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ESTONIAN LOCAL SHEEP WOOL PROPERTIES

RESEARCH ARTICLE

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Revaluation of Estonian local sheep wool – impact of different wool types on textile material properties

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ABSTRACT

The use of local sheep wool in Estonia – and consequently, sheep farming – has declined since the mid-20th century due to the increased availability of synthetic fibres and the import of finer, higher-quality wool. Nevertheless, it is possible to produce high-quality textiles from the more uneven local wool, indicating the need to revalue Estonian local wool and the textiles produced from it. There is limited research on Estonian local sheep wool (Estonian Darkhead, Estonian Whitehead, Kihnu Native sheep) fibre properties and no data on the combined effect of these fibre properties on textile material properties in various stages of textile production, such as yarn, knitted material, and knitted felted material. Therefore, specific fibre properties – including fibre length, linear density, diameter, cuticle scale height, and scale frequency – were analysed, and their combined effects on yarn, knitted material, and knitted felted material properties were evaluated. For comparison, wool from locally raised *Mérinos d'Arles* sheep was also analysed. The results showed that the fibres from the wool of Estonian breeds were more uneven, coarser, and longer, with higher linear density and lower cuticle scale frequency. However, yarns produced from these fibres demonstrated greater tensile properties. Material properties were influenced both by fibre and yarn properties.

1. Introduction

Sheep fleeces can be classified into three categories based on wool fibre types and their parameters [1,2]. These are archaic wool types with coarse overcoat wool hair, wool with transitional wool fibres, and fine wool. Hair sheep form a separate category [1]. Different wool types are used for different applications according to fibre properties. However, wool with less desirable properties – such as coarse and uneven fibres – is often left unused.

Estonian local wool is an undervalued bioresource, primarily due to its less desired properties. A significant portion of this wool is discarded, while at the same time, twice as much wool is imported for local textile production. The reason has been found to be the absence of a wool grading and purchasing system, as well as the absence of scouring facilities in Estonia [3–5]. To establish a functioning wool system, it is essential to understand the properties of local wool fibres and their effects on textile characteristics. However, in the case of Estonian sheep breeds' wool, research on fibre, yarn and textile properties, and their relationship is insufficient [6–9].

To enhance the use of Estonian wool and to develop a viable wool system, the influence of fibre properties on yarn and textile materials must be studied – the wool grading system should be based on fibre properties and possible applications of these fibres. Therefore, the aim of the study was to compare the properties of Estonian local sheep wool as fibres, yarns, knitted materials, and knitted felted materials, as well as to analyse how fibre properties affect textile properties. A possible application of felted knitwear was outerwear. Merino wool was additionally studied to compare Estonian breeds' wool to a desired and widely used wool in textile production. The following sub-sections provide an overview of sheep breeds and wool characteristics relevant to the study.

1.1. Sheep in Estonia

There are four Estonian sheep breeds: Estonian Native sheep (EML), with subgroups *Kihnu*, *Ruhnu*, *Hiiu*, *Saare*, and *Viru* [10,11]; Kihnu Native sheep (KML), an EML subgroup recognised as a separate breed; Estonian Darkhead sheep (ET); and Estonian

Fig. 1. Sheep in Estonia: Estonian Native sheep (KML breed) (a), imported sheep *Mérinos d'Arles* (b), Estonian Whitehead sheep (c), and Estonian Darkhead sheep (d). Photos by the authors.

Whitehead sheep (EV). The latter two were developed from EML sheep. In addition, many foreign breeds have been imported historically to meet the demand for fine wool [12,13]. Estonian sheep breeds are shown in Fig. 1.

EML sheep, native to Estonia [14,15], exhibit many aboriginal characteristics. Their wool is double-layered, consisting of an undercoat and overcoat and may also contain transitional wool fibres – coarser undercoat fibres with the properties of overcoat fibres. The undercoat contains fine, high-crimp fibres (10–40 μm), while the overcoat fibres are coarser and low-crimp (over 40 μm) [10]. EV and ET sheep were cultivated from EML sheep. Breeding began in 1926, and in 1958, both EV and ET were officially recognised as distinct breeds [16]. Both breeds produce transitional wool [1], and their wool has been characterised as having even quality and normal crimp [16].

1.2. Wool fibre properties

The properties of wool fibres are of great importance, as they influence the production of textile materials and the properties of the resulting yarns and textiles. Fibre properties vary among wool types and sheep breeds and are affected by breeding, living conditions, and nutrition [17]. Wool fibres typically range from 38 to 380 mm in length. A fibre length of 50–120 mm enables economical yarn manufacturing [18]. Fibre diameter is the primary parameter used for grading and pricing wool [19,20]. According to the micron system – the most technical classification – wool is categorised as fine (≤22.04 μm), medium or semi-fine (22.05–30.99 μm), coarse (31.00–36.19 μm), and very coarse (≥36.20 μm) [19]. Fibre fineness often determines the end use, as fibres with diameters over 30 μm may cause skin irritation and are therefore generally not used in apparel [20]. Crimp in wool fibres is associated with their mechanical properties [21]. The effect of crimp on fibre behaviour has been studied by Barach and Rainard [21], who have stated that the increase in crimp highly reduces the tensile strength of a fibre or yarn. Crimp also affects felting rate [22–24]. EML sheep wool is low-crimp, sometimes less than 1 cr/cm [12]. ET and EV wool have been characterised as having normal crimp [6], approximately 3–4 cr/cm [16]. Merino wool, in contrast, is high-crimp, usually exceeding 7 cr/cm [16,25]. The wool fibre cuticle consists of cuticle cells or scales with serrated edges. Scale frequency refers to the number of scales per 100 μm fibre length, often expressed as the number of scales per unit area or as an index in relation to the fibre diameter. Scale height indicates the height of the serrated scale edge above the underlying scale [26–29]. Both scale frequency and scale height influence felting tendency [26,27].

