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Navajo-Churro Wool Fiber Survey with References to Common Northern California Breeds

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Navajo-Churro Wool Fiber Survey with References to Common Northern California Breeds

By

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THESIS

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DAVIS

Approved:

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LIST OF ABBREVIATIONS

Abbreviation	**Meaning**
BLCK	Black Navajo-Churro Fleece
BLND	Blonde Navajo-Churro Fleece
BRN	Brown Navajo-Churro Fleece
CIE	International Commission on Illumination (*French abbrev.)*
DOR-F	Dorset Female Fleece
DOR-L	Dorset Lamb Fleece
DOR-M	Dorset Male Fleece
GRY	Grey Navajo-Churro Fleece
HAM-L	Hampshire Lamb Fleece
HAM-SUF-M	Hampshire-Suffolk Crossbred Male Fleece
MULT	Multicolored Navajo-Churro Fleece
SEM	Scanning Electron Microscopy
SRSBL	Southwestern Range and Sheep Breeding Laboratory
SUF-L	Suffolk Lamb Fleece
SUF-HAM-M	Suffolk-Hampshire Crossbred Male Fleece
UC Davis/UCD	University of California, Davis

ABSTRACT

Navajo-Churro sheep are sacred to the Navajo people and have a double-coated fleece that weavers shear, card, and spin into yarns to create exquisite, woven Navajo textiles. The only previous Navajo-Churro wool research from 1942 focused on fiber types within a fleece and their effect on textile qualities. Physical characteristics of guard and undercoat fibers were documented, but there is no complete fiber data set for Navajo-Churro wool. A Navajo-Churro fiber survey was created by measuring physical characteristics, including dimensions, colorimetric parameters, tensile properties, morphological features, and surface scale structure of guard hairs and undercoats fibers. In addition, UC Davis Dorset and Hampshire/Suffolk crossbred sheep fibers were measured to compare Navajo-Churro fiber quality to common northern California breeds. Navajo-Churro fleeces display long staples protruding from a bundle of short fibers. Meat breed UC Davis fleeces are a bundle of short fibers crimped together. Guard hairs are thicker and longer (majority 50 – 60 µm, 185 – 274 mm) than undercoat (28.3 – 32.8 µm, 99.2 – 185 mm) and UC Davis fibers (25.9 – 40.1 µm, 41.3 – 123 mm). CIE L*ab color parameters range within all individual fleeces. Variations in modulus, strength, and strain measurements among undercoat (1515 – 1955 MPa, 147 – 188 MPa, 63.8 – 73.5%) and UC Davis fibers (1202 – 2224 MPa, 136 – 202 MPa, 55.8 – 74.7%) are statistically analyzed. Guard hairs have no crimp and polygonal/elongated scale patterns. Undercoat and UC Davis fibers exhibit crimp and patterns of wrap-around and angled scales. This study’s data may be useful to breeders as a standard for Navajo-Churro wool quality parameters. Undercoat and UC Davis fibers are both medium type in fineness, so sheared UC Davis meat breed wool has potential for textile applications, as undercoat fibers are ideal for Navajo weavers’ use.

CHAPTER 1: REVIEW OF LITERATURE AND RATIONALE

Wool

Wool is the most widely used animal fiber in textiles. Since the ancient era, when writing, recording, and documenting human history began, wool has been used in the apparel and textile industry (Allafi, et al., 2022). Wool's sustainability, biodegradability, low carbon footprint, and energy efficiency in production, use, and end-of-life stages are ecological benefits of working with the shorn and processed fleeces of sheep in textile manufacturing (Kuffner, 2012). Currently, the purpose for raising sheep is primarily for meat production (lamb and mutton) or dual purposes (wool and meat production), breeding, and, less frequently, for milk. In majority, global wool production is currently best suited for interior textiles, as wool from dual-purpose sheep can be utilized in apparel but is not desirable like finer wools (IWTO, 2022). World wool production continues to increase, and new technical applications of the fiber are investigated. Using wool in construction for insulation (thermal and sound), in environmental health research for sorption of air pollutants, and in fertilizer applications are only a few topics of current wool research (Allafi, et al., 2022). As the global population of sheep continues to grow, wool will remain an abundant resource in modern society with great fiber potential to be explored in the textile industry or beyond.

History

The first Merino sheep were bred in fourteenth century Spain (Allafi, et al., 2022). From the late fifteenth to nineteenth century, European colonization of the southern hemisphere popularized wool production. Sheep numbers grew for pastoral production, and wool cutting, shearing, and ancient era China, Babylon, and Egypt felting tools and techniques were updated and refined (Allafi et al., 2022; Simpson & Crawshaw, 2002). Much of the wool harvested from colonized countries was imported back to Western Europe from the late 1800s to 1960s for manufacturing after the Industrial Revolution's influence catalyzed a transition from hands-on methods to machine operated manufacturing (Simpson & Crawshaw, 2002). Said wool manufacturing processes have since declined as competition with synthetic fibers has diminished natural fiber production. Still, sheep can be found in all countries of the world, and wool production at large scales remains in select countries. As of 2021, the major wool producing countries are Australia, New Zealand, and China (FAO, 2023).

Australia accounts for the highest percentage of wool production per country, mainly fine wools from Merino sheep, and accounts for about half of the worldwide wool on the open market (Simpson & Crawshaw, 2002). Wool from New Zealand, also a large contributor to worldwide wool production, is crossbreed in majority (Simpson & Crawshaw, 2002). According to the United Nations Statistics Division (UNSD), Australia and New Zealand sheep populations were 63.5 million and 26 million in 2020, down by nearly half since 2000. The reported greasy wool production in Australia and New Zealand in 2020 was 283,794 tons and 151,192 tons, compared to 671,000 and 257,200 tons in 2000 (UNSD, 2023). In 2020, the clean wool yield in Australia was about 75% of the greasy wool produced (221,356 tons), and 99,981 tons of clean wool (about 65% of greasy wool) were produced in New Zealand the same year (IWTO, 2022).

In the United States, the National Agricultural Statistics Service (NASS) sheep and lamb inventory reported 6.35 million head in 2003, but in 2023, the number has dropped to 5.02 million (USDA, 2023). In the last 20 years, shorn wool production in the United States has decreased by nearly fifty percent from 41.2 million to 22.2 million pounds (USDA, 2023). Though not as large a wool industry as Australia and New Zealand, the United States sheep and wool statistics are relevant to this fiber survey, specifically in California. Despite steadily decreasing every year, California remains the leading state in shorn wool production at 2.23 million pounds followed closely by Wyoming, Colorado, and Utah (USDA, 2023). California has the highest sheep and lamb population in the United States, behind Texas, with 550,000 head (USDA, 2023).

Like all natural fibers, wool is not a homogenous product, and depending on the environments, breeds, diets, genders, and ages of the sheep, the physical and performative properties of wool fibers can differ (Holman, 2012; Simpson & Crawshaw, 2002). Physical and performative properties determine the quality, price, and intended use of wool fibers. From the standpoints of producers and consumers, fiber diameter and staple strength are commonly understood to be the first and second most important fiber properties to consider when determining quality and price (Holman, 2012). In 2022, the average price paid for sheep and lamb wool in the United States was $1.53 per pound (USDA, 2023). Currently, wool costs increase year to year because of shrinking sheep and lamb populations across the country.

Fiber structure and morphology

Wool is a natural protein fiber that comes from the hair of sheep (*Ovis aries*). The term "wool" has also been used to describe the hair of other animals like goats or alpacas (Simpson & Crawshaw, 2002). Wool fiber's follicle is a living cell beneath the sheep's skin and produces the fiber shaft which is slightly elliptic in cross-sectional shape (Kuffner, 2012). The fiber shaft contains α-helical intermediate filaments of α-keratin, a fibrous protein, and is described as a 'cornified' multicellular tissue, commonly known as wool (Kuffner, 2012). The external cuticle cells and internal cortical cells compose the wool fiber structure and are held together by the cell membrane complex (CMC) (Allafi, et al., 2022).

All wool fibers have a cortex consisting of ortho-cortical (60-90%) and para-cortical (10-40%) cells in side-by-side or parallel arrangement along the fiber, causing crimp as they expand with moisture and twist together (Kuffner, 2012; Simpson & Crawshaw, 2002). In coarser wools, such as from Navajo-Churro sheep highlighted in this research, the ortho- and para-cortex cells are arranged as concentric cylinders, with the ortho-cortex cells located in the core (Kuffner, 2012). The natural fiber's cuticle cells are visible as high scales and are arranged in unique, irregularly distributed, overlapping patterns, pointing from the fiber's root (follicle) to its tip (Allafi, et al., 2022; Malik, et al., 2021; Shakyawar, et al., 2013). The fiber's scales are the structure's primary form of protection (Kuffner, 2012). Wool scales are only attached to the fiber at their base (Mahgoub, et al., 2010). Wool felting is caused by the interlocking of scales, a natural property unique only to wool fibers, so densely structured woolen fabrics such as blankets and overcoat materials may be produced by felting (Allafi, et al., 2022; Kuffner, 2012).

Coarse fibers often have a medulla or hollow space made of air-filled cells in the cortex (Kuffner, 2012). When medullation occurs in fibers, they do not spin or dye as easily as normal, unmedullated wool fibers (Macpherson, 2012). Short, opaque, brittle, medullated fibers are often found loosely throughout the fleece of some sheep after growing for a limited time and breaking off from the follicle (Macpherson, 2012). Known as kemp fibers, they are extremely coarse and unsuitable for wool processing, so they are removed from fleeces (Macpherson, 2012).

Fiber diameter and length

Fineness is the most notable fiber quality affecting the price of wool. Fiber diameter and variations of it determines up to 80% of raw wool's value (Macpherson, 2012; Mathis, 2002). Across most breeds' fleeces, fiber diameters range because fiber diameter is not uniform within a representative wool sample. The Australian Merino breed has fiber diameters around 11 µm varying 8 – 9 µm in a fleece, but carpet sheep breeds found in the northern hemisphere with coarse hairs have fiber diameters around 100 µm that can range from 10 – 70 µm in a fleece (Holman, 2011; Kuffner, 2012; Macpherson, 2012). On the body of the sheep, fiber diameters tend to be finer from neck and belly regions and coarser from back to rear regions (Macpherson, 2012). Single wool fibers vary in diameter along their lengths as much as diameters vary between individual fibers, staples, and fleeces (Macpherson, 2012). This variance is a result of diameter deviations during wool growth and development (Holman, 2012). Fiber diameter can be accurately and rapidly measured using laser scanning (LASERSCAN), optical microscopy (Optical Fibre Diameter Analysis, OFDA), or AIRFLOW, the least popular method of the three which uses gravitational variations between fibers to determine fiber diameter (Holman, 2012).

Classing and grading

Sheep breeding began in Australia during the late eighteenth century, but the Australian Wool Cooperation (AWC) implemented more effective, streamlined methods of handling, packing, transporting, and selling wool to remain competitive with synthetic fibers in the mid-1900s (Allafi, et al., 2022; Simpson & Crawshaw, 2002). Similarly, New Zealand also used its New Zealand Wool Board (NZWB) and research at the Wool Research Organization of New Zealand (WRONZ) to develop wool sampling, testing, and equipment standards (Simpson & Crawshaw, 2002). By the 1990s, testing and marketing procedures had been implemented in Australia, New Zealand, and South Africa (Simpson & Crawshaw, 2002). The proposed new standards were discussed via the International Wool Textile Organization (IWTO), the global authority for wool standards in the textile industry, and product approval according to the

International Wool Secretariat (IWS) Standards was developed and implemented (Simpson & Crawshaw, 2002).

Classing wool factors include sheep breed, fineness, length, strength, yield, color, and style in sorting (Macpherson, 2012; Mathis, 2002). Fleeces are sorted according to these classing factors into categories of fine, medium, long and carpet (coarse) or mixed wool breeds (Mathis, 2002; Sitotaw, et al., 2019). Classing ensures that wool fleeces have uniform processing capabilities and are salable to wool processors (Macpherson, 2012). When grading wool, only individual fiber fineness (diameter) is considered. A grade is given to an entire fleece to represent average fineness, so the fleece may be placed into grade lines with other fleeces of similar fineness (Mathis, 2002). Typically, in commercial production, fleeces with wool fibers averaging less than 30 µm in diameter produce the most comfortable garments (Holman, 2012).

Of the three wool grading systems used in the United States, The Micron System currently sets the worldwide standard for grading wools by fiber diameter range, measured in micrometers (Mathis, 2002). The least technical system, the American Blood Grade System, initially referred to the level of Merino genetics present in wool to grade but currently groups fibers diameter into broad groups including Fine, 1/2 Blood, 3/8 Blood, etc. (Mathis, 2002). The blood system is outdated and has not been recognized as an official classing system in the United States since 1955 (LeValley, 2004). The final wool grading system present in the United States is the Spinning Count System and is more technical than the latter system, yet less technical than the Micron System. The Spinning Count System uses a narrower range of fiber diameters to identify fine wools and divide them into 14 grades (LeValley, 2004). The number of “hanks” of yarn (560 yards = 1 hank) produced from a pound of clean wool are measured, and wools are grouped by “hanks” as 80s, 70s, 60s, etc. (Mathis, 2002). Once graded, the market value of wool is determined after considering the grade variation (standard deviation) of an amount of wool sample (Mathis, 2002).

Fiber properties

Certain properties of wool make it stand-out as a unique fiber used in textiles. Wool's fiber properties have been recognized and implemented into a range of utilizations in everyday life. Wool's tensile properties are notable from other natural fibers because wool is resilient and able to recover from strains of up to 30% (Kuffner, 2012). When measuring tensile strength, the force under constant strain rate or constant load to break a fiber is normalized by cross-sectional area, considered cylindrical for wool in tensile measurement calculations (Holman, 2012). In terms of commercial desirability, long wools are in high demand because their yarns are stronger than broken or short fiber yarns (Holman, 2012). From thin outerwear garments and socks to thick, robust textiles like carpeting, wool's high tensile strength and elasticity ensure the production of durable textiles (Allafi, et al., 2022; Mahgoub, et al., 2010).

