	16.2
1981	6.9	4.5	4.5	1.0	–	–	0.6	0.0	17.5
1982	7.6	4.5	4.5	1.0	–	–	0.6	0.0	18.2
1983	7.2	3.8	4.8	1.1	–	–	0.7	0.0	17.6
1984	8.1	3.5	5.0	1.0	–	–	0.7	0.0	18.3
1985	9.2	3.5	6.0	1.0	–	–	0.8	0.0	20.5
1986	11.0	3.0	7.2	1.0	–	–	0.8	0.0	23.0
1987	11.5	3.0	7.3	1.0	1.0	–	0.8	0.0	24.6
1988	12.2	2.9	7.8	1.0	1.0	0.4	0.7	0.0	26.0
1989	11.7	2.0	7.8	1.0	1.2	0.6	0.6	0.0	24.9
1990	10.1	1.8	7.3	1.0	0.6	0.4	0.6	0.0	21.8
1991	7.6	1.2	7.4	0.9	0.5	0.3	0.5	0.0	18.4
1992	6.7	1.2	7.1	0.6	0.5	0.3	0.4	0.0	16.8
1993	6.0	0.8	6.5	0.6	0.4	0.3	0.4	0.0	15.0
1994	5.7	0.8	5.4	0.4	0.4	0.2	0.4	0.0	13.3
1995	5.4	0.6	4.8	0.5	0.4	0.2	0.5	0.0	12.4
1996	5.6	0.4	3.5	0.4	0.4	0.2	0.5	0.0	11.0
1997	5.2	0.4	2.5	0.4	0.3	0.2	0.4	0.0	9.4
1998	5.0	0.4	1.5	0.4	0.3	0.2	0.4	0.0	8.2
1999	4.5	0.4	1.2	0.25	0.25	0.2	0.4	0.0	7.2
2000	4.3	0.4	1.0	0.3	0.3	0.2	0.5	0.0	6.9
2001	4.2	0.3	0.8	0.3	0.3	0.2	0.5	0.3	6.8
2002	4.2	0.3	0.8	0.3	0.2	0.1	0.5	0.3	6.6
2003	4.0	0.3	0.9	0.3	0.3	0.2	0.5	0.3	6.6
2004	3.7	0.2	0.85	0.3	0.3	0.2	0.5	0.2	6.1
2005	3.6	0.3	0.8	0.3	0.2	0.2	0.6	0.3	6.2
2006	3.4	0.3	0.8	0.4	0.2	0.1	0.75	0.2	6.1
2007	3.0	0.35	0.55	0.45	0.2	0.1	0.75	0.2	5.6

(*Continued*)

Table 9.23 Continued

Year	South Africa	Turkey	USA	Argentina	Australia	New Zealand	Lesotho	Other	Total
2008	2.9	0.35	0.5	0.45	0.2	0.05	0.75	0.1	5.3
2009	2.6	0.3	0.5	0.7	0.2	0.1	0.75	0.2	5.3
2010	2.3	0.170	0.48	0.7	0.180	0.05	0.75	0.20	4.8
2011	2.23	0.150	0.35	0.7	0.155	0.045	0.75	0.20	4.6

Source: Cape Mohair South Africa.



9.11 The effect of age on fleece and fibre characteristics in the Angora goat.[165,169]

summer than in the winter. In South Africa, mohair obtained from the first two shearings (i.e. at 6 and 12 months) is generally classified as Kids. That obtained from the third (and also sometimes from the fourth) shearing (i.e. at 18 months and sometimes at 24 months) is classified as Young Goats and after that (i.e. from the fourth or fifth shearing, i.e. from the age of 24 or 30 months) the hair is classified as Adults. Generally, mohair from Kids is finer than 30 μm (varying between about 20 and 30 μm), that from Young Goats finer than 34 μm (varying from about 27 to 34 μm) and that from Adults generally coarser than 34 μm (but ranging from about 30 to 40 μm). Goats are classed as Young Goats up to the age of 3 years in Turkey. The grades of mohair vary in different countries. In general, the best grades of mohair are from Kids (e.g. Super Summer Kids) under 6 months old (i.e. first shearing). In South Africa, mohair to be classified as Kids must be 30 μm or finer, and Young Goats 34 μm and finer. Young goats and Adult goats produce about 2–2.5 kg of greasy mohair every 6 months, rams generally producing considerably more and coarser hair than ewes.[165] In the case of Kids, the fleece barely weighs 1 kg at the first shearing and is generally less than 2 kg at the age of 1 year (i.e. at the second shearing).

Mohair does not have crimp in the true sense of the word but exhibits waviness or curl. Curvature values for mohair and some other animal fibres are given in Table 9.24.[170,171] Table 9.25 shows some average values and ranges of various mohair properties.[173]

The fleece of the Angora goat, when shorn, contains natural and applied impurities; typically a total of 10–15% of non-fibre is present. The sweat or suint, the water soluble component, and grease (wax) combined are termed yolk. The grease (wax) is secreted by the sebaceous glands and the sweat (suint) by the sudoriferous glands. Other natural impurities contained in mohair include sand and dust (i.e. inorganic matter), vegetable matter (e.g. burr, grass seed) and moisture. Applied impurities include branding fluids and dipping compounds. Generally, mohair contains considerably less grease than wool (4–6% on average, compared with an average of about 15% for wool). Because the yolk content of mohair is lower than that of wool, shearers are said to have to change combs and cutters more often than with wool.

Table 9.24 Curvature and diameter values of several different animal fibres[170,171]

	Mean curvature (cm^{-1})		
Fibre	Wet	Dry	Mean diameter (μm)
White alpaca	2.0	8.4	30.2
Fawn alpaca	1.2	6.0	40.0
Lincoln	2.4	5.0	36.0
Mohair	1.2	1.4	43.6
Cashmere	6.8	12.7	13.8
Southdown	18.8	32.0	23.8
Corriedale	10.0	16.4	29.7

Table 9.25 Some average or typical values and ranges of various mohair properties[173]

Property	Range	Average/ typical value
Diameter (μm)	22–42	32
CV (%)	20–33	26
Staple length (mm)	80–140	110
Medullation (%)	0.3–2.8	1.0
Curls per 10 cm	2.5–6.5	4.5
Vegetable matter content (%)	0.1–1.7	0.3
Grease (%)	2.0–8.0	4.5
Suint (%)	1.8–4.2	2.8
pH of suint	3.3–6.2	5.2
Scoured yield (%)	75–95	85
Compressibility (mm)*	10–13	11

*SAWTRI compressibility test.

Mohair, by virtue of its open fleece structure on the goat, is more exposed to weathering than is wool, the tips of the mohair fibres covering the back of the animal being damaged by sunlight or weathering, especially during the summer months.[172] This damage has an influence on the dyeing properties of the affected fibre part. Its wax is also more oxidised than that of wool,[174] making it more difficult to remove during scouring.[169] Ilse[175] compared the composition of mohair, Karakul and Merino wool waxes as shown in Table 9.26 and concluded that the mohair and Karakul waxes had the usual Merino wax components in surprisingly similar proportions.

Mohair from Kids and Young Goats contains more grease than that from Adults, with the grease content higher in winter than in summer[176,177] and also higher towards the root (e.g. tip = 2.0%, middle = 4.6% and root = 6.0%). Uys, quoted by Kriel,[177] found an average grease content of 4.5% for summer hair and 5.8% for the winter hair, with a melting point of 39°C. He found the acid value to be 14.6 compared with a published value of 14. The unsaponifiable fraction was 46%. Kriel[177] published values (given in Table 9.27) for the chemical constants for mohair grease.

Fibre dimensional and tensile properties

Fibre diameter (fineness) is generally the most important textile quality aspect and price determining factor by far of animal fibres, such as mohair. The finer the fibre generally the more sought after and expensive it is. Fibre fineness determines processing behaviour and performance and product type and quality, having a major influence on the finest yarn and lightest

Table 9.26 Characteristics of the waxes[175]

Characteristics	Merino wax	Mohair wax	Karakul wax
Wax content of the fleece (%)	14–16	5	3
Saponification value (mg KOH/g)	92–102	128	110
Acid value	4	14	9
Hydroxyl value	54	57	58
Iodine value	15–30	36	56
Acids (%)	49	55	50
Unsaponifiable material (%)	51	45	50

Table 9.27 Chemical constants for mohair grease[177]

Characteristics	Value	Literature
Saponification value	126–135	128
Acid value	14.6	14.0
Iodine value	14.8	36
Percentage acids	54	55
Percentage unsaponifiable fraction	46	45
Ester value	117	114

The experimental values of Kriel[177] are shown in the column 'Value'.

Table 9.28 Average values of coefficient of variation (CV) of fibre diameter corresponding to different mean fibre diameters[178]

Mean fibre diameter (μm)	CV of fibre diameter (%)
25	30
30	27
35	26
40	27
45	29

fabric which can be produced, as well as the handle and against body comfort of the fabric.

Hunter *et al.*[178] studied the diameter and variation in diameter, as measured by projection microscope, of some 852 samples of raw and scoured mohair and 380 mohair tops. They found that, although standard deviation tends to increase with increasing mean fibre diameter, the relationship was a tenuous one and the scatter large. There was a tendency for CV to decrease as mean fibre diameter increased up to a mean fibre diameter of somewhere around 35 μm, after which the reverse occurred. For most practical purposes, however, the CV of diameter could be regarded as largely independent of mean fibre diameter, with an average value of approximately 27%. Table 9.28 gives average (typical) values for CV of fibre diameter.

Wang *et al.*[179] showed that there was a relationship between coefficient of variation (CV) of mohair fibre diameter and CV of single fibre strength as predicted theoretically. Fibre length is of secondary importance to fineness, having an important effect on the processing route and behaviour and on yarn quality. Fibre tensile properties are also important from a textile point of view, fibre strength playing an important role in fibre breakage during mechanical processing, including spinning, yarn strength, fabric manufacturing and in the ultimate strength of the fabric. Generally, in the case of animal fibres, fibre strength increases almost linearly with the fibre cross-sectional area, more particularly the cross-sectional area of the thinnest (generally the weakest) place along the fibre. Therefore, fibre diameter, more specifically, that at the point of break, often the thinnest place along the fibre, has the main effect on the absolute strength of the fibre (i.e. uncorrected for the fibre cross-sectional area). The fibre strength divided by the fibre cross-sectional area at the thinnest place or point of break (i.e. the intrinsic strength or intrinsic tenacity) is fairly constant for mohair.

Smuts *et al.*[180] found that mohair generally had a higher single fibre tenacity, initial modulus and extension at break than wool of the same diameter (Table 9.29). The mohair cross-section corrected tensile characteristics (i.e. tenacity) were fairly constant over the whole range of diameters, probably because of the absence of crimp and variations in crimp and associated fibre

Table 9.29 Average values for some tensile properties of wool and mohair*[180]

Property	Mean	SD	CV %	Range	*n*
Wool†					
Fibre diameter (μm)	22.7	3.3	15	18.1–33.1	56
Linear density (dtex)	6.6	2.0	30	3.5–12.8	56
Staple crimp (cm^{-1})	4.2	1.2	27	1.9–6.5	56
Resistance to compression (mm)	17.5	2.8	16	13.6–24.7	56
Bulk/diameter ratio (μm/mm)	0.79	0.19	24	0.41–1.29	56
Tenacity (cN/tex)	12.7	0.9	7	10.9–15.0	56
Initial modulus (cN/tex)	290	27	9	230–392	56
Extension at break (%)	37.0	2.6	7	31.5–41.2	56
Mohair					
Fibre diameter (μm)	32.1	5.8	18	20.7–44.3	29
Linear density (dtex)	11.9	3.3	28	5.8–20.1	29
Tenacity (cN/tex)	16.7	0.7	4	14.6–18.1	29
Initial modulus (cN/tex)	407	13	3	384–430	29
Extension at break (%)	42.7	2.1	5	38.0–45.8	29

* 20 mm test length and rate of extension 20 mm/min.
† Low crimp wool excluded.

Table 9.30 Typical tensile properties of mohair[181]

Property	Bundle test*	Single fibre test
Tenacity (cN/tex)	**14.0**	16.7
Extension (%)	14.6†	43.0
Initial modulus (cN/tex)	–	407

* Leather linings were used and the tenacity values were multiplied by a correction factor of 1.16.
† The bundle test is not considered to give reliable extension values.

characteristics. Lustre wools (e.g. Lincoln and Buenos Aires) had tenacities and initial moduli close to those of mohair.[180]

Hunter and Smuts[181] found both bundle and single tenacity to be independent of mohair fineness, although the initial modulus increased slightly with an increase in fibre diameter (Table 9.30).

Fibre stiffness

The static bending and extension moduli of mohair fibres are similar, and of the order of 308 cN/tex,[182] with the optical cell densities in the medullae of kemp fibres affecting the bending but not the extension moduli. For kemp, having a virtually empty medulla, the bending and extension moduli were similar at about 77 cN/tex, whereas for the kemp with a virtually filled medullae, the bending modulus was about 365 cN/tex, which was higher than that of mohair.[182] The extension moduli of the two types of kemp fibres were similar, indicating that any material in the medullae did not contribute significantly to the tensile properties of the fibre, confirming the results of Hunter and Kruger.[183,184]

Fibre surface and frictional properties

Mohair, wool and hair are covered by a layer of sheet-like hardened cuticle cells (epidermal scales) which overlap each other, with their exposed edges towards the tip of the fibre. The cuticle plays an important role for the whole fibre because it is, on the one hand, exposed to environmental influences and, on the other hand, responsible for the surface properties of the fibre. Although, under a microscope, mohair is similar in appearance to wool, the epidermal scales (cuticle scales) of mohair are generally less pronounced and only faintly visible. The scale structure described above is responsible for mohair's smooth handle, high lustre, low against-scale friction and low felting propensity. The cuticle scales are quite thin and flat,[185] generally being less than about 0.6 μm (typically 0.4 μm) in thickness and hardly overlap.[172] They are anchored much more closely to the body of the fibre,[172,186–188] i.e. they lie near to the stem or are piled more tightly upon one another,[189] giving the fibre its characteristic lustrous and smooth appearance.

In general, mohair has a relatively low-scale frequency, with a wide distance between the cuticle scale margins. The number of scales per 100 μm is generally in the order of 5 compared with between 9 and 11 in fine wools, with the scale lengths ranging from 18 to 22 μm. In the case of kemp, the number of scales per 100 μm is 10 or more, which is twice that for mohair; and they are arranged in a coronal or ring pattern, with smooth margins.[172] The width to length ratio of mohair fibre scales is of the order 2.[190] Ryder and Gabra-Sanders[191] found that the width to length (W/L) ratios of scales from various goat fibres showed a clear sequence from the wild ancestor (*Capra aegagrus*) to mohair. They defined the scale width as equal to the fibre diameter. Indications were that the W/L ratio was independent of fibre diameter.

As in the case of wool, mohair fibres have a lower friction when rubbed from the root to the tip (i.e. with the scales) than when rubbed in the opposite direction (i.e. from tip to root, termed *against scale*). The low against-scale friction of mohair, relative to wool (Table 9.31),[192] which is one of its distinguishing features, can be largely attributed to its relatively smooth (unpronounced) scale structure. Mohair has a very small directional friction effect (DFE), due to the extremely easy deformation of the thin distal edges in mohair and also to the absence of tilted outer surfaces and other high

Table 9.31 Fibre frictional properties[192]

Fibre	μ_2	μ_1	$\mu_2 - \mu_1$	$\mu_2 + \mu_1$
Wool	0.40	0.22	0.18	0.66
Mohair	0.23	0.15	0.08	0.38
Human hair	0.19	0.09	0.10	0.28

Note: All measured in distilled water against felt.
μ_1 with-scale, μ_2 against-scale.
Source: Frishman *et al.*, quoted by Harris.[192]

asperities. The against-scale (μ_2) to with-scale (μ_1) friction ratio of mohair is about 1:1 compared to about 1:8 for Merino wool.[193] The 'scaliness' ((μ_2–μ_1) × 100%/μ_1) of mohair, measured dry, is about 5 compared to about 60 for a fine Merino wool (Speakman and Stott, quoted by Onions[193]). When measured wet, the respective values are about 16 for mohair and 120 for Merino wool. It is these characteristics which give mohair its low felting propensity.

Moisture related properties

Although mohair, as in the case of wool, can absorb large quantities of moisture (up to about 30%) without feeling wet or damp, its surface is naturally water repellent, largely due to the presence of a strongly bound thin surface layer of waxy or lipid material which requires strong chemical action to remove it. The moisture-related properties of textile fibres are extremely important as they play a crucial role in the comfort of the fibre and in its behaviour during wet treatment and drying. Temperature and moisture also play an important role in the visco-elastic properties of wool and mohair, which in turn is related to wear properties, such as wrinkling.

Speakman[194] published a table (Table 9.32) illustrating the absorption and desorption of moisture by wool and mohair at different relative humidities. Watt presented a comparative table (Table 9.33) of equilibrium water content (regain) for seven keratins, including mohair.

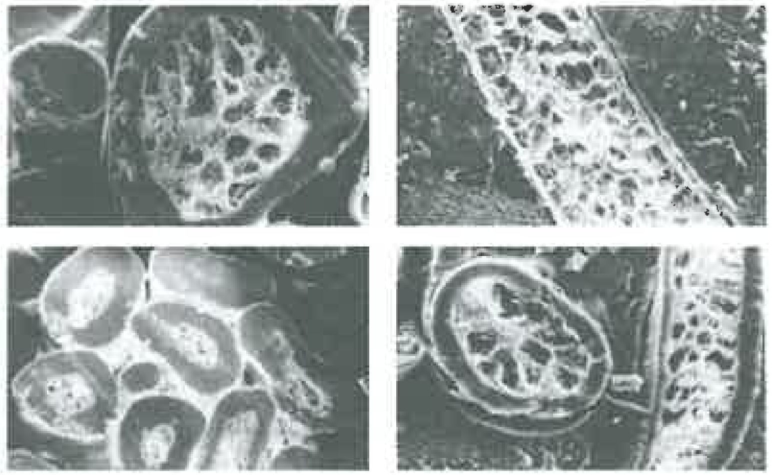
Table 9.32 **The absorption and desorption of moisture by wool and mohair at different relative humidities[194]**

	Percentage increase in weight of wool					
Relative humidity (%)	Geelong 80s Merino	South down	Oxford down	Leicester	Wensley-dale	Mohair
Absorption						
7.0	3.40	3.37	3.17	3.40	3.46	3.41
25.0	6.96	6.90	7.03	6.96	7.01	6.93
34.2	8.41	8.62	8.79	8.54	8.67	8.64
49.8	11.22	11.48	11.68	11.44	11.59	11.51
63.3	13.97	14.19	14.41	14.46	14.51	14.41
75.0	16.69	17.03	17.30	17.43	17.44	17.33
92.5	23.81	24.17	24.49	24.59	24.90	24.24
100.0	33.3	32.9	35.3	32.9	33.9	31.8
Desorption						
92.5	24.70	25.70	26.33	25.98	26.13	25.82
75.0	18.69	18.79	19.05	19.02	19.16	18.91
63.3	16.12	16.16	16.43	16.28	16.46	16.26
48.7	13.36	13.38	13.47	13.39	13.46	13.46
34.2	10.57	10.55	10.64	10.58	10.63	10.68
7.0	4.77	4.73	4.83	4.79	4.76	4.87

Table 9.33 **Equilibrium water contents for seven keratins at 35°C (in percentages)**

Relative humidity	Merino wool	Corriedale wool	Lincoln wool	Mohair	Monkey hair	Horse hair	Rhino horn
5	2.6	2.5	2.5	2.5	2.2	2.3	2.5
10	3.9	4.0	4.0	3.7	3.3	3.5	3.8
20	5.9	6.1	6.1	5.7	5.1	5.5	5.6
35	8.6	9.0	9.0	8.3	7.5	7.9	8.4
50	11.3	11.8	11.5	10.7	10.0	10.7	11.4
65	14.4	15.0	14.5	13.7	12.4	13.8	14.8
80	18.6	19.6	19.2	17.5	16.3	18.2	20.1
90	23.6	25.0	25.4	22.2	21.4	22.7	28.0
95	27.7	28.2	29.7	26.1	24.9	26.9	35.5
100	34.2	33.5	36.0	32.3	30.0	32.8	49.0

Source: Watt.