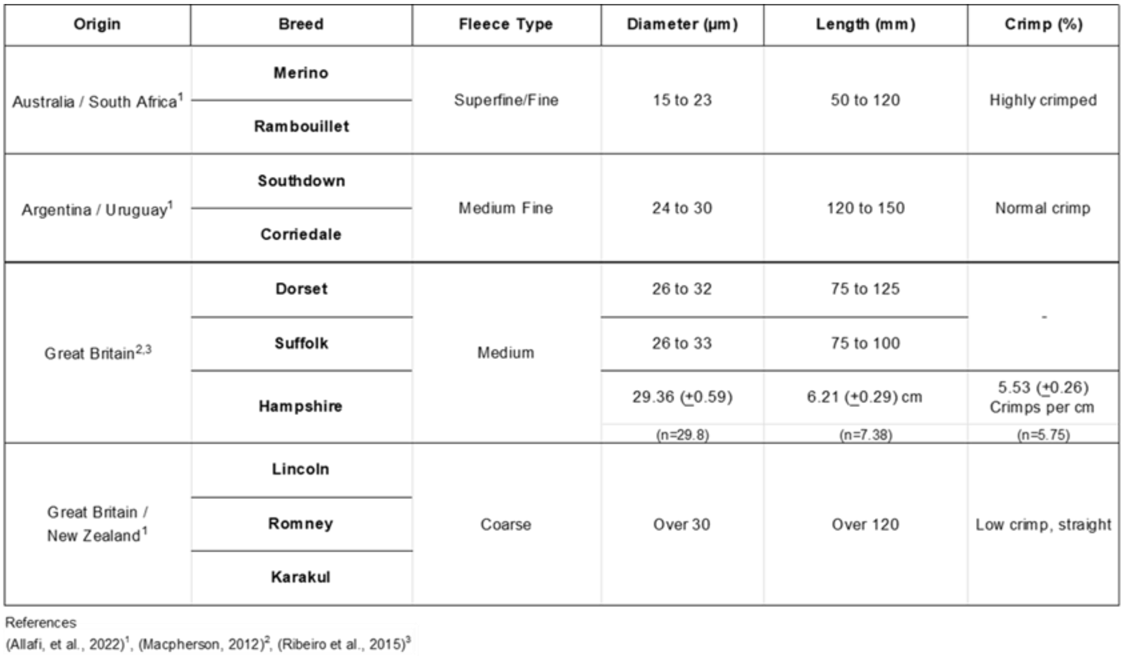
Another popular property of wool is its excellence in thermal insulation. Wool's hygroscopicity allows adsorption of moisture or liquid up to thirty percent of its weight without being wet to the touch (Allafi, et al., 2022). A high level of heat is generated from the sorption of moisture, especially from water vapor in high humidity environments (Simpson & Crawshaw, 2002). Liquid is adsorbed at a rate slower than vapor, so liquid drops appear repelled on the surface of wool (Allafi et al., 2022). Due to slower sorption of liquids in low humidity situations, wet wool will also dry slowly (Allafi et al., 2022). As a result of its hydroscopic properties and high nitrogen contents, wool has another beneficial quality of not burning quickly, making it ideal for application in flame protective textiles (Allafi et al., 2022). Also notable in analyzing wool is the raw color measurements of a fleece because the varying hues and shades determine the process of dyeing wool for textile creation (Kicinska-Jakubowska, et al., 2022).

Commercial Sheep Breeds

As previously mentioned, sheep may be raised for meat, wool, breeding, or for dual purposes, depending on the breeder. Common commercial breeds range in qualities of their produced wools (Table 1). Breeds with fine wools used for knitted and woven articles of clothing include Merino and Rambouillet (French Merino) sheep (Allafi, et al., 2022; Macpherson, 2012). Other breeds like Southdown and Corriedale (bred from Merino) are used for more robust and durable articles of clothing because their fibers are medium in fineness (Allafi, et al., 2022; Macpherson, 2012). Often known as carpet breeds, Lincoln (British Long Wool), Romney, and Karakul sheep produce wool used in interior textiles like carpets or furniture coverings (Allafi, et al., 2022; Macpherson, 2012). Alternately, some sheep are bred, in addition to fleece production, for mutton and prime lamb production. These sheep are referred to as dual-purpose or double-purpose breeds (Macpherson, 2012; Ribeiro, et al., 2015). Various Merino crossbreeds have been developed to produce sheep like the Corriedale that supply both wool and meat (Macpherson, 2012). Certain breeds exist solely for meat production and are raised and kept as breeding sheep. Notorious for fine grain meat, quick growth of lambs, and high dressing percentage (the ratio of carcass weight to live animal weight), meat breeds are mated to ewes that have been crossbred with breeds like British Long Wool and Merino sheep (Macpherson, 2012).

Suffolk and Dorset sheep are known as British Short Hair breeds and were developed to create a terminal crossbreeding sire breed for repeated mating with British Long Wool or Merino ewes, solely to produce prime lamb for sale at market (Macpherson, 2012). Though their hairs are relatively fine and fall between Merino and carpet breeds in fiber quality, Suffolk and Dorset fleece is harsh to handle and appears chalky because it lacks in luster (Macpherson, 2012). As mutton type rams, these sire breeds allow commercial producers to breed their flocks during an increase in meat price to sell lambs without compromising any wool-producing capacity of their sheep (Cloete, et al., 2003). Similar meat ram breeds like Hampshire sheep are often used in crossbreeding for lamb and mutton production to improve the income of producers raising fine wool sheep (Ribeiro, et al., 2015). The Suffolk, Dorset, and Hampshire breeds are ideal to raise in the northern California climate, as they are equipped to handle weather extremes from dry seasons to periods of heavy rainfall (Macpherson, 2012). These three breeds and their crossbred sheep are raised at the University of California, Davis to be sold for meat and breeding. The sheep are sheared roughly twice a year to prevent their fleeces from matting, but their sheared wool does not have a specific second use.

Table 1. Reference Breeds



Origin	Breed	Fleece Type	Diameter (µm)	Length (mm)	Crimp (%)
Australia / South Africa[1]	**Merino**	Superfine/Fine	15 to 23	50 to 120	Highly crimped
	Rambouillet				
Argentina / Uruguay[1]	**Southdown**	Medium Fine	24 to 30	120 to 150	Normal crimp
	Corriedale				
Great Britain[2,3]	**Dorset**	Medium	26 to 32	75 to 125	-
	Suffolk		26 to 33	75 to 100	
	Hampshire		29.36 (±0.59)	6.21 (±0.29) cm	5.53 (±0.26) Crimps per cm
			(n=29.8)	(n=7.38)	(n=5.75)
Great Britain / New Zealand[1]	**Lincoln**	Coarse	Over 30	Over 120	Low crimp, straight
	Romney				
	Karakul				

References
(Allafi, et al., 2022)[1], (Macpherson, 2012)[2], (Ribeiro et al., 2015)[3]

Navajo-Churro Sheep

History

Navajo-Churro sheep were introduced by Spanish missionaries and explorers to the southwestern United States in the 1600s and are the only recognized domesticated breed of sheep in the Americas (Halberstadt, 2003; Maiwashe, 2004). Once adopted by the Navajo, Navajo-Churro sheep became the people's first sheep and signified the economic independence of individual owners (Strawn, 2007). The resiliency of Navajo-Churros, due to their origin in the deserts of southern Spain, allowed them to survive the arid climates of Navajo reservations (Wilson, 2006). The connection between the Navajo and the sheep deepened as the sheep provided them food, clothing from weaving their wool, and, most notably, stability (Strawn, 2007). Their incredible ability to endure harsh seasons and disease in the southwestern United States and their fecundity have ensured the Navajo-Churro remain an active component of Navajo tradition, despite their tumultuous history (Strawn, 2007).

To subdue and remove Navajo from their homelands as westward expansion progressed, the federal government nearly destroyed the Navajo-Churro breed in 1863 (Strawn, 2005). Due to the low Navajo-Churro numbers, Navajo weavers transitioned from producing intricate, Navajo-Churro wool tribal blankets for their own use to rugs composed of commercial fibers and yarns for trade and economic growth (Grandstaff, 1942). As the weaving industry grew, old weaving materials were replaced by newer materials like cheap, cotton twine plus brightly colored blends of fine wools from American-raised sheep (Grandstaff, 1942). Many Navajo weavers found it more cost- and time-effective to use the other natural fiber and wool yarn sources for making textiles, as opposed to hand processing their Navajo-Churro sheep wool (Hedlund, 2003). As a result, colors in textiles started shifting from natural to brighter, introducing reds and greens, and aniline dyes grew in popularity as they could be purchased ready-to-use and had greater fastness than native, natural colorants (Grandstaff, 1942).

Despite the US's involvement in disrupting Navajo life, the "Diné" (a Navajo term referring to themselves as "the people") continued raising Navajo-Churros and weaving with their wool in the early 1900s (Maiwashe, 2004; Strawn, 2007). To assist Navajo economic security by increasing sheep production and crossbreeding Navajo-Churro with Rambouillet rams to improve their fleece uniformity for carpet wool production, the Bureau of Indian Affairs and Bureau of Animal Industry set up a joint laboratory in 1935 (Blunn, 1940; Grandstaff, 1942)). During crossbreeding, a small number of "old-type" Navajo-Churro sheep were kept pure breed to supply wool for weaving (Blunn, 1940). Although, because of the instigated crossbreeding with other sheep used for commercial wool production, the original, pastoral Navajo-Churro sheep became and remain endangered (Halberstadt, 2003; Strawn, 2005). By the early twentieth century, true Navajo-Churro wool composed only about 5% of wool produced on reservations (Grandstaff, 1942). However, in 1977 the Navajo Sheep Project was created to support pure bred Navajo-Churro preservation and growth, and the Navajo-Churro Sheep Association formed in 1986 and used prior Navajo-Churro research data to create ideal breed criteria requirements to register over 4,500 sheep and counting (Navajo-Churro Sheep Association, 2010).

Prior Navajo-Churro Research

Research by animal scientists on the suitability of spinning and weaving with Navajo-Churro wool was conducted by the Southwestern Range and Sheep Breeding Laboratory (SRSBL) beginning in 1936 and continuing into the late 1960s (Strawn, 2004). Wool samples were selected from wool produced by a flock of Navajo-Churro sheep maintained and bred at the

SRSBL. After laboratory analysis, each wool sample was woven into small rugs by an employed Navajo weaver to assess the wool’s weaving characteristics (Grandstaff, 1942). Other analysis was conducted on different qualities of Navajo blankets and rugs obtained from museums and private collections. The textiles were woven between 1800 and 1915 of Navajo-Churro wool and other adopted wools of varying characteristics (Grandstaff, 1942). After an extensive study of the physical characteristics of sheered wool and wool samples from Navajo textiles, the SRSBL concluded that Navajo-Churro fleece is well suited for carding, spinning, and weaving. Results and conclusions considering the fineness, length, diameter distribution, crimp, density, and shrinkage of Navajo-Churro wool were published through the US Department of Agriculture (Grandstaff, 1942).

Flock wool physical characteristics

Initially, four lots (groups) of wool (1.5 to 2 pounds each) with differing levels of fineness were selected from the SRSBL Navajo-Churro flock (Grandstaff, 1942). Lot 1 of wool had the coarsest fibers with a mean diameter of 34.40 to 36.19 µm (U.S. grade 44’s) (Grandstaff, 1942; LeValley, 2004). Lot 2 of wool had a mean diameter of 31.00 to 32.69 µm (U.S. grade 48’s) (Grandstaff, 1942; LeValley, 2004). Looking at lots 3 and 4, the mean diameters were from 29.30 to 30.99 µm (U.S. grade 50’s) and 26.40 to 27.84 µm (U.S. grade 56’s), respectively (Grandstaff, 1942; LeValley, 2004). Comparing the small rugs woven from Lot 1 and Lot 2, both rugs were coarse and fuzzy in appearance, indicating that the lots were not ideal for hand carding with their long, coarse, straight fibers (Grandstaff, 1942). Both lots 3 and 4 were determined to be the best for carding, spinning, and weaving because the rugs produced were soft and uniform due to high levels of undercoat fibers (Granstaff,1942).

Lot 3 and lot 4 wools were best suited for carding, spinning, and weaving. Therefore, the physical characteristics and effect of variations on fiber-diameter distribution of 5 Navajo-Churro lots of average diameters like those of lot 3 and 4, ranging from 26.40 to 27.84 µm (U.S. grade 56s), were determined (Grandstaff, 1942; LeValley, 2004). Fiber diameters were measured after carding, and the wool was then spun for further sample collection and cross section analysis (Grandstaff, 1942). Kemp and other medullated fibers within the fleece were identified during cross section analysis to factor in their quantity's effect on fleece quality. Samples were separated into long outercoat hairs and thin undercoat fibers for length measurement (Grandstaff, 1942). To measure percentage of crimp, fibers were selected from clean wool, suspended with tweezers, and measured at a natural crimp condition and a sufficient tension condition to calculate the difference in percentage of length (Grandstaff, 1942).

The wool collected and analyzed from the SRSBL's Navajo-Churro flock is considered medium-fine in fineness (Table 2a). The lots of wool with most fibers below 40 µm in diameter and little to no kemp is the most satisfactory wool for weaving (Grandstaff, 1942). The ideal length of outercoat hairs averaged 173 mm and undercoat fibers averaged 109 mm in length (n=100) (Grandstaff, 1942). Ideal Navajo-Churro undercoat fibers, like those in lot 3, averaged 15.3 percent crimp and outercoat hairs averaged 9.4 percent crimp (n=200) (Grandstaff, 1942). The data concluded that no constant relationship exists between wool fineness and fiber-diameter dispersion, a percentage measurement of the various fiber diameters occurring throughout a fleece (Grandstaff, 1942).

Analyses of historical Navajo blankets and rugs

The second portion of Grandstaff's study investigated how textile quality was affected by fiber characteristics like fineness, fiber-diameter distribution, percentage of coarse and kemp fibers, and medullation in fibers from yarns selected from several locations on textiles. Considering design, dyes/colors, workmanship quality, intended purpose, age, and manufactured yarn use, 162 well-preserved Navajo blankets and rugs from four chronological periods over a century were sampled from (Grandstaff, 1942).