9.12 **Cross-sections and longitudinal sections of medullated fibres illustrating the cellular nature of the medullae.[2]**

Medullation and kemp

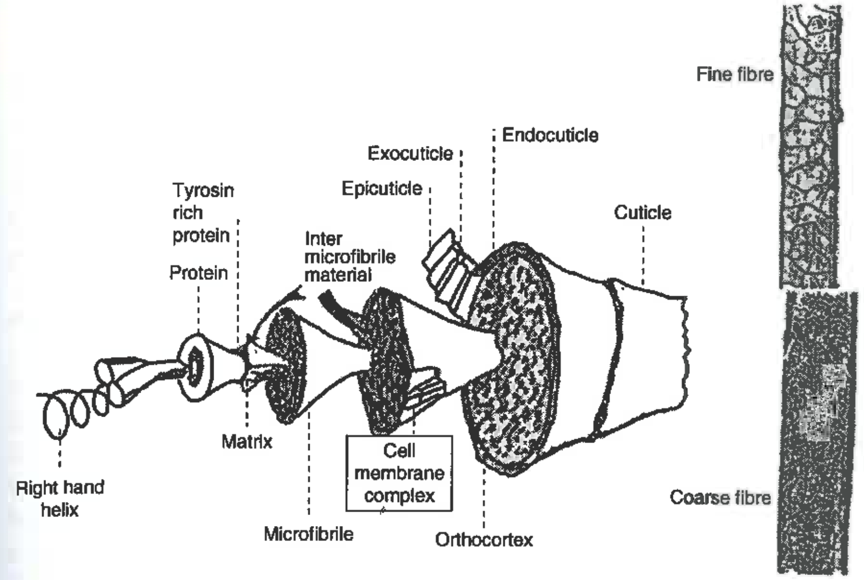
Medullated fibres in mohair can be a source of problems in many end-uses when they differ in appearance from the rest of the fibres which are not medullated. They are characterised by having a central canal (medulla) containing cell residues and air pockets, running in either a continuous or fragmented form along their length (Fig. 9.12[2]). The term 'kemp' is probably more familiar, but this traditionally refers to the more problematic and extreme form of medullated fibres (more recently referred to as 'objectionable medullated' fibres), which are clearly distinguishable by the naked eye, due to their chalky white appearance. Kemp is usually straight, and oval in cross-section. Of all the types of medullated fibres that occur in both wool and mohair, those collectively called kemp, which tend to have a relatively large medulla and to be relatively coarse, are the most visible and unwanted in the final product. Kemp occurs as short kemp, long kemp and hetero-type fibres. The 'short kemp' is generally the most common, being short, chalky white, medullated, and pointed at each end when it has fallen out and has not been shorn off. Kemp or 'objectionable medullated fibres' tends to be much coarser than the parent population (on average 1.8 times coarser than the mean fibre diameter of the parent population[195]).

Good quality mohair, such as Cape Mohair, contains very few objectionable (kemp type) fibres, and the presence of even a small amount of such fibres in a high-quality mohair can have a pronounced adverse effect on its value and price. The main problems associated with the presence of kemp (objectionable medullated fibres) are their chalky white appearance and their lighter appearance after dyeing. The chalky white appearance is largely caused by the decreased length of the light path through the dyed fibre material and light refraction at the fibre/medulla interface and within the hollow network of cells (aerian vesicles). This, and not a difference in the dyeability of the solid fibre material (i.e. fibre wall), is considered to be the main cause of the different (paler) appearance of kemp fibres after dyeing.

Fibre chemical, morphological and related structure and properties

The reader is referred to excellent and detailed reviews of this subject by Zahn,[188,196] Spei and Holzem[197] and Tucker *et al.*[8,198] Zahn *et al.*[199,200] reviewed the chemical and biological composite structure of wool, including mohair.

Mohair falls into the class of protein materials known as keratins characterised by its long filament-like molecules and insolubility in dilute acids and alkalis. Keratin can be regarded as a long fibrous composite, comprising crystalline, relatively water-impenetrable micro-fibrils, lying parallel to the fibre axis and embedded in an amorphous, water-penetrable matrix.[201] They generally have a high sulphur content when compared with other proteins.[202] All mammalian keratin fibres contain three main protein fractions,[203] termed low-sulphur, high-sulphur and high-tyrosine proteins, with the low-sulphur proteins generally representing the largest proportion. All animal fibres contain approximately 3–4% sulphur, largely as cystine. The mohair fibre generally consists of a cortex (cortical cells), the solid and main part or bulk of the fibre, which is predominantly ortho-cortex (cortical cells), and epidermis (cuticle cells) of numerous overlapping scales. The cuticle scales form a protective covering for the cortex and consist of three layers; epicuticle, exocuticle and endocuticle (see Fig. 9.13).[204] Each cuticle scale is enveloped by a thin semi-permeable[71,72] membrane called the epicuticle, which comprises protein and lipid.



9.13 Structure of adult mohair fibre.[204]

For further details and discussion of the physical and chemical composition of mohair see the references [1 and 2].

Objective measurement and trading

In practice, the quality of mohair is described as a combination of style and character, freedom from kemp, lustre, handle, yolk and uniformity of length and fineness.[205] The presence of kemp is often the most undesirable quality characteristic of mohair. Handle is largely determined by fineness, although a soft natural yolk and oleaginous dips also improve softness of handle. Mohair characteristics of economic importance are fineness (fibre diameter), length, style and character, contamination (kemp, coloured fibres and vegetable matter), and clean yield, lustre and uniformity in general. Fibre diameter is particularly important, as is the presence and level of kemp, with length having a smaller, though still important, effect on price and processing.

Style and character are judged subjectively, high-quality style being described as solid-twisted ringlets (staples or locks), while character is described as the waviness or crimp shown in the staple.[165,169] Style without character or vice versa is undesirable, and a good balance between these two characteristics is considered to be of paramount importance.[165,169] Table 9.34 is an attempt to consolidate and rationalise some of the different systems of quality, fineness and grades encountered in the literature.

Table 9.34 Some approximate quality types[1,2]

Spinning count: Tex	Worsted	English grades	Fineness/quality Bradford count	Age group	Crimp* per 10 cm	Maximum mean diameter (µm)	Mean fibre diamter (µm)	Description	Age (years)
14.5–15.5	58–60s	–	8	Kids	6.5–8.0	25	<26	SSK	$\frac{1}{2}$
16	56s	Kid	7	Kids	5.5–6.5	28	26–28	SWK	1
16.7–17.5	50–54s	30	6	Kids	5.5	30	29–30	WSK	–
–	–	–	6/5	–	–	32	–	–	–
18.5–19.5	46–48s	32	5	Young Goat	5.0–5.5	34	31–34	SYG	$1\frac{1}{2}$
20	44s	34	4	Adult	4.0–5.0	36	35–36	SWH	2
22–24.5	36–40s	36	3	Adult	3.0–4.0	39	37–39	SSF	$2\frac{1}{2}$
24.5–27.5	32–36s	38	2	Adult	2.5–3.0	–	>40	SFO	2
31.5	28s	40	1	–	1.5–2.5	–	–	WHO	2
								ARH	–
								CBH	–

* Preliminary.
SSK – Super Summer Kids.
WSK – Winter/Summer Kids.
SWH – Super Winter Hair.
SFO – Summer First and Older.
ARH – Adult (Ram's Hair).
SWK – Super Winter Kids.
SYG – Summer Young Goats.
SSF – Super Summer Ferals.
WHO – Winter Hair and Older.
CBH – Cross-bred Hair (Adult).

The textile processing performance, applications and general quality, and therefore value and price, of mohair are largely determined by the characteristics of the raw (greasy) mohair. It is therefore hardly surprising that considerable effort has been directed over the years towards the objective (i.e. instrumental) measurement of these characteristics to replace the subjective techniques traditionally used. Today, characteristics such as fibre diameter and yield can be, and often are, measured objectively with high accuracy.

Properties that need ultimately to be measured to characterise greasy mohair completely include the following:

1. Fibre diameter and its distribution (variability)
2. Yield (i.e. amount of clean fibre)
3. Staple (or fibre) length and strength, and their variability
4. Vegetable matter content and type
5. Inorganic matter content (e.g. sand, dirt, etc.)
6. Colour
7. Lustre
8. Medullation/kemp
9. Style/character

Douglas[206] discussed the advantages of objective measurement of mohair. He stated that the mohair top must achieve strict specifications to satisfy the spinning requirements such as:

- Quantity of top
- Mean fibre diameter
- Mean fibre length
- Maximum percentage of:
  - Short fibres (shorter than 30 mm)
  - Dark fibres
  - Vegetable matter specks
  - Entanglement (Neps)
  - Fatty matter
- Moisture regain
- Maximum percentage of kemp

In addition to the above, some spinners may have specifications which include:[206]

- Colour
- Distribution (CV%) of fibre diameter
- Bundle strength

Mohair base (i.e. the amount of clean dry fibre, free from all impurities, expressed as a percentage of the greasy fibre mass) is converted into the IWTO scoured yield.[206] This relates the tested yield to normal commercial yields for scoured greasy mohair. This yield is calculated from the mohair base to include all vegetable matter, standard residuals of grease and dirt, which would normally be retained in commercial scouring, and allows for a moisture regain of 17%, which means that yields of over 100% are possible.

There can be little doubt that mohair fineness (diameter) is one of its most important trading characteristics from the point of view of price and textile application and performance, with even a 1 μm change in diameter having a significant effect on price. It is therefore not surprising that mean fibre diameter, which can be measured by airflow, projection microscope, OFDA or Laserscan, is generally the main objectively measured and reported mohair characteristic, although the distribution of fibre diameter, in terms of CV, also has some textile significance. A major step forward in improving and standardising the inter-laboratory measurement of mohair fibre fineness occurred upon the introduction of Mohairlabs International Round Trials and associated issuing of Mohairlabs stamps in the early 1970s. Unfortunately this was terminated in 2003 with the dissolution of the International Mohair Association (IMA). In 2009 a similar body to Mohairlabs, called International Mohair Laboratories (IMLABS), was established in South Africa and became functional in 2011.

Turpie and co-workers[207–210] as well as others[211] reported on the calibration and application of the fibre diameter analyser (FDA)200 for the rapid measurement of mohair fibre diameter and its distribution. It was concluded that, within the ranges covered, kemp level had little effect on the relationship between FDA, projection microscope and airflow diameter values. It was found that different calibrations are required for mohair and wool on both the FDA[200] and the OFDA.

Turpie and co-workers[173,212–216] showed that the staple profile and length distribution could be used to predict the fibre length distribution of the staple and the top. The mohair staple has a very pronounced taper, indicating a fairly wide variation in fibre length within the staple. They found a reasonably good correlation between mohair staple length measured manually and that measured by the automatic staple length/strength tester.

Mohair burr and grass seed contaminants of mohair result in serious price penalties. Coloured (e.g. black or red) fibres, if present, could affect the finished cloth, particularly if light shades are dyed, and thereby the value of the mohair. Burrs or excessive vegetable matter in the fleece also have to be removed.[165] Urine and certain types of soil and vegetable matter contain substances that stain mohair permanently.[165] These affect the dyeing and the value of the mohair and the quality of the final product, Precautions must

be taken to limit such stains, particularly urine stains.[165] Clean yield (i.e. the percentage of actual fibre plus commercially allowed moisture content in raw mohair) generally varies between about 80 and 90% in most fleece classes, but may be as low as 60% in some outsorts, such as lox (locks), the remaining portion being made up of grease, dirt, dust and sweat.

9.9.2 Fibre processing

Scouring and carbonising

Scouring is a critical process in mohair production and often it is at this stage that the ultimate state of the finished article is decided. As previously mentioned, mohair generally contains far fewer impurities than does wool (e.g. 4–6% of grease compared to about 15% for Merino wool) and scouring generally causes a loss in mass of between 15 and 20%. Mohair is generally regarded as more sensitive to alkali than wool. Therefore, less, or even no, soda-ash (alkali) should be used during scouring, non-ionic detergents being preferred today.

Before scouring, individual mohair bales are often sorted on screens for style and quality, efficient sorting and blending playing an important role in the eventual quality of the yarn. The fibre can then be willeyed (opening/cleaning) before it is scoured, and this is advisable. Scouring conditions for mohair are generally gentler than they are for wool, and scouring rates lower; alkali not being necessary, the pH must be strictly controlled. Excess alkali in the fibre can lead to discoloration in dyeing. Care must be taken during scouring not to impair the lustre of mohair. Kriel,[174,217] quoting unpublished work by Veldsman, stated that a higher consumption of detergent was required to remove 1 g of grease from mohair than from wool. The relevant factors were the generally lower level of grease in mohair as well as its more oxidised nature, because of greater weathering than in the case of wool.

For the continental worsted system (French or rectilinear comb) of processing, which is very popular today, scouring to a residual grease content of 0.2–0.3% is advisable, with a total fatty matter level of between 0.7 and 0.9% (up to 1.2% for flexible card clothing) prior to carding.

Very little mohair (±2%) is normally classified as carbonising type, although in high rainfall areas and seasons it can rise to as high as 15%; mohair with vegetable matter exceeding 3% is normally carbonised.

Mechanical processing

Mohair is considered to be difficult to mechanically process because of its smoothness and lack of cohesion. Nevertheless, provided the correct processing additives (lubricants and anti-statics) and conditions and raw materials are used, very high quality mohair yarn can be spun with acceptable efficiencies. In converting mohair into yarn, similar machinery is used as in the case of wool. Considerable secrecy exists even today concerning the precise processing conditions used; firms which have built up this specialised knowledge and skills do not share it because it provides them with a competitive edge.

It is generally easier to disentangle mohair than wool during carding, with less fibre breakage in this process, although problems with static and fly generation often necessitate lower carding speeds. Mohair's low cohesion often necessitates that the fibres (slivers) be supported, for example by aprons, during processing. Mohair blends well with wool, the wool facilitating its processing, by increasing inter-fibre friction and cohesion. The application of the correct types and levels of processing lubricants and additives (such as anti-statics) and the selection of the most appropriate processing machinery and conditions (including atmospheric) are crucial in the efficient processing of mohair into a quality product.

Traditionally, mohair was processed on the Bradford worsted (oil-combed) system (drafting against twist) followed by flyer spinning.[218] Today, the bulk of mohair is processed on the continental or dry-combed (French/rectilinear combing), as opposed to the oil-combed, system. The French (continental or dry-combed) system of drafting and spinning involves French (rectilinear) combing, intersecting gilling and double apron drafting (drawing). It is possible to use either flyer (twisted) roving or rubbed (twistless) roving for subsequent yarn spinning. Most of the shorter mohair and also a significant amount of longer hair as well as mohair waste, such as carbonised noils, are processed on the woollen system. For the woollen system, a minimum amount of vegetable matter is essential. In woollen spinning, mohair shorter than about 75 mm staple length is generally used while for the worsted system the staple length is generally 90 mm and longer, with a staple length of some 120 mm often required.

The finest yarn which can be spun largely depends upon the mohair fibre diameter or fineness, traditionally expressed in terms of 'quality or quality counts', and these are related to the minimum number of fibres in the yarn cross-section. Wang and Khan[219] have reported on the use of pinned apron and bottom roller for the improved drafting of mohair during ring spinning.

Fancy (novelty) yarns

Mohair is used to particular advantage in fancy or novelty yarns, such as loop, knop, brushed, bouclé, flame, snarl, slub and gimp, where its properties provide outstanding aesthetic appeal and comfort. Such yarns are used in

blankets, stoles, shawls, scarves, knitwear (sweaters, cardigans, jerseys, etc.), travel rugs, curtaining, table coverings, upholstery, furnishings, pram covers, women's dress-wear, suitings and coatings. Adult hair is often used to form the loops of bouclé yarn properly.[220]

Fabric production and machinery

Generally, mohair yarn is converted into knitted and woven fabrics using similar equipment as for wool, though sometimes in a modified or adapted form and under special conditions, which allow for the more hairy, and often weaker, nature of the yarns.

Dyeing and finishing

Dyeing and finishing represent crucial stages in the manufacture of mohair products of the outstanding quality and appearance associated with items bearing the label 'mohair', acid and metal complex dyes being popular. It is generally the case that firms which dye and finish mohair also dye and finish wool and hence similar machinery is used for the two fibres. Furthermore, it is very rare to find pure mohair in yarns and fabrics. It is mostly present in blends with wool, often yarn blends, which means that the dyeing and finishing machinery and conditions used must be suited to both fibres.

There is a vast literature on the dyeing and finishing of wool, much of which is to a large extent also applicable to mohair. There is far smaller literature available on the specialised knowledge of conditions and procedures required for the dyeing and finishing of mohair products because most of such knowledge is a well-kept secret. In general, milder conditions (temperature and time) are used for the dyeing and finishing of mohair than for wool, partly because of the need to conserve the lustre of mohair and partly because mohair is more sensitive to wet treatments than wool. It is common practice to dye at temperatures below the boil, preferably below 90°C, and to limit the time of dyeing at high temperatures, so as to curtail any adverse effects on lustre and other desirable properties. It is also possible to limit damage to the fibre by using fibre protective agents.

9.9.3 End-uses

The textile application of mohair goes back many thousands of years and the fibre has found application in almost every conceivable textile end-use. Today, up to 80–90% of mohair consumption, especially of the Adult hair, can be affected by fashion.

Mohair, often in blends with other natural fibres, notably wool, with which it blends well, is used to great advantage in knitwear (ladies sweaters)

Table 9.35 Mohair consumption by end-uses[221]

End-uses	Share (%)
Hand-knitting yarns	65
Men's suiting fabrics	15
Women's woven accessories and rugs	12
Woven furnishings and velours	8

and hand knitting, mostly in brushed, loop or some other fancy form where brushing imparts softness and warmth without weight. Knitwear traditionally represented some 80% of mohair's outlets, but this sector is fairly sensitive to cyclical fashion changes.

Mohair also finds significant application in woven suiting and coating type fabrics, particularly in men's lightweight summer (tropical) suits where it provides the wearer with considerable comfort and good wrinkle resistance. Mohair is widely recognised as having very good wrinkle resistance and recovery, which, together with its stiffness, make it an ideal fibre for use in comfortable lightweight tropical type fabrics.