Five distinct qualities of wool were found in the textiles from the four time periods. The highest quality wool had an average fineness of 26.9 (±0.23) µm which described most wool samples from the second period of textiles (1850-1870), acquired through Navajo and US Army trading (Grandstaff, 1942). Over half of the rugs and blankets from all periods contained low percentages of outercoat hairs, as hand separation of those coarse fibers was a practice sometimes followed by Navajo weavers (Grandstaff, 1942). The coarsest wool samples came from the first period (1800-1850) containing garments from Navajo burials explored during archaeological research (Grandstaff, 1942). Most textiles from periods two and three (1870-1890) were made from the highest quality wool containing mostly undercoat fibers (Grandstaff, 1942). Factors signifying low quality rugs, associated with textiles from the fourth period (1890-1915), are a visible separation of undercoat and outercoat hairs and a high percentage of coarse fibers, kemp, and fibers with medullation found in the textiles (Grandstaff, 1942). No significant difference in mean diameters of fibers from all four periods were found, i.e., between the second and third, the second and fourth, and the third and fourth periods (Table 2a) (Grandstaff, 1942).

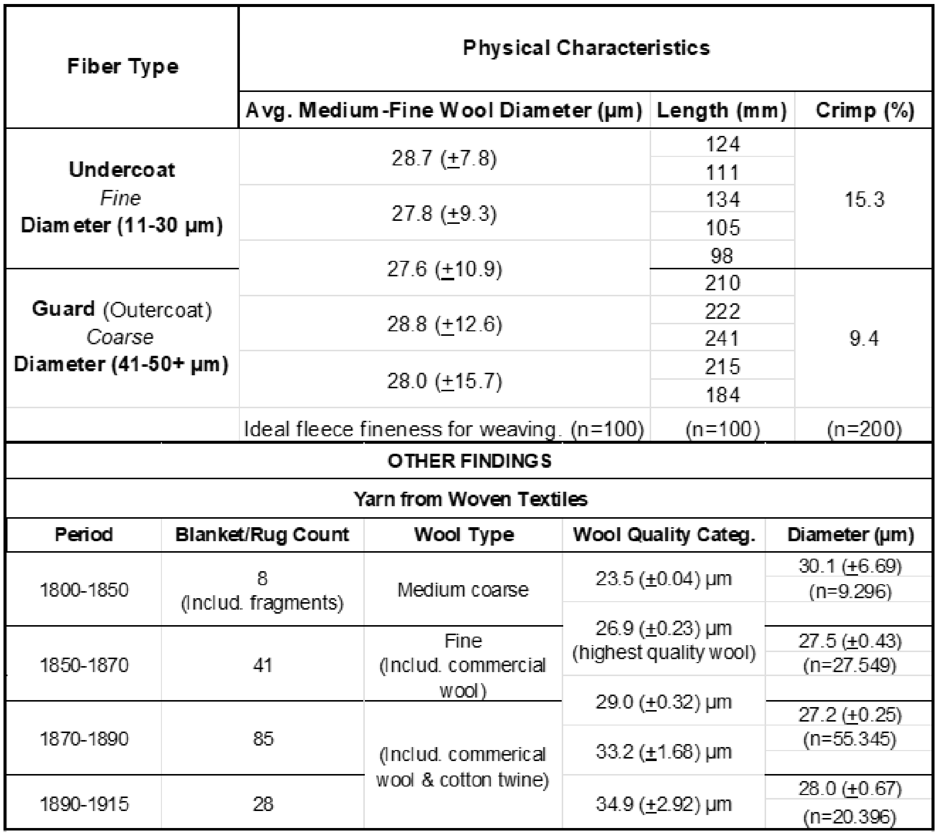
It was determined that overall fiber fineness, considering distribution of fiber types within a fleece, is worthwhile in determining the quality of Navajo-Churro wool. Medullated fibers within a sample or fleece were not significant in identifying wool quality (Grandstaff, 1942). The same relationship of fine wool producing soft, uniform rugs and coarse wool producing stiff, scratchy rugs in the first portion of Grandstaff's research was found for the newest and oldest period specimens (Grandstaff, 1942).

Improved breed physical characteristics

A small side project during research explored the results of crossbreeding Navajo-Churro with improved breeds. Navajo-Churro's double-coat fleece of long and coarse outer fibers in contrast with short and fine inner fibers labeled Navajo-Churro as an "unimproved" breed (Strawn, 2004; 2007). Rambouillet wool was measured to mimic the wool from crossbred Navajo-Churros during historic breed improvement efforts (Grandstaff, 1942). Crossbreeding studies considered the fineness, high crimp, shrinkage, and lumpy rug produced from the lot of Rambouillet wool and deemed it best suited for power machinery weaving and not ideal for Navajo hand-carding, spinning, and weaving (Grandstaff, 1942).

Overall, Grandstaff concluded the Navajo-Churro's non-greasy, non-dense, open fleece for easy fiber separation and the wool's low percentage of crimp in its fibers make Navajo-Churro wool best-suited for handling, carding, spinning on a Navajo spindle (a supported spindle without weight-aided spinning), and weaving (Grandstaff, 1942). More specifically, Navajo-Churro wool of medium fineness is best suited for Navajo weavers because of its desirable length of 100 to 200 mm, high proportion of fine, undercoat fibers to coarse, outercoat hairs, and its relative freedom from kemp fibers (Grandstaff, 1942). This data will be compared to the physical characteristics of Navajo-Churro wool collected in this fiber survey. (Table 2a).

Table 2a. Navajo-Churro Fleece Characteristics (Grandstaff, 1942)



Fiber Type	Physical Characteristics		
	Avg. Medium-Fine Wool Diameter (µm)	Length (mm)	Crimp (%)
Undercoat *Fine* **Diameter (11-30 µm)**	28.7 (±7.8)	124	15.3
		111	
	27.8 (±9.3)	134	
		105	
	27.6 (±10.9)	98	
Guard (Outercoat) *Coarse* **Diameter (41-50+ µm)**		210	9.4
	28.8 (±12.6)	222	
		241	
	28.0 (±15.7)	215	
		184	
	Ideal fleece fineness for weaving. (n=100)	(n=100)	(n=200)

OTHER FINDINGS

Yarn from Woven Textiles

Period	Blanket/Rug Count	Wool Type	Wool Quality Categ.	Diameter (µm)
1800-1850	8 (Includ. fragments)	Medium coarse	23.5 (±0.04) µm	30.1 (±6.69) (n=9.296)
1850-1870	41	Fine (Includ. commercial wool)	26.9 (±0.23) µm (highest quality wool)	27.5 (±0.43) (n=27.549)
1870-1890	85	(Includ. commerical wool & cotton twine)	29.0 (±0.32) µm 33.2 (±1.68) µm	27.2 (±0.25) (n=55.345)
1890-1915	28		34.9 (±2.92) µm	28.0 (±0.67) (n=20.396)

Relevant fiber surveys

Notable research has been conducted to collect wool fiber information from coarse sheep breeds and improved crossbreeds native to different countries, some comparable to the Navajo-Churro breed. These breeds include crossbred Arkharmerino with local Ghezel sheep and native Naeini sheep from Iran, select native Polish sheep and crossbreeds, Karacabey Merino sheep wool from Tukey, indigenous Changthangi sheep from India, and Omani sheep native to Oman (Table 2b).

In all studies, the wool fibers of most native or indigenous sheep tend to be medium to coarse. When native breeds are crossed with fine-wool breeds like Merino sheep, the resulting crossbreed wool falls between fine and coarse in fleece type. The range of fiber diameters highlights the differences in fine and coarse wool types. Fiber length data shows how coarse fibers tend to be longer than fine fibers, as in Kicinska-Jakubowska et al.'s research on Polish native breeds and crossbreeds. Atav, et al.'s study of Karacabey Merino sheep in Turkey included findings on fiber dimensions and tensile properties of different sexes and ages of sheep. This data shows slight differences between male and female fibers plus lamb and adult fibers. Atav, et al.'s study will be relevant to the Navajo-Churro fiber survey when studying common California sheep breeds of different ages and sexes.

Select studies included data on color and tensile properties in their wool analyses. Results from Ghermezgoli et al., Dashab et al., and Kicinska-Jakubowska et al. show notable differences in fleece color values between their native breeds which can be compared to Navajo-Churro colorimetric parameters collected in this study. Tensile property data, mainly modulus and stress values, of native sheep is not presented in standardized units, but the strain of select native breeds is different than finer wool breeds (Table 2b). Tensile properties of Navajo-Churro wool and meat breed northern California wool will be compared to document the relationship of tensile properties and fiber diameters.

Scale patterns have been documented through scanning electron microscopy (SEM) imaging for Changthangi and Omani sheep and show a variety of patterns found on some or all fibers within a fleece. Malik et al.'s data shows that scale types are different on primary (guard) hairs and secondary (undercoat) fibers. Mahgoub et al.'s research did not specify the type of fibers containing each scale pattern, but the study included four scale pattern types observed throughout the Omani sheep fleece. These patterns will be considered when studying the morphology and surface characteristics of Navajo-Churro guard hairs and undercoat fibers.

Finally, the Changthangi sheep research of Malik et al. includes the crimp count of staple fibers and, along with Omani sheep data from Mahgoub et al.'s study, shows how coarse wools have less crimp than finer wools. The crimp count of Navajo-Churro guard hairs and undercoat fibers, compared to coarse and fine wool data, will be referenced in results and discussion (Table 2b).

Objectives

The overall objective of this study is to create a fiber survey of Navajo-Churro wool in the context of common northern California commercial meat breeds. The specific objectives are as follows:

1) Collect fiber quality data of Navajo-Churro wool fibers including colors, dimensions, tensile properties, surface characteristics, and morphology.
2) Collect fiber quality data on wool fibers from northern California meat breeding sheep at the University of California, Davis including colors, dimensions, tensile properties, surface characteristics, and morphology.
3) Compare fiber quality of Navajo-Churro wool with prior research, relevant fiber surveys, and meat breed wool for potential applications.

Table 2b. Relevant Fiber Surveys

Study Location / Origin	Breed	Fleece Type	Physical Characteristics			Color			Tensile Properties			Morphology	OTHER FINDINGS				
			Diameter (µm)	Length (mm)	Crimp (%)	L*	a*	b*	Modulus	Stress	Strain (%)	Scale Pattern					
Iran[1,2]	**Arkharmerino**	Fine	15.8 (+3.1) (n=100)	19.0 (+2.9) cm Age = 9-15 mos (n=75)	-	85.6	-0.1	12.2	5.9 den	2.6 (+0.2) cN/den Linear density = den	19.6 (±1.2)	10 to 13	-	-	-	-	-
	Naeini *(Native)*	Medium	28.5 (±4.33) (n=200)	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Ghezel *(Local)*	Coarse	27.6 (±5.2)	9.9 (±4.4) cm Age = 9 to 15 mos (n=99)	-	65	4.1	15.5	14.4 den	0.8 (±0.3) cN/den	11.1 (±3.8)	14 to 18 Scales per 100µm	-	-	-	-	-
Poland[3]	**Polish Merino**	Fine	24.9	94	108 deg/mm	82.9	-0.6	9.6	-	-	-	-	-	-	-	-	-
	Olkuska *(Native)*	Long wool	30.2	162	95 deg/mm	75	0.6	12.9	-	-	-	-	-	-	-	-	-
	Żelaźnieńska *(Native/Merino/Other Crossbreed)*	-	29.3	127	86 deg/mm	83.9	0.2	9.8	-	-	-	-	-	-	-	-	-
	Polish Lowland Sheep *(Native/Merino/Other Crossbreed)*	-	31.9	120	95 deg/mm	76.1	0.5	16.6	-	-	-	-	-	-	-	-	-
				(n=1000)													
Turkey[4]	**Karacabey Merino**	Medium											**Range of Age**	**Diameter (µm)**	**Length (mm)**	**Stress (cN)**	**Strain (%)**
			29.72 *(Male)*	89.1 *(Male)*	-	-	-	-	-	8.34 cN *(Male)*	20.75 *(Male)*	-	0-2 yrs	30.17 (n=240)	87.6 (n=480)	8.58 (n=480)	19.42 (n=480)
			27.61 *(Female)*	88.9 *(Female)*	-	-	-	-	-	7.52 cN *(Female)*	20.13 *(Female)*	-	2-4 yrs	27.55 (n=150)	91.8 (n=300)	7.1 (n=300)	20.78 (n=300)
			(n=255)	(n=510)						(n=510)			4-6 yrs	28.27 (n=120)	87.6 (n=240)	8.1 (n=240)	21.11 (n=240)
India[5] Jammu and Kashmir	**Changthangi Sheep** *(Indigenous)*	Undercoat (Secondary) Medium	14.35 (±0.50)	overall length: 134.58 (±21.41) mm diam: 31.19 (±4.27) µm	4.13 (±2.16) per staple	-	-	-	-	-	-	Simple Coronal	-	-	-	-	-
		Guard (Primary) Medium	40.04 (±1.40)			-	-	-	-	-	-	Mosaic Regular					
				Age = 1-2 yrs, (n=36)	Number (n=36)												
Oman[6]	**Omani Sheep** *(Native)*	Coarse *(Carpet Wool)*	45.9 (±12.26)	22.86 (±4.31) cm	4.30 (+0.80) per staple	-	-	-	-	-	-	Wrap-around, Angled type, Elongated, & Polygonal	-	-	-	-	-
		Female	(n = 2,000)	Staple (n=100)	Number (n=100)												

References

(Ghermezgoli, et al., 2020)[1], (Dashab, et al., 2006)[2], (Kicinska-Jakubowska, et al., 2022)[3], (Atav, et al., 2022)[4], (Malik, et al., 2021)[5], (Mahgoub, et al., 2010)[6]

CHAPTER 2: NAVAJO-CHURRO WOOL FIBER SURVEY WITH REFERENCES TO COMMON NORTHERN CALIFORNIA BREEDS

Introduction

Sheep have provided humans across the globe with meat, wool, and other resources for thousands of years. Navajo-Churro sheep are no exception and have served the Navajo, an indigenous people of the southwestern United States, for over 350 years (Strawn, 2005). Navajo-Churro sheep are a vital part of Navajo traditions. The Navajo-Churro sheep are distinctive from other breeds with their small, narrow bodies, long limbs, and wide range of horn appearances, sometimes having four horns in total (Maiwashe, 2004; Strawn, 2004). Though the breed has a low wool production of 4 to 5 pounds per sheep verses 8 to 12 pounds per sheep of high-production breeds, the character of Navajo-Churro staple and non-greasy fibers is desirable for Navajo weavers (Strawn, 2007). The Navajo-Churro's double coat fleece consists of an outer protective layer of long, coarse hairs (10-20%) with a varying amount of very short, medullated kemp fibers (<5%), removed physically or by carding before weaving processes, and an inner layer of fine, undercoat fibers (80%) (Grandstaff, 1942; Navajo-Churro Sheep Association, 2010). The low grease content of Navajo-Churro fleeces repels sand and dust and does not require frequent washing (Grandstaff, 1942). Processing and weaving Navajo-Churro wool into textiles are long-established customs and cultural beliefs that have been passed down through generations of the Navajo people (Strawn, 2005).