Table 9.35[221] lists some of the end-uses of mohair, and a detailed list of mohair applications is given by Hunter.[1,2] In lean worsted-type lightweight tropical suits, mohair is regarded as a cool fibre, whereas in brushed articles, such as shawls, stoles, rugs, sweaters and blankets, mohair provides warmth without weight. Mohair's characteristics of hard-wearing durability, resilience or springiness, crease resistance, moisture absorption, comfort, lustre and smoothness make it ideally suited to many applications in apparel and interior textiles, such as upholstery and any pile fabric (e.g. plush, velour, velvet and moquette, etc.), furnishings, rugs and curtains and it is virtually unsurpassed for general durability, recovering very quickly after being crushed. Because of its general smoothness and low static propensity, except under dry conditions, the smooth fibres do not allow dirt to collect readily, and stains are generally fairly easily removed.

Mohair, in blends with wool, bamboo and other fibres, has found significant application in comfort socks, particularly for active sports wear (e.g. cricket, mountaineering, etc.) and medical applications (e.g. for diabetics).

Further information on mohair is given in the references. [1 and 2]

9.10 Musk-ox

9.10.1 Fibre production, harvesting, properties, processing and end-uses

The musk-ox (*Ovibos moschatus*), a hollow horned ungulate (ruminant), native to the Arctic, is in fact not an ox, and has no musk, its nearest relative

9.14 Musk-ox. (By kind permission of Ms Nancy Bender, The Musk Ox Company, 633 Hatchery Road, Hamilton, Montana 59840, USA.)

being thought to be the goat.[222] It reportedly has the largest and thickest hair of any mammal on earth.[223] The prehistoric animal, also called 'omingmak' by the Eskimo people, is huge, and looks like a Bison[223] (see Fig 9.14). Adult male animals have an average weight of some 360 kg (up to 450 kg), and a shoulder height up to 1.8 m.[222] It originally bred wild and undomesticated in the Northern territories (Arctic lands) of Canada, and wild animals are still found in Canada's Northwest Territory and in Greenland.[222] The musk-ox essentially has a two layered fibrous coat, namely a relatively coarse, dense and long (up to 600 mm) guard hair (outer coat, dark brown in colour) and a relatively fine (≈ 13–17 μm) and short (40–80 mm) undercoat (brown-grey) of down fibres, known as qiviuk; the latter has been gathered and used since time immemorial by the Eskimo people.[223]

The musk-ox skin has an exceptionally high secondary primary follicle ratio between 40:1[224] and 37:1 (Rowell *et al.*[225]), the qiviut being primarily produced by the secondary follicles and the guard hair by the primary follicles. Rowell *et al.*[225] reported, however,[225] that there appears to be an intermediate (medium) group of fibres, coarser than qiviut but finer than the guard hair, variable in diameter and produced by the primary follicles, these being easily visible in combed fleeces. They are fine, like qiviut, near their roots and coarsen considerably towards the tips.[225] They are shed annually and can be medullated.[225] This group of fibres is believed to account for most of the fibres between 30 and 50 μm,[225] and is important in terms of the de-hairing process.

The musk-ox became extinct in Alaska around 1850,[224] but was re-introduced around 1953. The Canadian government placed the animals, which are easily hunted, under some protection in 1926, and in the 1930s the

US Department of Interior obtained animals from Greenland and released them on the uninhabited Nuaivak Island in Alaska.[222] First attempts to domesticate the musk-ox for its fibre occurred in the 1950s. The calves were captured in game sanctuaries in the North West Territories and the first successful musk-ox farm was established in Alaska during the 1960s,[225] when fibre production also started. In the 1980s there were two domesticated herds, one at College, Alaska near Fairbanks, and the other in Northern Quebec.[222] In a joint venture between the United States and the USSR, around the 1980s, musk-ox calves were captured at Nuaivik Island and sent to the Soviet Union, the latter attempting to re-establish the musk-ox in Siberia.[222] Originally mainly hunted for their fat-rich meat, the musk-ox is now mainly valued and bred for its fibre.[226,227] Selective breeding improved the fibre colour and yield and animal domestication, and reduced the size of the animal, thereby increasing its cost effectiveness.[228] In recent times, commercial harvesting of fibre from wild musk-oxen on Banks Island and elsewhere in the North West Territories of Canada has made available relatively large quantities of de-haired qiviut fibre, yarn and finished products,[225] fibre harvesting taking place semi-regularly since around 1982.

The musk-ox sheds its soft 'silvery grey/white' undercoat in a tightly synchronised moult each spring,[225] from around April to June (i.e. around late spring, with temperature playing a role).[228] The animals are placed in pens and the fibre is readily and easily combed out or plucked (pulled off) by hand, over a number of days, the undercoat being easily removed in sheets, which continues until early June.[228] The total collection (plucking) time per animal is slightly more than 2 h.[228] Fibre is also collected from objects against which the animals brush and which retain the fibre, the undercoat being found in great tufts on the bushes of the boreal tundra[223] where the animals graze. The guard hair is separated and removed by hand from the fine down.

The fibre removed from the musk-ox is referred to as raw fibre (i.e. containing a mixture of qiviut and hair).[225] Adult animals annually yield between about 2.5 and 3.5 kg of hair (raw fibre),[222,225] yielding about 2 to 3 kg of qiviut.[226] Females produce about 2 kg of qiviut, while mature bulls yield more fibre than females and younger animals.[228] For the purposes of their study Rowell *et al.*[225] defined qiviut to be all fibres ≤ 30 μm. The fine undercoat (qiviut) of the musk-ox has an average fibre diameter of about 20 μm,[31] numerically, more than 90% of fibres in a 'raw' sample being ≤ 30 μm.[225] Rowell *et al.*[225] reported that the average diameter for raw fibre shorn from the shoulder region of musk-oxen was 21.5 μm for adult males and 19.5 μm for 2-year-old females, and that of the qiviut (taken to be fibres ≤ 30 μm) 16.5 μm for yearling males and 18.2 μm for adult males. The fibre diameter for both the raw fibre and qiviut increased slightly with age. For example, both the raw fibre and qiviut increased by about 1 μm from 1 year to 4 + years of

age. The CV of diameter of the raw fibre was around 65%, and that of the qiviut around 27%,[225] the CV of diameter decreasing with age, for both the raw fibre and qiviut. The female animals tended to have slightly lower mean fibre diameters than the male animals, except at the age of 1 year.[225] The root section of the fibre is generally 1–2 μm finer than the middle section of the fibre.[225] Guard hair and qiviut staple length increases slightly with age, averaging around 120 and 52 mm, respectively, for the shoulder region of the musk-ox. The relatively low qiviut staple length (±50 mm) reported by Rowell *et al.*[225] was attributed to both their sampling site (shoulder) and the fact that the fibres were shorn (i.e. the fleeces were cut from hides) and not shed.[225]

Qiviut fibre quality is judged technically in terms of length and diameter, the fibres being similar in diameter, on average, to cashmere, and considerably longer.[222,228] Musk-ox hair can be de-haired on the same machines as cashmere.[228]

Musk-ox fleeces are virtually free from contamination, such as vegetable matter and dirt, and contain very little grease (< 7%) and suint,[225] it being almost possible to spin it directly from the animal's back.[228] Rowell *et al.*[225] reported an average scoured yield of about 93% for 3-year-old and adult musk-ox, increasing only slightly with age.

Alaskan Inuit (Eskimo) women hand knit caps, scarves, stoles, sweaters, shawls and tunics from qiviut,[222,229] about 115 g of qiviut fibre being sufficient for a sweater for a large man.

The fibre bleaches and dyes well, with garments made from musk-ox fibre being very light and comfortable, and highly suitable for temperatures below freezing. Garments made from musk-ox fibre reportedly do not shrink when washed.[226]

9.11 Vicuña

9.11.1 Fibre production, harvesting and properties

Vicuña (Lama genus: *Vicugna vicugna*), a ruminant (pseudo-ruminant) descended from the guanaco, is the smallest (0.7–0.9 m in height and weighing about 50 kg) and most timid member (see Fig. 9.15) of the South American Camelid family,[80] producing the finest and softest under-hair of any animal. Its fibre, sought after for around 10 000 years,[230] has been termed[231] 'Fibre of the Gods' and 'Silk of the New World'.[232] The individual fibres range from about 6–35 μm in diameter and 12–65 mm in length, the chest hairs being longer and lighter (almost white) in colour.[13] Only some 5000 kg of 'raw' (harvested) fibre is available annually,[233] which is reduced to almost half after scouring and de-hairing.[233] The vicuña originally had to be killed to obtain its fine coat of fibres,[234] although, reportedly,[235] the Incas

9.15 Vicuña. (Reproduced from Pier Giuseppe Alvigini, *The Fibres Nearest the Sky*, Mondadori Editore, Verona, by kind permission of Mr Pier Alvigini at Alvigini S.A.S., 13900 Biella Via Dante, 12 Casella Postale 430, Italy.)

some 500 years ago had captured, shorn and released thousands of vicuñas. During the time of the Inca empire, around 1400 AD, only the royal family and the handful of youthful ladies, chosen by the sovereign as ladies-in-waiting were allowed to wear vicuña garments.[232]

Vicuña is native to the central Andean countries of Peru and Bolivia (also Chile and Argentina), living in the Cordelleros of Peru and surrounding country, at altitudes around 3500–6000 m, and grazing on ichu grass.[12,232] They can exist at higher altitudes than other members of the Camelid family.[230] Millions of vicuña once roamed Peru's 4000 m high Altiplano. During the pre-Columbian Inca civilisation, vicuñas were hunted only once every 4 years.[236] After the Spanish invasion in the early 1530s, the vicuña population dropped dramatically, to only some 5000 in Peru in the mid-1960s,[236] due to uncontrolled hunting for their fibre and meat. Simon Bolivar passed the first law protecting vicuñas in 1825.[236] Peru passed a similar law in 1921, while a South American Agreement was introduced in 1969 which prohibited the commercial use of vicuña. The number of animals increased from some 5000 in Peru in the mid-1960s to between 10 000 and 15 000 by the end of the 1960s,[237] these being kept in the area Pampas Galeras (the 15 000 acre Pampas Galeras Naturel Reserve established in 1967), started as a programme of conservation and managed by the Peruvian government,[234] resulting in the vicuña numbers there increasing to 38 000 by 1978, and the world population to 60 000.[234]