Initially created for practical uses such as riding blankets and floor coverings, Navajo textiles are woven tightly and nearly waterproof (Grandstaff, 1942). Navajo textiles emphasize the unique, rare colors of natural and dyed Navajo-Churro fleeces comprised of antique grey and brown, light tan, black, silver, creamy white, blue-grey, red-brown, and multicolored fibers (Halberstadt, 2003: Strawn, 2007). The Navajo have historically used the most natural dyes from local vegetation and materials in their woven work compared to other indigenous tribes in the southwest United States, but commercial aniline dyes are also used because of global advancements in textile processes (Brough. 1988). Known for their geometric designs and mixed, bright colors from native vegetal dyes, the bold blankets and rugs woven by Navajo weavers showcase creative skills and artistic expression (Grandstaff, 1942).

Since few pure-bred Navajo-Churro sheep remain due to government interference with Navajo life, non-Navajo private breeders began raising the sheep in addition to the Navajo. The sheep are now found throughout western states, specifically in California because of its large wool industry. In the last year, California reported 300,000 sheep and lambs for breeding and 250,000 for market to be sold for meat (USDA, 2023). Of the total sheep and lambs in the state, 380,000 were shorn for their wool last year (USDA, 2023). The wool quality of common California wool and meat producing breeds has been studied and documented. Such breeds including Merino, Southdown, Lincoln, and others have origins throughout the world and are found in many countries, making their wool commercially available with a range of fiber characteristics from fine, short, and very crimped to coarse and long like Navajo-Churro fibers (Table 1). However, no complete wool fiber survey exists for the unique, survivalist Navajo-Churro breed that endured the dry climates of Navajo reservations for centuries. Navajo-Churro wool has been mainly referenced in historically focused studies of the Navajo culture.

The only study of Navajo-Churro wool was in the first half of the twentieth century on fibers collected to study the influence of fineness, fiber-diameter dispersion, variations in fiber-diameter distribution, length, shrinkage, crimp, and frequency of kemp and other medullated fibers on the quality and texture of woven textiles (Grandstaff, 1942). Beginning in 1937, this sole study of Navajo-Churro wool was conducted by the Southwestern Range and Sheep

Breeding Laboratory (SRSBL) in New Mexico to understand what fiber characteristics make Navajo-Churro wool more suitable to Navajo weavers than wool from other breeds (Grandstaff, 1942). The study's report "Wool Characteristics in Relation to Navajo Weaving" written by James O. Grandstaff, an associate animal fiber technologist, concluded that fleeces containing fibers with little crimp, fibers with most diameters under 40 µm, and fibers between 100 and 200 mm in length are most ideal for the Navajo handicraft (Table 2a). The study did not include fleece color measurements, fiber tensile properties, or a report of fiber morphology and surface characteristics which would all be important data contributions to build a fiber survey of Navajo-Churro wool.

Understanding the qualities of Navajo-Churro wool in the context of fiber science is vital for classifying the fibers into commercial wool categories to contribute to general knowledge of a breed so important in American history. This research focused on gathering and analyzing the color, physical characteristics, tensile properties, surface characteristics, and morphology of Navajo-Churro wool to create a comprehensive fiber survey of the breed. It also collected similar fiber data on Dorset, Suffolk, and Hampshire medium wool meat breeds and crossbreeds commonly found in California's diverse population of sheep (Weir & Albaugh, 1954). Comparing Navajo-Churro wool fibers with wool from breeds raised to sell their meat at market is a meaningful representation of the distribution of wool qualities found in California.

Experimental

Materials

Navajo-Churro fleece samples were provided by a Navajo-Churro breeder in northern California. From the 17 samples, five large fleece samples that best represented the range of general appearance in hue, shades, fiber length and their variations of all fleeces were selected for analysis (Figure 1). The five selected Navajo-Churro fleeces were labeled based on their overall color appearances of brown (BRN), blonde (BLND), multicolored (MULT), grey (GRY), and black (BLCK). Fleece samples were obtained from the UC Davis Sheep Facility to represent three common northern California commercial breeds. Sampled breeds include Dorset (DOR), Hampshire (HAM), Suffolk (SUF), and HAM-SUF and SUF-HAM crossbreeds. Seven fleece samples were collected and labeled according to sheep breed and sex/age: one sample from the neck region of a female Dorset sheep (DOR-F, 1 year of growth), three samples from the neck regions of male adult sheep (DOR-M, HAM-SUF-M, SUF-HAM-M), and three samples from unspecified body regions of lambs (DOR-L, HAM-L, and SUF-L) during their first shear (6 months of growth).

Figure 1. Navajo-Churro fleeces by gradient and labeled fleeces representing all samples: brown (BRN), blonde (BLND), multicolored (MULT), grey (GRY), black (BLCK). Images were taken against a bleached cotton background using flash in shaded, natural light.

Characterization

Color

A *GretagMacbeth, Color-Eye 7000A* Colorimeter paired with *Color iControl* Software was used to identify fleece colors. The Colorimeter was calibrated as instructed by the software with black and white Colorimeter tiles. As there is no current AATCC standard for wool, the standard was set and measured using bleached plain-woven cotton fabric (as received). The entirety of each fleece sample was used for measurements to ensure the wool covered the Colorimeter's lens. Color measurements from the tip, middle, and sheared end of each Navajo-Churro and UC Davis fleece sample were collected. In total, 10 measurements were collected per sample.

The *Color9-Eye 7000A* determined each sample's International Commission on Illumination (CIE) L*ab color parameters including ΔL*, Δa*, Δb*, ΔC*, and ΔH* values. Using the standard and the sample, the L*, a*, and b* indexes were calculated for each fleece. The L* index is lightness value from black/dark (0) to white/light (100), the a* index is color saturation from red (+) to green (-) value, the b* index is color saturation from yellow (+) to blue (-) value, the C* index is chroma (+ for brighter, - for duller), and the h° index is hue (Kicinska-Jakubowska, et al., 2022). The color difference ΔE* (equation 1), between two fleeces is 0, the fleeces are the same in color, and if ΔE* is 100, the fleeces are exactly opposite in color.

$$\Delta E^*_{ab} = \sqrt{(L^*_2 - L^*_1)^2 + (a^*_2 - a^*_1)^2 + (b^*_2 - b^*_1)^2} \tag{1}$$

Fiber diameter and length

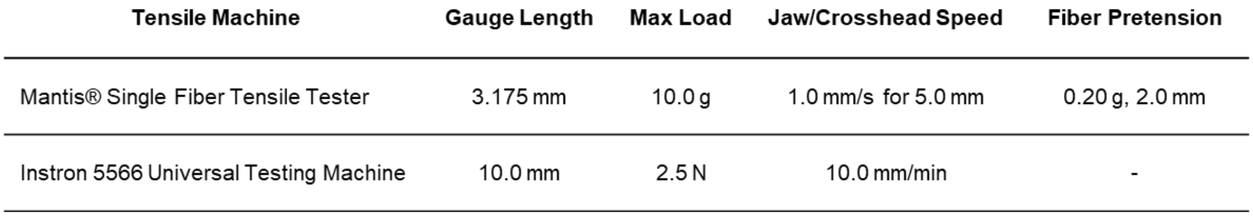
Individual fibers were randomly selected from each fleece sample with tweezers for analysis. Because this fiber survey is of raw, untreated Navajo-Churro wool, no fibers were cleaned or treated before analysis. To determine Navajo-Churro guard hair diameter, the *Leica DM* 2500 optical microscope was used with the *ProgRes® CapturePro 2.6* desktop program. The *Mantis® Single Fiber Tensile Tester* calculated the diameters of Navajo-Churro undercoat fibers and all UC Davis fibers. To determine fiber length, individual fibers from each sample of Churro (guard and undercoat) and UC Davis wool were measured to the closest mm using tweezers to suspend individual fibers across a metric ruler and against a black background. For diameter and length measurements, undercoat fibers were selected from the sheared, bundled end of Navajo-Churro fleeces, and guard hairs were pulled from the long staples protruding from the bundle of undercoat fibers. Because the BRN fleece is uniform, randomly selected fibers were included in both guard and undercoat diameter measurements, but BRN length calculations were performed only once. All statistical analysis is conducted at a confidence interval of 95%. Dimension comparisons among Navajo-Churro guard and undercoat fibers and UC Davis fibers were made using one-way analysis of variance (ANOVA). To determine which specific means are/are not significantly different from the others, a Tukey HSD post-hoc test was run after ANOVA. Student t-tests were conducted for length values between DOR-L and DOR-F fibers and diameter values between HAM-L and HAM-SUFF-M fibers.

Single fiber tensile properties

The *Mantis® Single Fiber Tensile Tester* was used for the first time with wool for tensile and diameter measurements of Navajo-Churro undercoat fibers and UC Davis fibers (Table 3). For each Navajo-Churro or other wool sample, 50 undercoat fibers were randomly selected and individually centered tautly between the two jaws and *Mantis®* suction tubes, avoiding as much slack as possible. The *Mantis®* measures fiber diameter using laser scanning. Jaws between the *Mantis®* suction tubes clamp to fiber ends and pull apart the fiber to calculate the stress and strain of each fiber breaking under constant loading. The stress-strain curve was graphed to determine Young's modulus with twenty-five points selected from each fiber's elastic region. All statistical analyses are performed at a 95% confidence interval. Tensile properties among Navajo-Churro undercoat fibers and UC Davis fibers are compared using one-way analysis of variance (ANOVA). A Tukey HSD post-hoc test was run after ANOVA to determine which specific means are/are not significantly different from the others. Student t-tests were conducted between all tensile values of HAM-L and HAM-SUF-M fibers.

Navajo-Churro guard hairs are too thick in diameter to measure their tensile strength on the *Mantis®*, so the *Instron 5566 Universal Testing Machine* was used with *Bluehill® 2.35* software (Table 3). Per Navajo-Churro sample, 50 guard hairs were selected for testing. Individually, fibers were suspended and clamped between two *Instron* jaws tautly, avoiding as much slack as possible. Once the *Bluehill®* software runs, the suspended fiber is pulled apart to calculate the load (N) and extension (mm) of breaking Navajo-Churro guard hairs under constant loading. Because the BRN fleece is uniform, fibers were randomly selected to be included in both guard and undercoat tensile measurements. The stress and Young's Modulus were normalized using the average diameter determined by optical microscopy.

Table 3. Tensile Experiment Parameters



Tensile Machine	Gauge Length	Max Load	Jaw/Crosshead Speed	Fiber Pretension
Mantis® Single Fiber Tensile Tester	3.175 mm	10.0 g	1.0 mm/s for 5.0 mm	0.20 g, 2.0 mm
Instron 5566 Universal Testing Machine	10.0 mm	2.5 N	10.0 mm/min	-

Morphology by optical microscopy

From each of the five Navajo-Churro fleece samples, 50 guard hairs were individually placed on glass slides with tape securing the fiber ends. Cover glass was added atop fiber midsections for analysis. Each guard hair was observed at 10x magnification under an optical microscope (*Leica DM 2500)* and photographed using *ProgRes® CapturePro 2.6* software. Fiber diameter measurements (μm) were taken at 10x magnification using the software's calibrated scale bar. For further fiber characterization, multiple Navajo-Churro undercoat fibers and UC

Davis fibers from all fleece samples were prepared and imaged at varying magnifications of 5x, 10x, and 40x. A cross polar lens was used in accordance with the optical microscope, and photos were obtained at 10x or 40x magnification. Water was used as a mounting media with cover glass to enhance scale structure and patterns.

Surface characteristics by scanning electron microscopy

Using the *Thermo Fisher Quattro S* environmental scanning electron microscope (SEM), surface characteristics and morphology of fibers were observed. Snippets from the middle of Navajo-Churro undercoat and guard hairs and UC Davis fibers were mounted on standard vacuum grade aluminum SEM stubs with carbon tape underneath the fibers. Conductive copper tape was used to secure each end of the fibers. Using the *Denton Desk II*, gold was sputter coated onto the fibers for 20 seconds at a current of 30 mA and pressure of 100 mTorr. The gold coated fibers were then viewed in the SEM at a beam voltage of 10.00 kV and 3.0 spot size. Images of fibers were captured at different magnifications according to their size, ranging widely from 250x – 3500x, with most images captured around 750x magnification.

Results and Discussion

Navajo-Churro Wool

Physical characteristics

The five Navajo-Churro fleeces selected for analysis represent the 17 samples' general appearances of color, shade range, and distribution of undercoat and guard fibers (Figure 2). All Navajo-Churro samples contain a visible difference in fibers throughout each fleece, composed of mostly shorter, undercoat fibers, contained in the sheared end of fleeces, and long, outercoat, guard hairs. The exception is the BRN sample which appears uniform in length, possibly due to crossbreeding. The long staples protruding from BLND, MULT, GRY, and BLCK fleeces are guard hairs naturally adhered to each other. This is common of sheep producing coarse wool, especially fleeces from the first shear of the animal's life (Mahgoub, et al., 2010). Physical characteristics of BLND, MULT, GRY, and BLCK fleeces agree with observations made in Grandstaff's study in which a lock of Navajo-Churro wool was analyzed and separated into long/coarse outercoat and short undercoat fibers. Observations also agree with Changthangi sheep research by Malik et al. identifying primary and secondary fiber types in the indigenous sheep's fleece, comparable to Navajo-Churro guard hairs and undercoat fibers.

*Figure 2. Navajo-Churro fleeces by color: brown (BRN), blonde (BLND), multicolored (MULT), grey (GRY), black (BLCK). CIE L*ab color parameters included.*

Color

Navajo-Churro wool has a low to neutral lightness with L* values ranging from 41.9 to 64.0. BLND has the highest L* value of 64.0, as expected from the lightest sample (Figure 2). BRN has the lowest L* value of 41.9 because of its uniformity in color. Parts of the BLCK fleece are darker than BRN but some are lighter, so BLCK's L* value of 44.1 is the next lowest. The higher standard deviation in L* values of BLCK and MULT is expected because of the lightness variation throughout the fleece. BRN has the highest a* value of 9.8, meaning that it is the sample with the reddest saturation. BRN and BLND fleeces are the yellowest in saturation with b* values of 19.0 and 19.9, respectively. The a* value is positive across fleeces, indicating that Navajo-Churro wool is mostly red in chromatic color. The positive b* index of Navajo-Churro samples shows that the wool is mostly yellow.

BLND, MULT, and GRY fleeces are most similar in color appearance, so the color difference equation (1) was used to quantify color variation between fleeces. The total color difference between BLND and GRY fleeces is the largest at 17.6 = ΔE*. Between BLND and MULT fleeces, 14.9 is the total color difference. MULT and GRY fleeces appear closest in color appearance with a ΔE* of 3.0. The BRN fleece compared to the lightest (BLND) and darkest (BLCK) fleeces shows a color difference of 23.1 and 9.8, respectively. BRN and BLCK fleece colors are more similar than BRN and BLND fleece colors. Overall, quantitative analysis of CIE L*ab color values using ΔE* concludes that no Navajo-Churro fleeces are identical in color.

Fiber diameter and length

Average guard hair diameters range from 37.0 to 72.0 µm, but most are between 50 and 60 µm (Figure 3a). BLCK guard hairs have the highest average diameter with the highest standard deviation. Among all average hair diameters, at least one fleece is significantly different from the others according to ANOVA. Implementing a Tukey HSD post-hoc test shows that fleece averages are not significantly different between BLND (51.3 µm) and MULT (54.9 µm) and between MULT and GRY (58.3 µm). The BRN (37.0 µm) and BLCK (72.0 µm) average hair diameters are significantly different from all other fleeces.

Average guard hair lengths range from 185 to 274 mm. The GRY fleece sample contained guard hairs with longest average length with the highest standard deviation. Most samples’ average lengths remain above 200 mm. The difference among average lengths of Navajo-Churro guard hairs is significant according to ANOVA. A Tukey HSD post-hoc test shows averages are not significantly different between BRN (185 mm) and MULT (196 mm) and between BLND (202 mm) and MULT. The GRY (274 mm) and BLCK (224 mm) average hair lengths are significantly different from all other fleeces.

Average undercoat fiber diameters range about 5 µm from 28.3 to 32.8 µm (Figure 3b). The BLCK undercoat fibers have the highest average diameter of 32.8 µm. The difference among fleeces of average fiber diameter values is significant when conducting ANOVA. Using a Tukey HSD post-hoc test identified no significant difference in average diameters between BRN (32.6 µm) and GRY (30.1 µm), BRN and BLCK (32.8), BLND (28.8 µm) and MULT (28.3 µm), BLND and GRY, MULT and GRY, and between GRY and BLCK. Overall, post-hoc results show that BRN and BLCK average fiber diameters are significantly different from the other fleeces.

The range of average undercoat fiber lengths is from 99.2 to 185 mm. Most samples' average lengths remain above 100 mm except BLCK. According to ANOVA, the variation among all fleeces of average fiber lengths is significant. However, a Tukey HSD post-hoc test shows no significant difference in average lengths between BLND (110 mm) and MULT (115 mm) and between BLND and BLCK (99.2 mm). The BRN and GRY average fiber lengths are significantly different from all other fleeces.

Looking at aspect ratios, guard hairs range from 3107 to 5000 and undercoat fibers range from 3024 to 5675. BRN has the highest aspect ratios of both fiber types, and BLCK has the lowest aspect ratios of both guard hairs and undercoat fibers. GRY and MULT fleece samples show a noticeably higher undercoat aspect ratio than guard. BLND and BLCK guard aspect ratios are very similar to their corresponding undercoat aspect ratios. GRY and MULT fleece samples show a noticeably higher undercoat aspect ratio than guard.

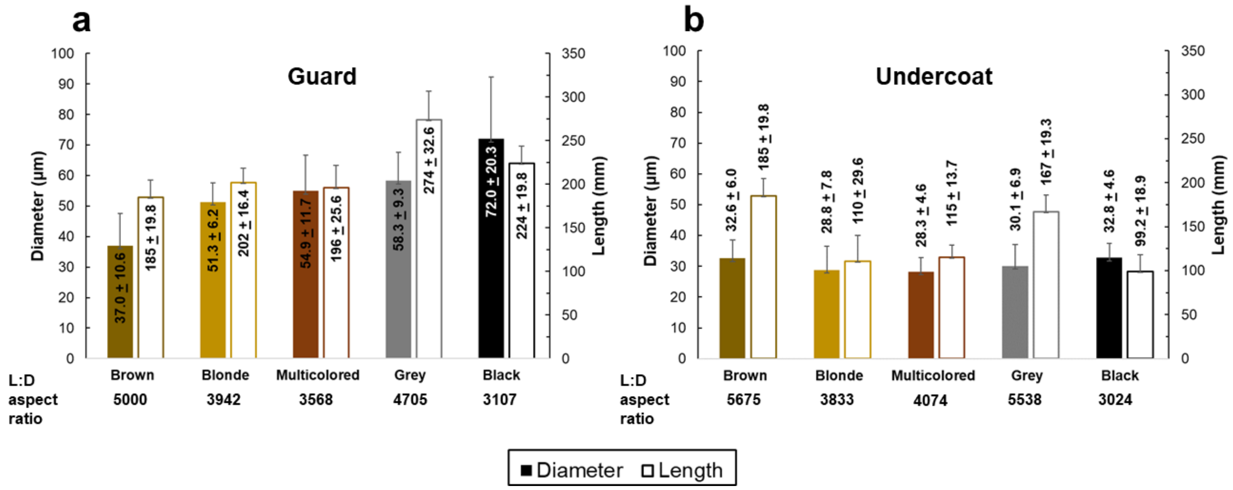


Figure 3. Navajo-Churro wool dimensions: (a) guard hairs; (b) undercoat fibers.

Finally, comparing our dimension measurements with Grandstaff's research, undercoat diameter values from this fiber study fall within the ideal fiber fineness range for weaving (Table 4). Guard and undercoat fiber lengths determined in this study generally agree with Grandstaff's results, only they show a slightly larger range.

Table 4. Navajo-Churro Fiber Dimensions

Fiber Type	Study	Diameter Range (µm)	Length Range (mm)
Guard Hair	Our Results	37.0 – 72.0	185 – 274
	Grandstaff, 1942	-	184 – 241
Undercoat Fiber	Our Results	28.3 – 32.8	99.2 – 185
	Grandstaff, 1942	27.6 – 28.8 (ideal fineness for weaving)	98 – 134

Single fiber tensile properties

Undercoat fiber tensile data ranges from 1515 to 1955 MPa in modulus, from 147 to 188 MPa in strength, and from 63.8 to 73.5% in strain (Figure 4b). BLND undercoat fibers are the strongest and BLCK undercoat fibers are the weakest. MULT and GRY fleeces have the most similar undercoat fiber tensile properties and standard deviations. According to ANOVA, Navajo-Churro undercoat fiber tensile data shows significant statistical variance among samples when comparing modulus, strength, and strain values. Looking closer at modulus, a Tukey HSD post-hoc test identifies BRN (1955 MPa) as significantly different from every other group except BLND (1722 MPa). It also shows that BLND (188 MPa) is the fleece with a significantly different average fiber strength from all other fleeces except BRN (172 MPa). Average strength values are also significantly different between BRN and BLCK (147 MPa) fleeces. Lastly, the Tukey HSD post-hoc test identifies the average fiber strain of only the BLND (63.8 %) fleece is significantly different from every fleece except MULT (68.9 %) and BLCK (66.5 %) fleeces.

Guard hair tensile modulus ranges from 2113 to 3374 MPa, strength from 74.8 to 131 MPa, and strain from 36.5 to 50.3% (Figure 4a). The strongest average guard hairs are from the BLND fleece. The sample with guard hairs of the highest average modulus is MULT. On average, BLCK guard hairs have the lowest overall modulus, strength, and strain values. Tensile results of Navajo-Churro guard hairs show significant variance among samples when comparing modulus, strength, and strain values according to ANOVA. The Tukey HSD post-hoc test identifies the average modulus of the BLCK fleece as significantly different from every other group. It also shows average strength values are not significantly different between BRN and BLCK fleeces, but both fleeces are statistically different from all other groups. Finally, the Tukey HSD post-hoc test shows that average strain values of BRN and BLCK fleeces are not significantly different from each other, but they are significantly different from every group. The exception is that there is no significant difference between BLND and BLCK average strains.

Overall, BRN undercoat fibers are the most significantly different from the group in average modulus. The BLND undercoat fibers are the most significantly different from other fleeces in average strength and strain. Looking at guard hairs, the average BLCK modulus value is the most significantly different from the fleece values. BRN and BLCK average strengths of guard hairs are the most different from the other fleeces. Lastly, the BRN average guard hairs are significantly different in average strain values from the group. Because guard hairs and undercoat fibers were measured on different tensile machines, their tensile properties may not be compared.

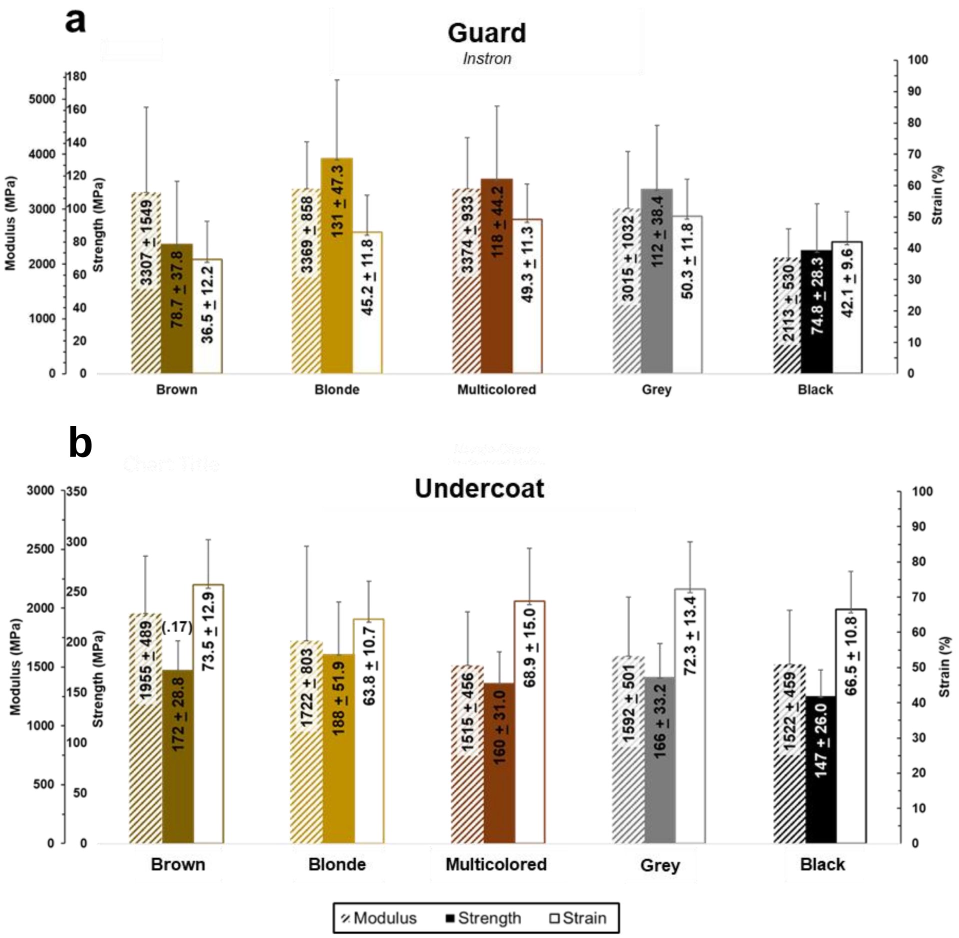


Figure 4. Navajo-Churro wool tensile properties: (a) guard hairs; (b) undercoat fibers.

Morphology by optical microscopy

Water and glycerol were both used for optical microscopy analysis, but no apparent differences between the two mounting medias were observed in images. Therefore, water was selected as the media of choice for viewing all fibers.

At least slight variation in fiber diameter distribution along a single fiber was observed in all Navajo-Churro fibers. Differences in guard hair diameters along single fibers is very apparent (Figure 5a). Medullation in guard hairs from all Navajo-Churro fleeces was observed as a dark, hollow space inside fibers. Few Navajo-Churro undercoat fibers showed medullation (Figure 5b). In Grandstaff's previous research, medullation is associated with fibers unsuited for weaving, so Navajo-Churro guard hairs in this study may not be suitable for woven applications.

Results show that BLND, MULT, GRY, and BLCK guard hairs have different scale patterns than undercoat fibers. Guard hairs have scales that do not wrap around the fiber shaft nor show any specific organization or pattern. Navajo-Churro undercoat fibers have wrap around scales, but the structure was difficult to detect with optical microscopy. The scales on BRN fibers are not as well-defined as other Navajo-Churro fibers. Scale patterns of Navajo-Churro fibers are further observed using SEM images.