The vicuña was considered endangered between 1960 and 1990.[238] According to one report,[239] the vicuña had been hunted to virtual extinction for its fleece,[239] and by the 1970s the species had virtually been wiped out in certain areas, the fabric fetching up to $1500 per square metre at the time. CONAF, Chile's forestry commission, in 1970 created the Lauca National Park in Northern Chile to protect the vicuña's natural habitat and increase their numbers. As a result of this there were some 28 000 vicuñas in the park around 1990.[239] Attempts also started at around that time to determine whether the animals could be safely trapped and shorn in the wild, leaving enough fleece to protect them from the cold.[239]

Because of the danger of extinction, export bans on fibre in Peru and Bolivia were supported by import bans in manufacturing countries.[12] In the USA, vicuña was listed as endangered on 2 June 1970,[240] reclassifying it to 'threatened' in 2002, other markets having sanctioned imports in 1995. The Peruvian government, and afterwards in 1976, the UN Convention on International Trade in Endangered Species (CITES), stepped in to make trading in vicuña an offence,[232] with a resultant dramatic increase in their numbers. In 1987 CITES changed the designation of the vicuña to Appendix II, allowing fleeces to be harvested and converted into fabric.[52] By 2001 it was estimated that they numbered over 200 000 in Peru[240] alone. In 1994 there were an estimated 66 500 vicuñas in Peru,[230] of the purest bloodline, the number thereafter increasing as shown in Table 9.36. There were estimated to be some 55 000 vicuñas in Northern Chile, Bolivia and Argentina[230] in 2000.

The project for Rational Utilisation of Vicuña, under which thousands of vicuña were culled for their fibre and meat in Peru, was terminated early in the 1980s.[241] The vicuña has never been domesticated, though bred in semi-captivity and herded. The rounding up in Peru is referred to as a Vicuña Chaccu/Chakku (also done by the Incas[230]) and the animals are shorn and released. This is called a 'Chakku'[151] in Bolivia, while the 'Compesinos' herd vicuñas for shearing in Peru.[232] In Peru, vicuña are shorn between 15 May and 15 November,[242] the total production amounting to a little over 6000 kg in 2007. Electric shearing is used where feasible, although clippers are considered preferable[243] for shearing.

Table 9.36 Vicuña population in Peru[230]

Year	Number
1994	66 500
1997	103 000
1998	120 000
1999	140 000
2000 (Est.)	165 000

The fleece of the vicuña ranges in colour from golden to typically a rich, deep fawn (cinnamon) colour, with that of the underbelly and extremities being off-white. Hair from six vicuñas is required to produce one sweater and from 35 to produce one coat.[244] Vicuñas have a double coat, a relatively coarse guard hair and a very fine undercoat or down, the most prized fibre being from the 'apron' of long whitish hair that falls between the front legs.[232] Vicuña fleece ranges from 12 to 15 μm in mean fibre diameter, and from about 15 to 50 mm in mean fibre length,[91] more typically 20–25 mm. The fine (13 μm) vicuña hair is found on the lower chest just behind the front legs and is a short (≈ 50 mm) downy undercoat, the outer hair being much coarser and longer (up to 45 μm in diameter and 65 mm in length[237]). Commercial vicuña typically ranges from 13 to 15 μm.[7] Greaves and Rainsford[7] reported little change in vicuña fibre fineness and quality from 1970 to 2005. An adult vicuña only produces about 200–250 g of fine hair every two years.[232,244]

First quality fibre averages about 37 mm in length and 12 μm in diameter,[245] and contains a small quantity of coarse and dead (kemp) hair. Second quality fibre comes from skirtings, is 3–4 μm coarser[245] and contains a relatively large proportion of coarse and dead hair.[245]

CONACS (Consejo Nacional de Camélidos Sudamericanos), the National Council for South American Camelids, is the government authority of the Ministry of Agriculture in Peru charged with commercialisation of vicuñas and the certification of fibre shorn from live animals.[246] Hair from slaughtered animals is illegal under Peruvian law.

9.11.2 Processing

Vicuña is sorted by hand to remove coarse fibres, a worker taking a week to separate (sort) by hand 1 kg of mixed fibre and down.[232] This is followed by de-hairing. Vicuña is traditionally de-haired by hand, but more recently also by machine. By hand, it can easily take seven 8-hour shifts for a sorter to obtain 700 g of fine fibre,[17] of which only a small percentage is as fine as 13 μm. Its length (typically 20–25 mm) largely limits processing to the woollen system, as opposed to the worsted system.[17] Specially collected vicuña fibres, 35 mm in length, have, however, also been processed, in 100% form, on the worsted system into blazer cloth. This was claimed to be a 'first' in textile history[247] (fibres from 5 vicuñas being required for one blazer length fabric). It was also claimed that the world's first 100% vicuña suiting from worsted spun yarn was produced in 2008.[248]

Woollen yarn as fine as Nm25 (40 tex) and worsted yarn as fine as Nm46 (≈ 26 tex) have been produced from pure vicuna fibre,[249] manual removal of kemp and impurities taking place at the fabric stage.

9.11.3 End-uses

Vicuña re-appeared on the market in the mid-1990s after an absence of 20 years. In 1994 the International vicuña Consortium won the rights to exclusively process and market vicuña globally.[17]. According to the agreement in 1995 to commercialise vicuña hair, only 100% vicuña could be used in fabrics, this being amended around 2000 to include blends with wool,[237] 80% vicuña/20% fine wool (20.5 μm) blend fabric (580–600 g per linear metre), for example, being used for skirts, dresses, scarves, jackets and overcoats.[245,250] Legally exported vicuña fabric is identified by a CITES-designated trademark 'Vicun–Andes'.[236]

Vicuña is popularly used in cardigans and sweaters and is highly sought after due to its very fine and soft nature. Scarves, parkas, throws, shawls, dresses and blankets, in 100% vicuña, also popular.

Vicuña fabric can cost US$4000 per metre,[232] and a full-length 100% vicuña overcoat costs as much as US$12 000.

In the case of woven fabrics, mainly plain weave fabrics are produced, with some common weights and end-uses as follows:[230,237]

- Average fibre length: 20–25 mm
- Yarn count: Nm 18 to Nm 40 (55 to 25 tex)
- Fabrics
  - 430 g/m for suitis
  - 550 g/m for jackets
  - 690 g/m for overcoats
  - 100 g/m (150 × 30 cm) for men's scarves
  - 190 g (180 × 30 cm) for ladies' scarves

9.12 Yak

9.12.1 Production, harvesting and properties

The yak (*Bos grunniens*), a member of the hoofed Bovidae family, is chiefly found in Tibet, living above the snowline on the Qinghai–Tibet Plateau, called 'The Roof of the World'. It is used in the mountainous region as a beast of burden,[251] and for subsistence through its milk and meat,[252] herdsmen in more recent times earning additional income from selling its hair. It was estimated that towards the end of the previous century there were some 13 million domesticated yaks on the plateau flanking the Himalayas, of which some 12 million were in China,[251] one-third of which were in the Qinghai province bordering on Tibet, making up the single biggest herd in the world.[251] Yaks were also dispersed on the vast pastures in the adjoining provinces of Sichuan and Gansu and in Tibet,[251] and there were also over

100 000 in India.[253] It was estimated that there were some 4 million wild yaks in the deep valleys and remote mountain areas. In the Himalayas, the domestic YAK is usually found at altitudes above 2000 m.

The yak weighs about 300–350 kg and its thick coat of long hair almost reaches to the ground (see Fig. 9.16). Wild yaks tend to have black hair but domestic yaks, kept by most herdsmen, have hair which is often a piebald colour, predominantly black and brown, with white markings.[251,252] The yak has a double-coated fleece, consisting of a long coarse guard hair (outer coat), and a soft down (undercoat) which it sheds annually in spring and which is either combed out by hand or shorn.[254] Based on a relatively low yield of 0.5 kg of fine fibre (down) per animal, some 7 million kg per annum of fine fibre should be produced according to the number of yaks from which hair is harvested. In fact, in 2006 the production of yak hair was estimated[254] at 7 million kg, mainly coming from China and Mongolia. A specially selected 'fibre line' of Jiulong yak can yield up to 10–12 kg of fine fibre (without coarse hair) per head which is some 10 times the normal yield (1–1.2 kg)[254] per animal.

The yak hair varies in fineness according to the part of the body from which it comes.[253] The underside of the animal is covered with long coarse hairs, which form a fringe, the outer sides of the legs being covered with the same type of hair.[253] The back none on the neck and spine as well as the occipital and frontal parts of the head are also covered with coarse, but much shorter, hair. The yak's tail is similar to that of a horse,[254] but much thicker. A steel comb is used in Mongolia to harvest the down fibre from yaks. The lower sides and belly of the animals are combed soon after the spring moult,[252] to remove the soft fine undercoat, whereas the neck, back and hind quarters are not

9.16 Yak. (Reproduced from Pier Giuseppe Alvigini, *The Fibres Nearest the Sky*, Mondadori Editore Verona, by kind permission of Mr Pier Alvigini at Alvigini S.A.S., 13900 Biella Via Dante, 12 Casella Postale 430, Italy.)

combed.[252] The hair clip varies from 300 to 900 g, at 2 years being from 400 to 500 g, and under 1 year 500–1300 g. For female yaks aged 3 years or more the figures are 200–600 g and for 2 years it is 300–500 g.[253]

Yak fine hair (down) varies in diameter from roughly 15 to 30 μm and that of the coarse guard hair from about 35 to 80 μm,[130,255] the corresponding fibre length values being about 10–60 mm, and 45–160 mm, respectively. The under-hair (down) of a 1-year-old calf has a diameter of 15–17 μm, and is 40–50 mm in length. The corresponding figures for the adult are 18–20 μm and 30–35 mm, respectively.[252]

It is laborious to remove the hair from the yak, first involving thinning the hair as summer approaches and before the yaks are put out to pasture, the soft hair being pulled from the animal by hand.[251] Shears tend to be forbidden, because they can expose the flanks of the animal as winter approaches.[251] The white hair is the most precious. Fine yak hair is mainly produced in China,[256] where the hair is pulled or combed during the spring[252] moult, and the coarse outer 'guard' hair has to be separated from the down hair thereafter. Well de-haired yak fibre can have a mean fibre diameter between 19 and 21 μm,[76] with a CV between 20% and 25%.

In India, *Clipped yak* fibre refers to fibre from the body of the yak obtained by shearing with hand shears or a shearing machine,[253] while *Pulled yak* fibre refers to fibre removed from the yak by pulling out the fibre, with or without the aid of a soap or depilatory solution.[253] *Mixed fibre* refers to a combination of clipped and pulled yak fibre,[253] with 'Lot' meaning the total quality of yak fibre offered for grading, of one colour and type only.[253] Laboratory yield percentage of yak fibres vary from 65% to 80%. According to one study[253] the percentage of foreign matter varies from about 1% to 6%, with length varying from 28 to 37 mm. A maximum of 3% vegetable matter for different grades of yak fibre has been suggested.[253]

Tentative specifications for Indian yak fibres have been proposed as follows:[253]

Colour of fibres: (a) white, (b) brown, (c) black
Texture: (a) extra fine, (b) soft, (c) coarse
Foreign matter: 2%
Moisture percentage: 3%
Length: 10 cm

Yak fibres tend to be oval to circular in shape and generally do not contain a medulla. Yak fibres have a fine scaled structure, the scales not being very prominent, and are typically deeply pigmented, with an average diameter around 20 μm. In one study[257] yak fibre scale height was found to be 0.36 μm on average, varying from about 0.21 to 0.65 μm, for an average fibre diameter of 20.7 μm, the scale frequency averaging 6.9 scales per 100 μm, varying from about 4 to 10 per 100 μm, the figures for scale height and frequency being very similar to those found for cashmere fibres (15.6 μm mean fibre diameter) in the same study.[257]

9.12.2 Fibre processing

Yak hair does not appear to be sorted at the time of harvesting, being packed into large sacks (bags) which are sent to the warehouses or sorting factories where it is hand sorted to reduce the quantity of guard hair present in the down and also to separate the natural colours.[252] Sorters are only able to handle some 10 kg per day. After sorting, the fibre is packed into bales and sent to the processor for converting into yarn.[252]

The approximate proportions of the different natural colours are as follows:[252]

- White ≈ 10%, the most valued due to its dyeing potential
- Fawn ≈ 20%
- Dark grey (blue) ≈ 10%
- Dark brown ≈ 60%

Because fine yak hair is much cheaper than cashmere, it is economical to bleach it,[256] although bleaching tends to impair its handle. Reasons for the deterioration in handle and ways of improving it by, for example, adding a chelating agent, have been discussed.[256] The deterioration in handle was ascribed to cleavage of the disulphide bonds. Work has also been carried out[258] to reduce the diameter of yak fibres by a stretching (i.e. slenderising) treatment.

9.12.3 End-uses

The coarse yak hair (outer coat) is used locally for tents, ropes, huts, blankets and mats,[252] while the fine down fibre is used in apparel fabrics.[252] De-haired fine down fibre can be spun into yarn which is comparable to cashmere,[252] and blended with other animal hair and polyamide (nylon), is used in knitwear.[251] Yak hair is used in the felt industry and that of yak calves in the textile industry for the manufacture of high quality, generally thick, fabrics.[253]

9.13 Other animal hair fibres

9.13.1 Bison hair

The properties of hair shed by the North American bison (*Bison americanus*) have been measured[259] and it was found that the guard hairs were hollow and

ranged in diameter from 21 to 110 μm, while the fine down hair was solid (i.e. unmedullated), ranging in diameter from 12 to 29 μm, with a scale structure similar to that of wool. The moisture regain ranged from 13% to 20%.[259]

9.13.2 Cervelt (soft deer hair)

Cervelt is the soft undercoat (down) from the red deer,[260] having a mean fibre diameter of about 13 μm (CV = 18%). Each animal produces only about 20 g of fine fibre and the total world production is some 1000 kg.[260] The down fibre from about 14 deer is required to produce a sweater and from about 40 deer to produce a man's overcoat.[260] The fibre has a curl rather than crimp. It is used in menswear, women's fashion, knitwear, accessories and furnishings.[260] When the name cervelt is used it is in its pure form, i.e. unblended with other fibres.[260]

9.13.3 Common goat hair

Common goats (*Capra aegagrus hircus*) or milk goats generally have a double coat containing very little, but rather fine (≈ 15 μm), down fibre.

Debnath *et al.*[261] gave the following properties for the goat hair waste available from tanneries in India:

Average fineness (tex): 3.6–5.1
Average length (mm): 20–21
Average tenacity (gf/tex): 13–19.4
Average extension at break (%): 49–88

Paul *et al.*[262] obtained the following results on the hair from Gaddi goats:

Average fibre diameter (μm): 76.7 (range = 46–88)
Average fibre fineness (tex): 4.6 (range = 2.1–7.0)
Average medullation (%): 75
Average fibre length (mm): 101 (range 60–121)
Average fibre tenacity (gf/tex): 13.8 (range = 7.8–18.7)
Average fibre elongation (%): 26.0 (range = 2.4–39.0)

9.13.4 Horse hair

Horse (*Equus Caballus*) hair has been used since prehistoric times to make fishing lines and nets, but over the past 200 years it was also commonly used for upholstery (soft furnishing), the fabric being prized for its durability (up to 100 years).[263] It is also used in linings and handbags. Horse hair fabrics represented one of the most traditional coverings for fine furniture, widely employed by the eighteenth-century masters, like Chippendale and Hepplewhite,[264] but then coming down market in the nineteenth century to become the favourite covering of the parlour sofas of the rising middle class.[264] It can be combined with other natural fibres, such as cotton and silk.

The horse has short (≈ 10–30 mm) and coarse (≈ 80–100 μm) body hair and much longer (≥ 300 mm) mane and tail hair. Horse tail hair generally has an average fibre diameter greater than 140 μm,[265] ranging from about 75 to 280 μm. The mane hair is finer (average ≈ 110 μm) and ranges from about 50 to 150 μm. Bolormaa *et al.*[266] reported that the Mongolian horse tail hair they tested were medullated, and had a mean fibre diameter of around 180 μm, with the diameter increasing from about 130 μm at the tip to about 230 μm at the root. The fat content (according to MNS 379:200 test method) was 2.4% and the moisture content (according to MNS 380:2001 test method) 10.5% for the greasy hair and 16.8% for the scoured hair. The breaking extension ranged between about 43% and 52%, increasing with increasing diameter. Initial breaking modulus ranged from about 2.6 to 4.9 GPa, decreasing with increasing fibre diameter. The cuticle scales of the hair were smooth, with the height (thickness) of the cuticle scale edge lower than that of speciality fibres.[266]

9.13.5 Shatoosh, Shahtoosh, Shah-tus, Shah-tush, Tosh

There is some confusion concerning the precise definitions, origins and sources of fibres or products variously referred to as Shatoosh, Shahtoosh, Shah-tus, Shah-tush and Tosh. Nevertheless, it appears that they are variously applied to fibre and fibre products from wild animals, notably the ibex wild goat and the Tibetan antelope.

The official taxonomy currently lists four wild *Capra* species (*aegagrus, ibex, falconeri and cylindricornis*), although there may be three or more distinct species of Ibex,[267] the only CITES-listed species being the markhor (*Capra falconeri*), with the *Capra ibex* the typical ibex.[236]

Tosh fibres are obtained from an animal (antelope?) belonging to the ibex family,[268] which is found in Tibet and the adjoining areas of the Ladakh region of India. Its fibre is collected from the bark of trees. It is mainly used to manufacture shawls in the Kashmir Valley, which are known as 'ring' or 'shah-tosh'.[268] The following results were obtained on a sample of raw Tosh fibres:

Fine down yield (%): 71
Mean fibre diameter (μm): 11.9 (CV = 3.9%)
Mean fibre length (mm): 42.7 (CV = 6.2%)
Scouring yield (%): 86

The percentage of fine fibres (71%) was reportedly similar to that found for a Pashmina fleece.

The Asiatic ibex or wild goat, Siberian ibex (*Capra ibex sibirica*), also called the Yangir (wild cashmere) mountain goat, is considered to be the wild species most commonly exploited for textile fibres.[267] It lives in the mountainous areas (Himalayas) from India to Mongolia. The fibres are obtained from the skins of dead animals and de-haired manually, fibres from the throat areas being regarded[269] as the most desirable. It is thought 15 000 animals have to be killed to produce 1000 kg of de-haired fibre,[267] i.e. each animal produces around 70 g of de-haired fibre. Tonin *et al.*[267] found a value of 13.6 μm (range 13–15 μm[270]) for the mean fibre diameter of the de-haired Yangir fibre sample they tested, the CV of fibre diameter being 22.6% and coarse fibre (> 30 μm) content 0.1%. They also found the scale density to range from 5/6 to 18/20 scales per 100 μm, and the scale height > 0.8 μm.[270]

According to tradition, and certain reports, Shatoosh (Shah-tus) is the hair from the Tibetan antelope (*Pantholops hodgsoni*), called 'Chiru' in Tibetan,[267] present mainly in the Tibetan region of China. Shahtoosh/shahtus, which means 'king of wools' in Persian or Urdu[271] (reference[52] and CNN Italy, www.cnnitalia.it/1999/STILE/11/04/sciarpa.tibetana, No. 15, 1999, quoted in reference[267]), is one of the finest fibres and used to manufacture 'ring shawls' (they can pass through a wedding ring), each weighing ≈ 120–150 g. The animal is mostly killed to harvest its hair. Hair from at least five animals is necessary to produce a shawl. It was first thought that shah-tus was the shed under-wool of the wild ibex collected during the spring moult, such fibre being used[271] and the shawls referred to as *Shahtoosh*.[272] As much as 30% of ibex guard hair is present in Tosh shawls.[272] According to Ryder[273] the finest fibre in India was named Shah-tush and collected from wild animals, which could include goats, and that it had become illegal to sell shawls made from this fibre because antelopes were being killed to obtain the fibre.