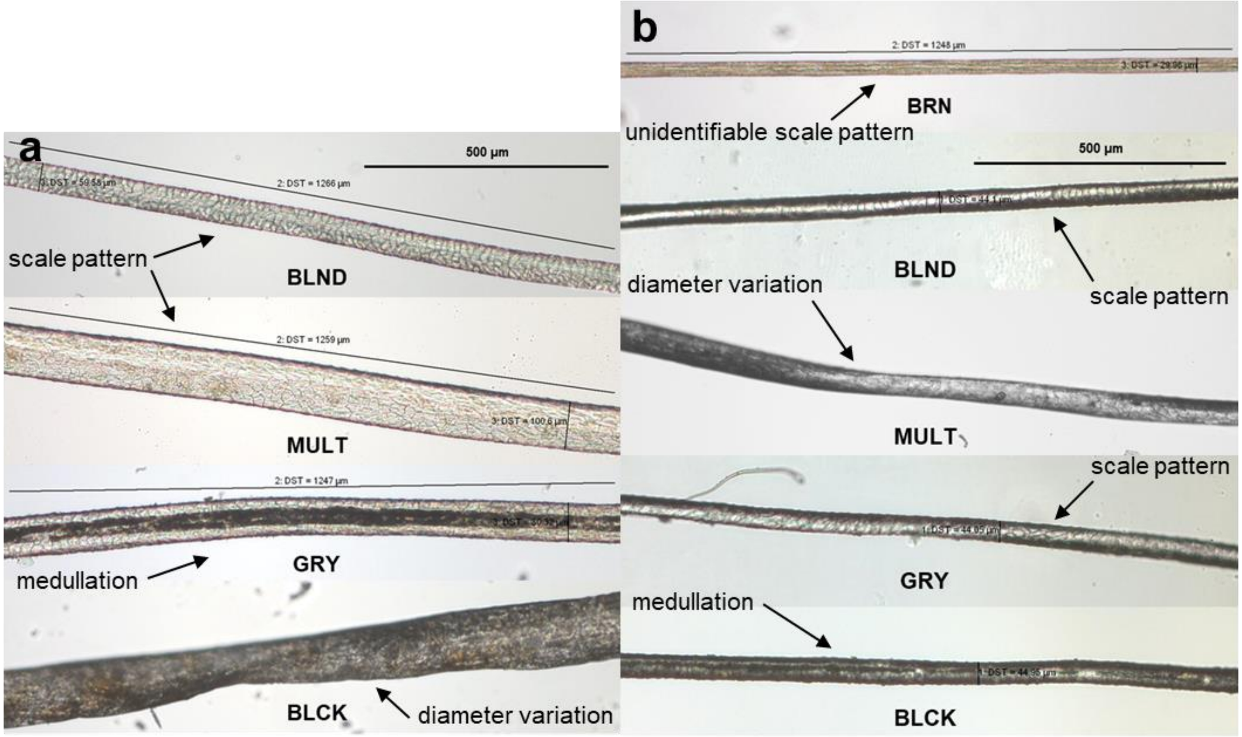


Figure 5. Optical microscopy images of Navajo-Churro wool at 10x magnification: (a) guard hairs; (b) undercoat fibers.

Surface characteristics by scanning electron microscopy

Variations in scale patterns from fibers in each fleece sample were further examined using scanning electron microscopy images to supplement optical microscopy observations.

BLND, MULT, GRY, and BLCK guard hairs and undercoat fibers have distinct scale pattern differences. Guard hairs have scales that are hexagonal in shape and form a mosaic pattern (Figure 6a). The scales are more sunken than their edges which are clearly raised like a wall around the scale. Undercoat fibers have thick scales pointing down the fiber. The scales overlay each other along the direction of the fiber shaft, and the exposed scale edges are raised (Figure 6b). Scales on undercoat fibers also wrap around the fiber shaft. Scale frequency appears to be similar on all guard hairs as well as between all undercoat fibers, but guard hairs have a higher scale frequency than undercoat fibers.

The scale patterns were further identified according to the four recognized as wrap-around, angled, elongated, and polygonal patterns (Woods & Orwin, 1982). Elongated and polygonal scale patterns can be seen on BLND, MULT, GREY and BLCK guard hairs. Looking again at optical microscopy images of guard hairs confirms that the longer side of the scale ridge is parallel to the fiber axis (elongated) and/or the scales have no preferred orientation to the fiber axis (polygonal) (Woods & Orwin). The undercoat fibers from BLND, MULT, GRY, and BLCK fleeces have wrap-around scales, but some fibers have occasional angled scale patterns. The long axis of the ridge pattern is oriented around the fiber in wrap-around scale patterns and at an angle to the fiber axis in angled scale patterns (Woods & Orwin, 1982). Though faint and not raised, BRN fiber scales appear to be mostly wrap-around in pattern (Figure 6c).

SEM image analysis concludes that Navajo-Churro guard hairs have elongated and polygonal scale patterns, and undercoat fibers have wrap-around scale patterns and occasional scales arranged in angled patterns. Guard hair results agree with research conducted by Woods & Orwin concluding that polygonal scale patterns are usually found on fibers with large diameters. In Mahgoub, et al.'s study of Omani native sheep, large-diameter hairs were also reported as having mostly elongated and polygonal scale patterns. Malik, et al.'s Changthangi sheep research identified mosaic regular scale patterns on primary (guard) fibers and simple coronal scale patterns on secondary (undercoat) fibers. Malik, et al.'s simple coronal patterns are comparable to wrap-around patterns, and mosaic regular patterns are comparable to polygonal patterns in Wood's & Orwin's work. In this fiber survey, determination of scale patterns was subjective and conducted by a single observer, but consistent.

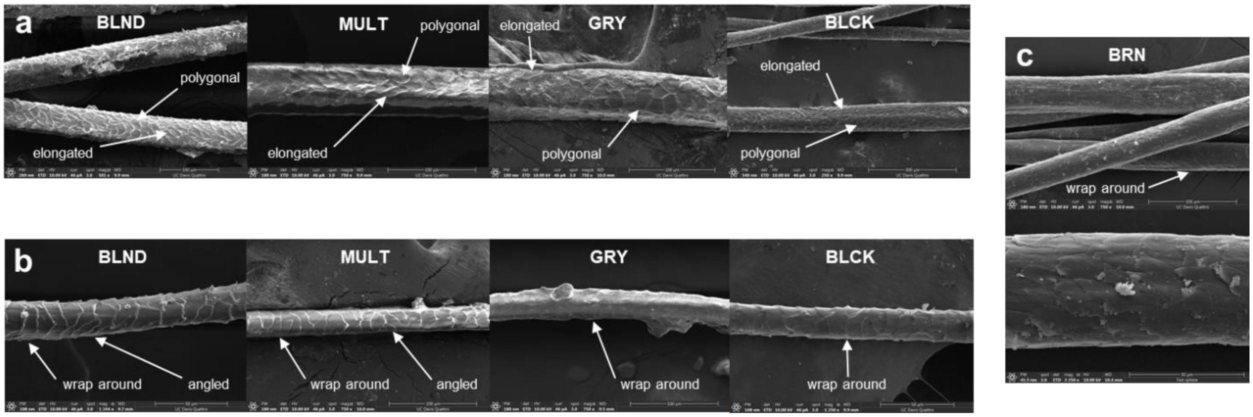


Figure 6. SEM images of Navajo-Churro wool with labeled scale patterns: (a) guard hairs; (b) undercoat fibers; (c) BRN fibers.

In further examination of scanning electron microscopy images, the crimp difference of Navajo-Churro guard hairs (little or no crimp) and undercoat fibers is very apparent. Among BLND, MULT, GRY, and BLCK fleeces, guard hairs have no visible crimps, but undercoat fibers have roughly two crimps per 5 mm (Figure 7). In Grandstaff's Navajo-Churro research, undercoat fibers have a higher percentage of fiber length due to crimp (15.3%) than guard hairs (9.4%). Although, differences between guard and undercoat fiber crimp ended up having no influence on the suitability of wool for hand weaving (Grandstaff, 1942). Both this survey and Grandstaff's research conclude that as fiber diameter increases, the number of crimps in the fiber decreases. The same conclusion was also reached in a study characterizing sheep fleeces containing fine and coarse fibers conducted by Sitotaw, et. al.

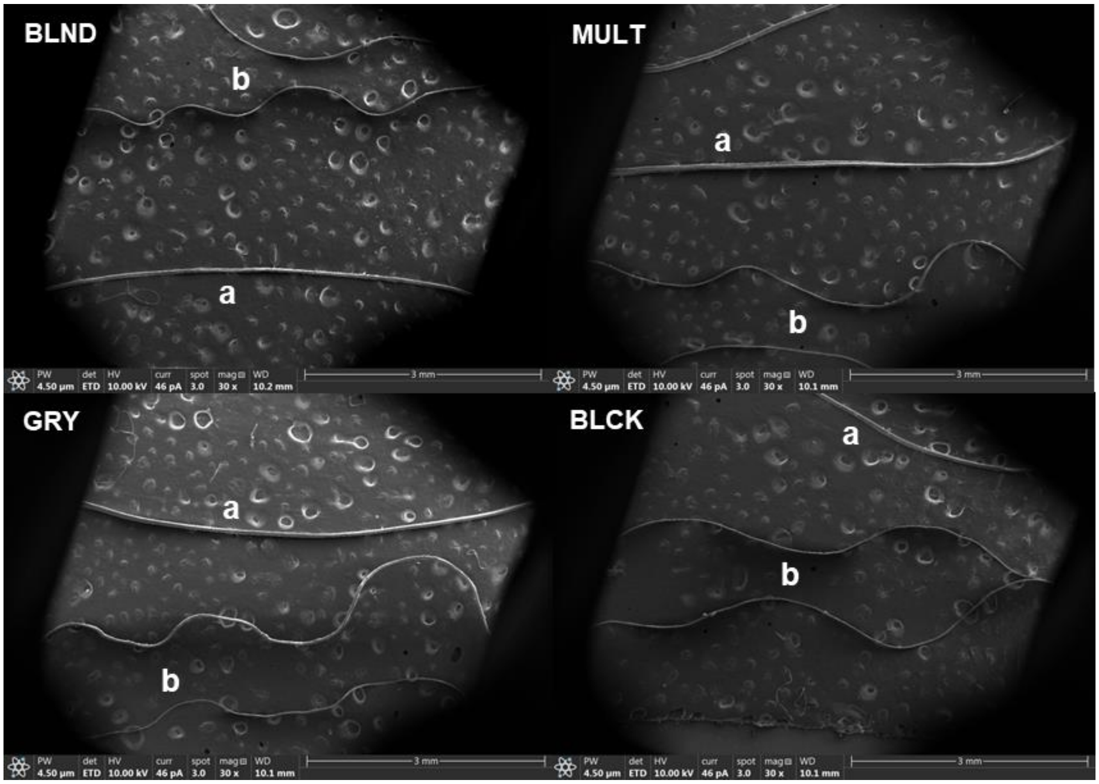


Figure 7. SEM images of Navajo-Churro wool showing crimp differences at 30x magnification: (a) guard hairs; (b) undercoat fibers.

UC Davis Wool

Color

UC Davis fleeces are uniform in fiber appearance, composed of one type of short/thin fibers, and long/thick fibers cannot be seen. Some fleeces show fiber crimp like DOR-L. Differences in color are apparent within and between fleece samples. The lightest sample from UC Davis sheep with the highest L* value of 74.4 is the SUF-L fleece (Figure 8). With an L* value of 43.2, the HAM-SUFF-M fleece is the darkest. Looking at Dorset fleeces, the L* of DOR-L is the highest at 67.0, though not much higher than the L* values of DOR-M and DOR-F. Across Dorset fleeces, a* and b* values are relatively uniform. Both values are positive which indicates that Dorset wool is more red than green and more yellow than blue in saturation. The L* values of HAM-L and HAM-SUF-M are nearly the same and slightly below neutral lightness (L* = 50). The

L* value of SUF-L is larger than SUF-HAM-M, but both values are above L* = 65 and, therefore, are high in lightness. HAM-L and SUF-L fleeces vary most in color compared to the males, as is reflected with L* standard deviation. The darkest fleeces also have the lowest b* values, so they are bluer in saturation than the other breeds. The a* values of Dorset fleeces indicate that the breed is the reddest in saturation compared to the other UC Davis breeds. A noticeable trend of L* values is that fleeces grow darker, if only slightly, from lamb to adult sheep.

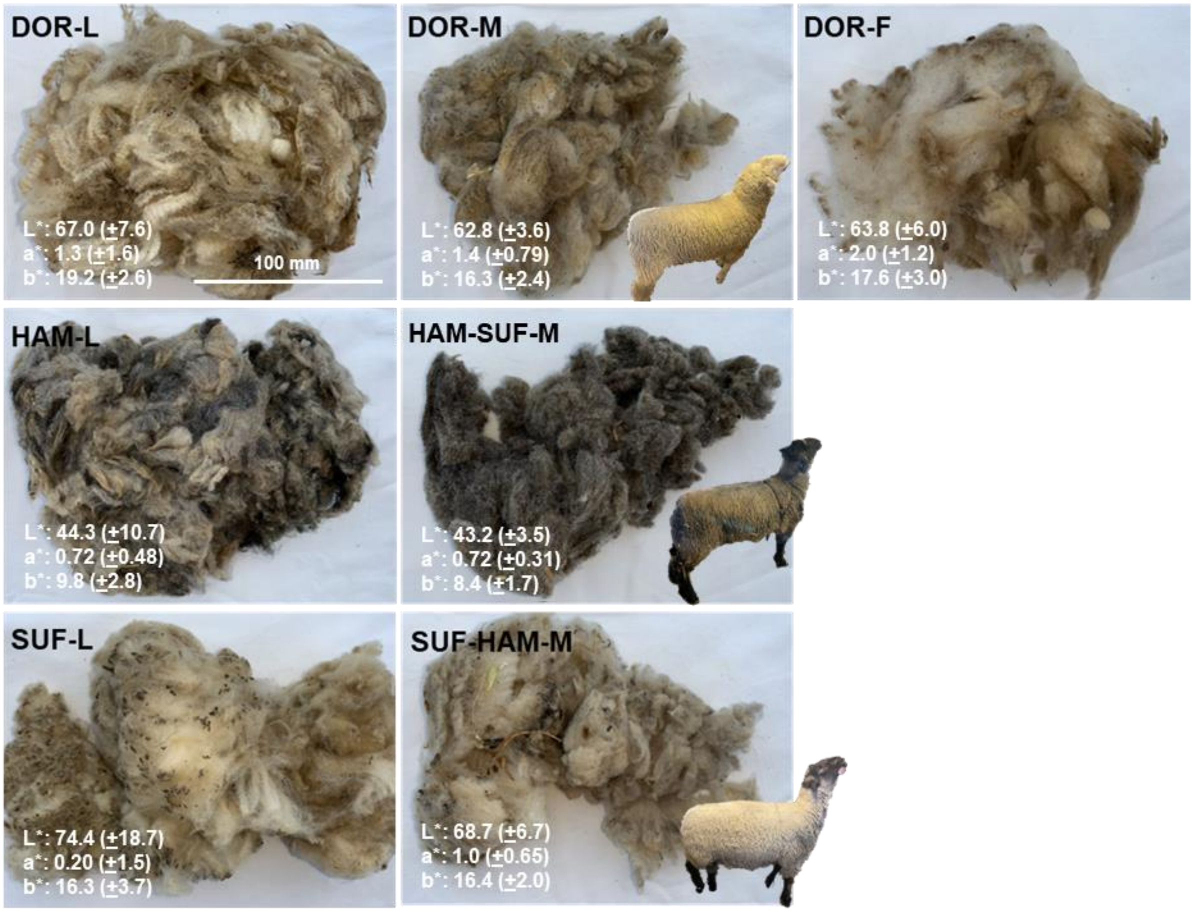


*Figure 8. Dorset (DOR), Hampshire (HAM), Suffolk (SUF) fleeces: lamb (L), male (M), female (F). CIE L*ab color parameters included.*

Lighter fleeces are difficult to tell apart within and between breeds. HAM-L and HAM-SUF-L fleeces are visibly distinguishable by color from the other breeds but not from each other. Therefore, the color difference equation (1) is used to quantify differences between select fleeces. Within Dorset fleeces, the most similar in color appearance are the DOR-M and DOR-F fleeces

(ΔE* = 1.7). The least similar are DOR-L and DOR-M fleeces (ΔE* = 5.1). The ΔE* between DOR-L and DOR-F is 3.6, so Dorset fleeces do not vary much in color from each other, overall. Between HAM-L and HAM-SUF-M fleeces, ΔE* = 1.8, so they are nearly identical in color. The difference in color is 8.0 when comparing DOR-L and SUF-L fleeces. Between SUF-HAM-M and SUF-L fleeces, the ΔE* value is 5.7, and ΔE* = 5.9 comparing SUF-HAM-M and DOR-M fleeces. Although some fleeces have ΔE* values close to 0, no UC Davis fleeces are identical, even if they appear to be at first glance.

Fiber diameter and length

Dorset breed results show that DOR-L has the highest average fiber diameter (38.7 µm), and DOR-M has the lowest (34.0 µm) (Figure 9a). The difference among Dorset fleeces is significant because of DOR-M according to a Tukey HSD post-hoc test. The results are higher than the expected diameter range of 26 to 32 µm (Table 1). The gap in average lengths of DOR-L (72.5 mm) and DOR-F (123 mm) fibers is nearly double. The variance is significant according to a student t-test. Since each fleece had different periods of growth before shearing, it is expected that DOR-F has a much higher aspect ratio (3262) than DOR-L (1873). Notably, DOR-L and DOR-F results roughly represent the low (75 mm) and high (125 mm) length parameters for the Dorset breed (Table 1).

Average lamb fiber diameters range from 34.8 µm (HAM-L) to 40.1 µm (SUF-L), and male diameters range from 25.9 µm (SUF-HAM-M) to 36.6 µm (HAM-SUF-M) (Figure 9b & 9c). Both HAM-L and SUF-L average diameters are higher than the expected 26 to 33 µm range (Table 1). The SUF-HAM-M’s average diameter is expected from Suffolk and Hampshire breeds, but the HAM-SUF-M’s value is higher than expected (Table 1). The average diameter of HAM-L is significantly different from every lamb fleece according to a Tukey HSD post-hoc test. In addition to ANOVA, the same post-hoc test shows that all average male diameters are significantly different from each other. Comparing within breeds, a student t-test shows that HAM-L and HAM-SUFF-M average diameters are not significantly different. In Atav, et al.'s study of different aged Karacabey Merino sheep, lamb fibers had higher average fiber diameters than adult fibers which generally agrees with our results (Table 2b).

Lamb average fiber lengths range from 41.3 mm (HAM-L) to 72.5 mm (DOR-L). All lamb average lengths are significantly different from each other according to a Tukey HSD post-hoc test. The average HAM-L and SUF-L lengths are much shorter than the expected range of about 62 – 100 mm, probably because they represent only half a year's growth (Table 1). Lamb aspect ratios reflect average fiber length differences and range from 1187 (HAM-L) to 1873 (DOR-L).

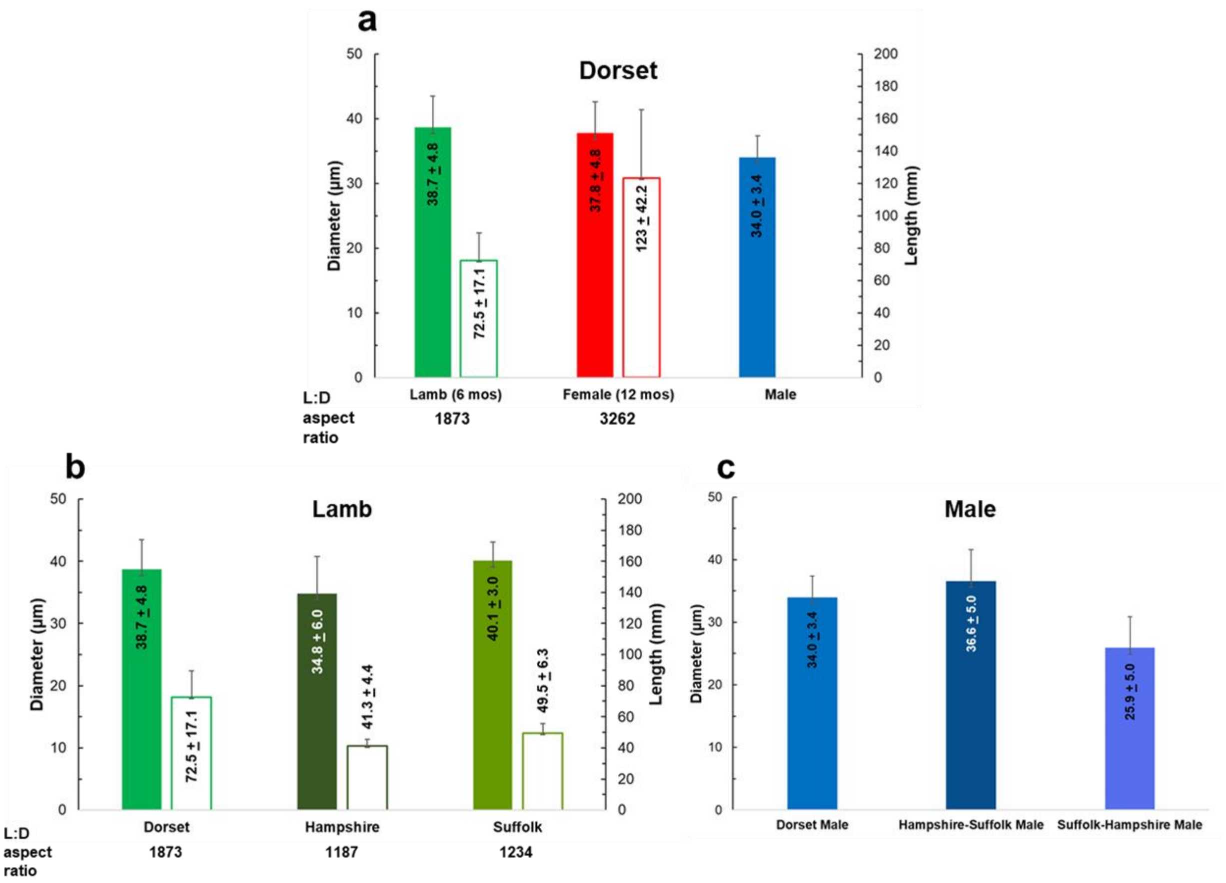


Figure 9. UC Davis wool dimensions: (a) Dorset; (b) lamb; (c) male fibers.

Single fiber tensile properties

Of lamb, female, and male Dorset fibers, tensile data ranges from 1875 to 2224 MPa in modulus, from 162 to 202 MPa in strength, and from 55.8 to 69.0% in strain (Figure 10a). The DOR-M fibers are the strongest and have the highest strain value, but they are outliers. The average strength of DOR-M fibers is much higher than DOR-L and DOR-F, almost by 40 MPa. The strain at breaking for DOR-M is at least 10% higher than DOR-L and DOR-F. The DOR-L and DOR-F average modulus, strength, and strain values are not significantly different according to ANOVA and a Tukey HSD post-hoc test.

Lamb fiber tensile data ranges among breeds from 1202 to 1979 MPa in modulus, from 136 to 166 MPa in strength, and from 59.7 to 74.7% in strain (Figure 10b). Tensile ranges of male fiber data are from 1597 to 2224 MPa in modulus, from 151 to 202 MPa in strength, and from 59.2 to 69.0% in strain (Figure 10c). The average modulus of DOR-L fibers is significantly different from other lambs. There is no significance in difference among lamb strength values according to ANOVA. In SUFF-L fibers, the average strain at breaking point is a very high outlier, nearly 75%. This could be explained by uncontrollable slack due to the highly crimped fibers. Comparing male sheep shows that DOR-M has the highest average tensile values of modulus, strength, and strain. There is significance of variance among all male fleeces' tensile results except in strain values. Between DOR-M and HAM-SUF-M and between HAM-SUF-M and SUF-HAM-M average strains, there is no significant difference. Notably, when comparing lamb to male results, there is no significant difference between all HAM-L and HAM-SUF-M tensile values according to a student t-test.

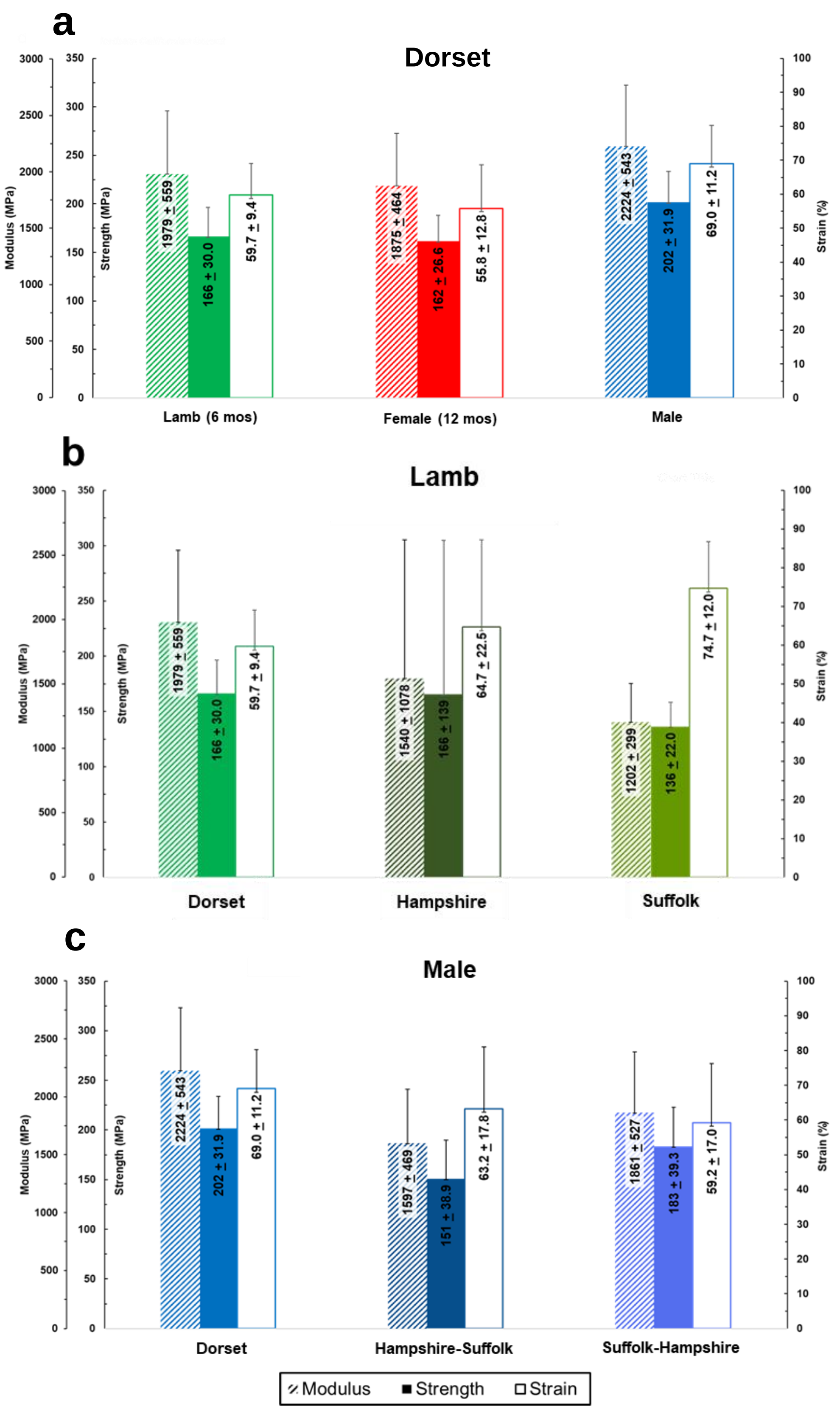


Figure 10. UC Davis wool tensile properties: (a) Dorset; (b) lamb; (c) male fibers.

Morphology by optical microscopy

At least slight variation in fiber diameter distribution along a single fiber was observed in all UC Davis fibers imaged (Figure 11). Crimp can be seen in some UC Davis fiber images, but no medullation. UC Davis fibers have visible scales, but patterns were difficult to detect with optical microscopy, so scales are further studied in SEM images.