Tibetan antelope is classified by CITES in Appendix I, its highest level of protection, banning all international trade in the species.[267] It was estimated that there were fewer than 75 000 of the antelopes at the beginning of the twenty-first century.

Tonini *et al.*[267] obtained a value of 11.5 μm for the mean fibre diameter of the de-haired Shatoosh they tested, the CV of diameter being 20.1% and coarse fibre (> 30 μm) 0.1%.

The fibres contain 5–6 scales per 100 μm,[274] their natural colour being grey-brown. It takes between 3 and 5 Chiru to produce the 300–600 g of raw fibre required to produce a Shahtoosh shawl,[52] each animal producing about 150 g of fibre. Shamina shawls, made from the fibre of domestic cashmere goats, are sold in India to protect the Chiru.[271] In South Africa a fringed wrap called a 'shu-shu', consisting of blend of Cape summer kid mohair and superfine Cape Merino wool has been produced.[271]

Shah-tush also refers to very fine fibre shed by wild animals, including wild goats[273] (e.g. wild ibex) and the Tibetan antelope, and the name Shahtoosh (Shatoosh) is also employed to describe shawls from the ibex goat.[272] Rollins and Hall[272] found that the fibres from the Tibetan antelope rarely exceeded 10 μm, generally ranging from 7 to 9 μm, while those from the ibex goat were generally 10 μm or coarser, the guard hair from the ibex having a thicker cell wall (i.e. relatively narrower medulla) than that from the Tibetan antelope (i.e. the latter had a relatively wide medulla). The fibre diameters of the guard hair of the Tibetan antelope varied from 50 to 100 μm or even greater, and those of the ibex goat were rarely over 50–60 μm.[272] The finer fibres generally did not have distinct medulla.

For further reading see the references.[267,269,271, and 274–276]

9.13.6 Opossum (possum) fur

Opossum (*Didelphis* genus, also known as possum) fur has received renewed attention in countries such as New Zealand, where it is blended with superfine Merino wool (e.g. 70%) to produce luxury knitwear. It is also used as duvet filling; it taking 15 bush-tailed possums to produce 1 kg of useable fur,[277] the fur being removed from dead animal skins. It was estimated (in 1999) that there were some 70–80 million possums in New Zealand. The fur ranges in colour from almost black to grey, in mean fibre diameter from about 12 to 16 μm and in mean fibre length from about 15 to 25 mm,[277] the latter making it suitable for spinning on the woollen system, although processing on the worsted system also takes place for the long fibres.[277] The fibre need not be scoured, and is blended with wool prior to carding.

Gore and Laing[278] obtained the following results on the fibres (excluding re-growth) from New Zealand possum (*Trichosurus vulpecula*) fur:

Mean fibre diameter (μm): 19.9 (CV = 49%)
Mean fibre length (mm): 26 (CV = 46%)

For re-growth fibres, they found a typical fibre length of 10 mm and diameter of 18.9 μm (CV = 61%).

9.13.7 Pashmina

Pashmina is a Persian word[271] used to describe cashmere in India, Kashmir and Nepal,[279] but is often also used to describe products containing a blend of cashmere and silk (e.g. 70% cashmere/30% silk).[271] The 'Pashmina' goat

(*Capra hircus*) is bred by nomadic herdsman (Tchang Tang shepherds) in the Ladakh region of Northern India, at altitudes of some 4800 m[223].

Pashmina (Pashm, Pashim, Pushima) can be taken as the fine, downy fibre (undercoat) obtained from, or shed by, the Himalayan Pashmina goat and several other species of goats (ordinary and mountain) in Kashmir and other parts of India.[271] It is generally combed out or gathered from the ground or bushes when the warmer season arrives.

The fibre properties, including diameter (12–14 μm)[52] (or 14–16 μm)[271] and length, processing and applications are generally the same as for cashmere.

Pashmina shawls and scarves were originally produced in Kashmir from hand-spun and woven fine cashmere fibre gathered from the ground and bushes where the goats had been feeding.[2]

9.13.8 Karakul

The karakul (*Ovis*) breed of sheep, also known as Persian lamb, originally came from fat-tail sheep in the Bokhara district of Russia, which resembled the karakul sheep in their zoological characteristics, and were found in this region as early as 1600 BC.[280] The word 'Karakkul' originated from the ancient Assyrian word 'Kara-Gjull' which means a flower (black rose)[281] or something else of beauty.[280] For many centuries this breed was found only in Russia, and it was only at the end of the nineteenth century that some of these sheep were exported to Austria, the first karakul show in the world being held in Vienna in 1898.[280] In 1907 the German Governor of South West Africa (now Namibia) imported 10 ewes and 2 rams from Austria and the country became the largest supplier of karakul pelts in the Western world.[280] The karakul pelts were the main purpose of farming with the breed, the wool being considered as only a by-product. The adult animals were normally shorn twice a year producing about 2–3 kg of wool annually,[282] the wool having a clean yield of some 65%. The colour of the natural pigmented karakul fibre varies from white to grey, brown and black, the pigment being fast to water if initially scoured under neutral or acid conditions.[280]

In South Africa, karakul wool was sorted into 54 different types prior to sale. Production was some 7.1 million kg in the 1978/79 season[281] and in 1996 some 278 000 kg of karakul wool was sold in South Africa and Namibia.[282] The karakul wool staples consist of a short fine under-growth and coarse long fibres, the latter having a diameter up to 70 μm, whereas the under-growth can be as fine as 20 μm. The mean fibre diameter of karakul wool ranges from about 30 to 40 μm, with an overall average (typical) value of about 35 μm (**CV ≈ 35%**).

The length of karakul wool varies from about 20 to 150 mm (typically 50–100 mm), the length being important in determining the type into which it is sorted. The shorter, free from vegetable matter, karakul wool is processed on the woollen system and the longer types on the worsted system. Karakul processed on the woollen system, often in blends with other wool, were mainly used in carpets, blankets, upholstery and curtaining, but also in protective clothing[280] and mulch fabrics.

Karakul types, 65 mm and longer, lend themselves to combing, with the noils produced being used in the woollen system, needle punching (e.g. protective clothing, insulation, carpeting) or in industrial felts. The good felting properties of karakul have been ascribed to the presence of the fine undercoat fibres with the coarser outer coat fibres. Yarns produced on the worsted system were mainly (some 80%) used in interlinings. The processing of karakul on the woollen, worsted and semi-worsted systems as well as the manufacturing of products have been investigated by various researchers.[283–290]

The natural pigmentation (colours) of karakul limited its application, although the lighter types of karakul wool (e.g. white, steel, silver and fawn) could be dyed to almost any colour, the most suitable dyes being reactives and chrome. Because of the limitations resulting from its natural colours, considerable work was carried out on the cost-effective bleaching of Karakul[291–293] with the minimum amount of damage. A number of processes were developed, mordant bleaching in particular,[292] and ferrous mordanting prior to peroxide bleaching.

China is the largest producer of karakul today. The virtual demise of the karakul pelt industry, largely resulting from pressures by animal lovers and environmentalists, drastically reduced the production of karakul wool in South Africa and Namibia. Current production is only some 250 000 kg clean wool in Namibia.

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Bioengineered natural textile fibres

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Abstract: Cellulose is a biological renewable resource whose biomass can be used in the production of paper, textiles, biofuels and chemical compounds. Cellulose rarely occurs in its pure form and is usually found in the form of lignocellulosic biomass. Recently bacterial cellulose (BC) of microbiological origin, synthesised by microorganisms, has also been developed. The transformation of lignocellulosic biomass is not a simple task and typically involves two stages: first, pre-treatment, and second, hydrolysis of the pre-treated cellulose and hemicellulose to form simple sugars (saccharification). Further understanding of the complex mechanisms that allow termites to decompose cellulose-based material of this type may make it possible to apply similar solutions on an industrial scale. One potential future direction in this area is the development of modified natural fibres and biomaterials such as biosilk and fibres based on polylactic acid (PLA) and polyhydroxybutyric acid (PHB), but this is very much in the early stages at present.

Key words: lignocellulosic biomass, bacterial cellulose, lignocellulose pre-treatment, termite symbiotic system, modified natural fibres.

10.1 Introduction

Cellulose is a commonly occurring renewable biological resource, used to manufacture fibers, paper, polymers, lacquers, photographic films and thermal insulation materials as well as biofuels such as ethanol. Cellulose $(C_6H_{10}O_5)_n$ is a non-branched polysaccharide biopolymer, composed of anywhere between a few to several hundred thousand glucose molecules linked by β-1,4-glycoside bonds; it is the principal constituent of plant cell walls. It is insoluble in water, acids and alkalis. In the presence of oxygen, cellulose is decomposed by many fungal species as well as cellulosic bacteria, resulting in water and carbon dioxide production. In anaerobic conditions, cellulose is broken down to methane by bacteria of the *Clostridium* genus found in the rumen of ruminants, while bacteria of the *Cellulomonas* genus hydrolyse cellulose to shorter chains, including glucose. However, due to the absence of cellulose-decomposing bacteria in their gastrointestinal tracts, mammals are unable to use this compound as a source of energy, and can only use it as a bulk food component.