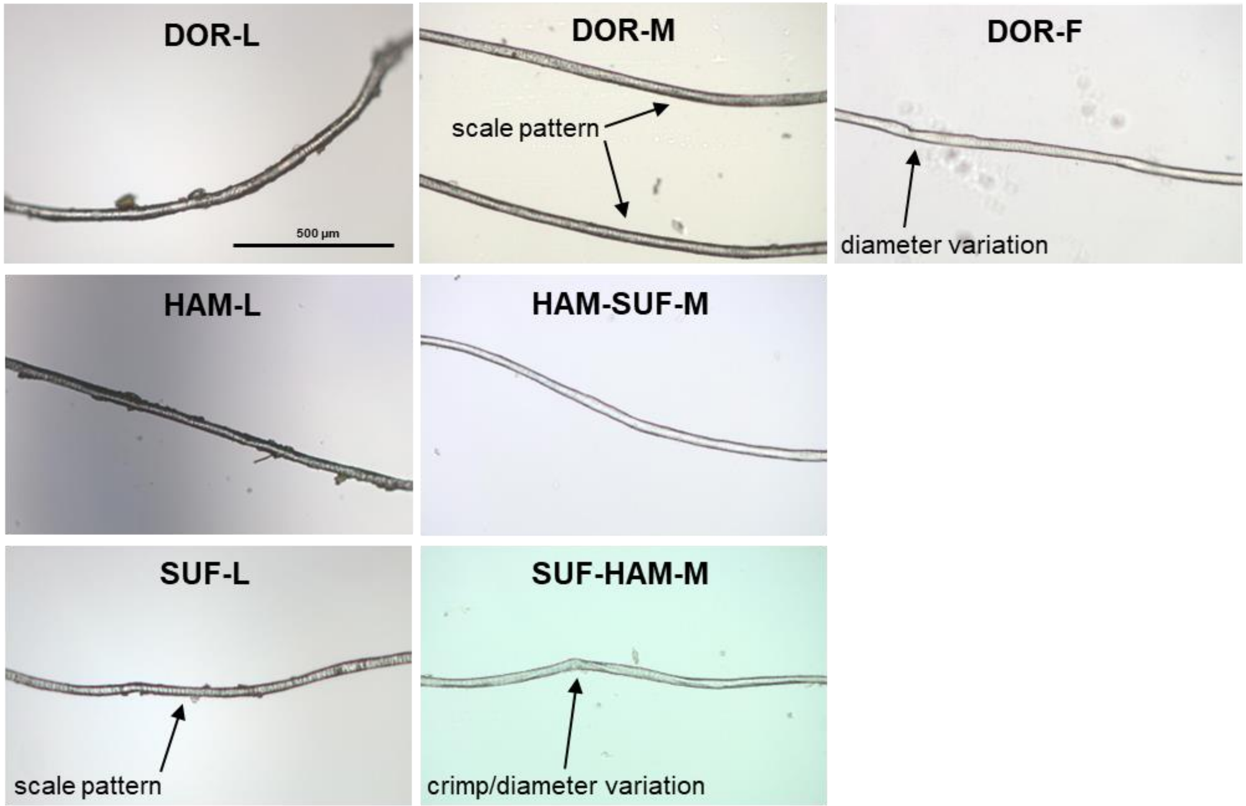


Figure 11. Optical microscopy images of Dorset (DOR), Hampshire (HAM), Suffolk (SUF), and HAM-SUF and SUF-HAM crossbreed fibers at 10x magnification.

Surface characteristics by scanning electron microscopy

DOR-M and DOR-F images show long-slender scales that wrap-around the fiber shaft (Figure 12). This pattern is expected when compared to the results of Robson, et al.'s study identifying Dorset wool scales. Scales on DOR-L fibers are larger than on adult Dorset fibers, but they appear to also wrap-around the fiber shaft. Looking only at Dorset images, the DOR-F fibers have the highest scale frequency per 100 µm (Ghermezgoli, et al., 2020).

When analyzing male sheep, DOR-M fibers have a higher scale frequency per 100 µm than HAM-SUF-M and SUF-HAM-M (Figure 12). The DOR-M scales are smaller than HAM-SUF-M and SUF-HAM-M scales. Both DOR-M and HAM-SUFF-M fibers have scales that wrap-around the fiber shaft. The DOR-M fiber has higher, raised scales. The scales on SUFF-HAM-M fibers are slightly angled compared to other breeds' scales.

Lamb images show that DOR-L and HAM-L fibers have scales that wrap-around the fiber shaft, and some are angled. The SUF-L fiber scales stand out as round in shape without a definite pattern, and some scales slightly wrap around the fiber shaft. Both HAM-L and HAM-SUF-M fibers have scales that are not as raised as other sample's fiber scales. Scales on the SUF-L fibers are smaller than the scales on SUF-HAM-M fibers.

Overall, UC Davis wool fibers contain scales arranged in wrap-around and angled patterns according to Woods & Orwin's research. The exception is the SUF-L image that shows a fiber with polygonal and elongated scales that slightly wrap-around the fiber shaft. Combinations of scale patterns may be found along one fiber shaft, so some UC Davis breeds' fibers could be more varied in scale pattern than others. (Woods & Orwin, 1982).

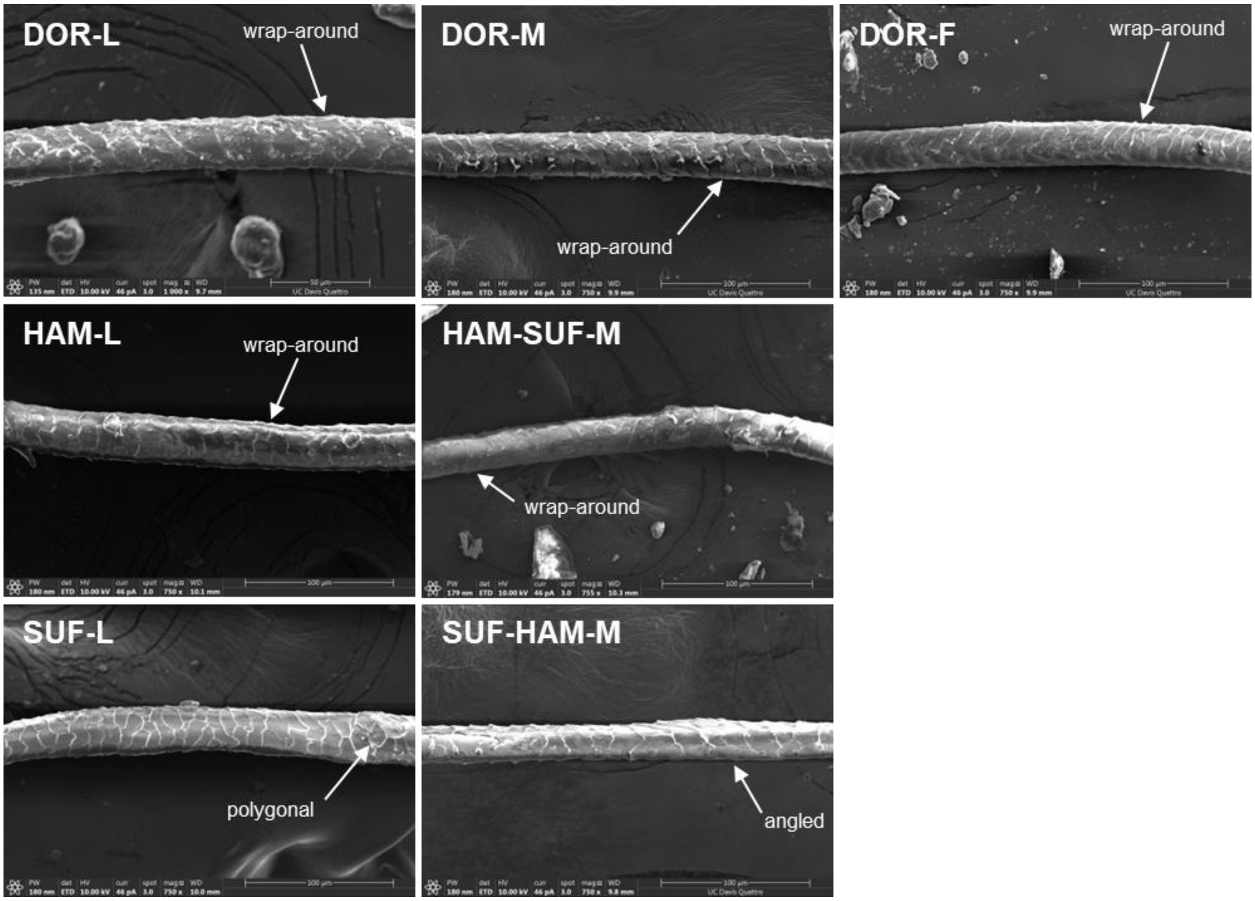


Figure 12. SEM images of Dorset (DOR), Hampshire (HAM), Suffolk (SUF), and HAM-SUF and SUF-HAM crossbreed fibers.

Comparison

Both groups of fleece samples are visibly distinguishable from each other. Navajo-Churro fleeces are long and lay naturally flat, but fleeces from DOR, HAM, SUF, and HAM-SUF and SUF-HAM crossbreed are tangled together due to crimp. Unlike BLND, MULT, GRY, and BLCK Navajo-Churro fleeces, the UC Davis fleeces are uniformly composed of one apparent fiber type. Although the BRN outlier Navajo-Churro fleece is also uniform in fiber composition, it has long fibers and does not show crimp like UC Davis fleeces.

Navajo-Churro guard hairs are the thickest and longest of the fibers surveyed in this study. Undercoat fibers and SUF-HAM-M fibers are similar in average diameter, but the rest of UC Davis fleeces contain fibers with slightly higher average diameters consistently above 34 µm. Average Navajo-Churro fiber lengths are much longer than lamb fiber lengths, but the average length of DOR-F fibers falls within the range of Navajo-Churro fiber lengths determined in this fiber study. Therefore, the aspect ratios of Navajo-Churro undercoat fibers are generally higher than those of all lambs and comparable to DOR-F.

High standard deviations for tensile measurements are expected for natural fibers. Navajo-Churro undercoat fibers have average modulus values that are slightly lower than UC Davis fibers overall, and the difference is significant. The average strengths of undercoat and UC Davis fibers are similar and around 160 MPa. Average fiber elongation at breaking is above 70% for BRN and GRY undercoat fibers and SUF-L fibers. All other undercoat and UC Davis fibers have breaking strain values ranging from 50-70% with all undercoat fiber values above 60%. Compared to breeds in relevant fiber surveys, the breaking strains for undercoat and UC Davis fibers are much higher (Table 2b).

Morphologically, at 10x magnifications using optical microscopy, Navajo-Churro guard hairs and undercoat fibers show no crimp. Images of UC Davis fibers at the same magnification show crimp, specifically in areas of diameter variation (Figure 11). The guard hair scale structure of Navajo-Churro sheep is the most distinguishable surface characteristic when compared to undercoat fibers and UC Davis sheep fibers. Navajo-Churro undercoat fibers have similar wrap-around and angled scale patterns to fibers from UC Davis fleeces. Such wrap-around and angled scale patterns could be better suited for wool felting than polygonal and elongated patterns. DOR-L, HAM-SUF-M, and SUF-HAM-M fibers have a comparable scale frequency to BLND, MULT, GRY, and BLCK undercoat fibers. The remaining UC Davis fleece fibers have a higher scale frequency looking at SEM images of 750x magnification, indicating that they are duller fibers and less ideal for felting than fibers with low scale frequency (Ghermezgoli, et al., 2020).

Color results show a range of colors within each fleece sample from all breeds studied in this fiber survey. Differences in shade throughout a fleece like in BLCK and HAM-L samples is reflected in CIE L*ab color values' high standard deviation measurements. No two fleeces within a breed are alike in color, as supported by the color difference equation (1). Collecting raw color measurements of wool is important for determining the process of color matching and dyeing.

CHAPTER 3: CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

Conclusions

Navajo-Churro guard hairs and undercoat fibers from its double-coated fleece have different fiber qualities that are presented in this study. Prior research conducted by the SRSBL in the 1930s documented Navajo-Churro wool physical characteristics that made the fibers ideal for Navajo weaving including fineness, length, and crimp (Grandstaff, 1942). This fiber survey confirmed Grandstaff's fiber dimension data and further completes fiber science information on Navajo-Churro wool (Table 2a). The physical characteristics, color, tensile properties, morphology, and surface characteristics of Navajo-Churro wool in this survey create a fiber standard for the breed. Navajo-Churro breeders may use this data to set parameters for wool quality and consider certain fiber qualities when crossbreeding. This fiber survey could also supplement ideal breed criteria requirements for registration of pure-bred sheep with the Navajo-Churro Sheep Association.

Navajo-Churro wool was studied in conjunction with wools from common northern California meat breeds. While the guard hairs in Navajo-Churro fleeces are coarse, the majority undercoat fibers are comparable in their medium fineness to Dorset and Suffolk/Hampshire crossbreeds. Therefore, as Navajo-Churro undercoat fibers are best suited for Navajo carding, spinning, and weaving, shorn meat breed wools also have potential for use in textiles as medium-type fleeces. Results of this fiber survey support the idea that common northern California meat breed sheep's shorn fleeces, currently an under-utilized byproduct of mutton processes, may be used for textile and other industrial applications, if not for fine clothing production.

Recommendations for Future Research

Certain additions to this fiber survey would make the profile of Navajo-Churro wool more complete. Not included in this study is the chemical analysis of wool fibers using Fourier transform infrared spectroscopy (FTIR) which would be beneficial for further documenting fleece colors for matching and dyeing. Identification of the wavelength of melanin would help with understanding the pigments present in fleeces. Accurately measuring properties of Navajo-Churro guard and undercoat fibers on a single tensile machine would further complete this study. Because the diameter of guard hairs is much higher than undercoat fibers, they could not be measured on the *Mantis*, so the *Instron 5566* was used to collect guard hair tensile data. The *Instron 5566* is built for industrial material testing, so the smallest load cell (2.5 N) was far too large for accurate measurements of single fiber tensile properties. Such guard hair measurements ranged from 2113 to 3374 MPa (modulus), from 74.8 to 131 MPa (strength), and from 36.5 to 50.3% (strain). Kemp fibers from Navajo-Churro fleeces were not studied in this survey because they are irrelevant to weaving practices according to Grandstaff's research. However, kemp fiber properties could be further explored in future Navajo-Churro wool research because they are prominent parts of fleeces and have no current useful applications.

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