There has been little research on the fibre properties of local sheep breeds. While material properties have been assessed, fibre and yarn properties have not been widely studied, nor has their impact on material properties been thoroughly analysed. The relevant research is discussed below.

During the Soviet era, EV and ET wool were classified as crossbred wool of the 56 quality class (27.1–29.0 μm) [16]. A more detailed study of EV and ET wool was conducted in the 1990s by Kaie Zarens (now Ahlskog) [6]. Although the research focused on breeding, it provided comparative data. The average fibre diameter for EV wool was found to be 30.5 μm, while ET fibres were coarser, with an average diameter of 35.7 μm [6]. A more recent study was carried out at Pallas University of Applied Sciences (Tartu, Estonia) in 2019 [7]. In addition to examining the effects of sorting and processing, the study measured the fibre diameter of EML sheep wool. Fibre fineness was determined with an accuracy of ±5 μm. Ten fibres were measured from the sorted wool by wool type. The results showed that EML sheep wool fibre diameters ranged from 18 to 60 μm, with the average values as follows: lamb wool 37 μm, neck wool 31 μm, breech wool 32 μm, and coarse wool 52 μm [7]. The latest research on Estonian wool fibre parameters was conducted in a co-operation project between Estonia and Norway [8]. In this study, linear density was measured for KML, EV, and ET wool fibres, alongside yarn and material parameters. It should be noted that the testing environment did not comply with the standard atmosphere for conditioning and testing: the average temperature during testing was 26 ± 2 °C and the relative humidity was 44 ± 4% [8]. Linear density tests were conducted on unscoured wool samples taken from the sides and backs of sheep, as well as from slivers. The study determined the average linear density of unscoured wool as follows: EV – 16.21 dtex, ET – 13.31 dtex, and KML – 12.13 dtex. For wool fibres sampled from slivers, the average linear density was as follows: EV – 11.66 dtex, ET – 12.06 dtex, and KML – 11.15 dtex. The research also noted that linear density varied between herds [8].

1.3. Wool yarn properties

Three alternative yarn manufacturing systems are used to produce wool yarns industrially: the woollen (W), semi-worsted (SW), and worsted (WR) systems [18]. In Estonia, only the W and SW systems are currently in use. These systems differ in the number of processing stages, the machinery used, the suitability for different wool types, and the properties of the resulting yarns [30]. The W system is the simplest, involving the fewest production stages, while the WR system is the most complex [18,30]. In W yarns, fibres are not aligned through a dedicated process, unlike in the SW and WR systems. Misalignment leads to protruding fibre ends in W yarns. Additionally, longer fibres can undergo reversals in direction, contributing less to yarn strength than in a fully extended position. Consequently, W yarns are generally weaker than SW and WR yarns, where fibres are aligned. WR yarns are stronger than SW yarns because short fibres are removed during combing [30]. W yarns tend to be coarser and exhibit greater diameter irregularities than SW and WR yarns [18]. Yarns are stronger when the fibres have been combed into a parallel arrangement [30]. Moreover, fibre strength affects yarn strength. Bouagga et al. [31], who studied the properties of Tunisian wool, found that fibre tensile strength, tenacity, and elongation are correlated with fibre diameter. According to their research, coarser fibres demonstrated greater strength.

In the Estonia–Norway co-operation project, the tensile strength of SW yarns made from ET, EV, and KML wool (with a thickness of 316 m/100 g) was tested. The testing environment differed from the standard atmosphere for conditioning and testing, with the average temperature being 26 ± 2 °C and the relative humidity 44 ± 4% during testing [8]. The average maximum force sustained was 2251.64 cN for ET, 2217.08 cN for EV, and 2584.47 cN for KML yarns. The average elongation values were 8.98% for ET, 8.27% for EV, and 10.18% for KML yarns. The study noted that both the maximum force sustained and elongation were similar for ET and EV yarns, while KML yarns extended more and withstood a higher maximum force [8].

1.4. Woollen knitted textile structure and its properties

In addition to fibre properties and the yarn production method, textile properties also depend on the material structure [32]. Fibre and yarn properties, along with the stitch density during knitting, affect fabric properties and felting properties [33].

Pilling is one of the most critical properties for knitted materials. Pilling formation rate is affected by physical fibre properties, including tenacity, elongation at break, fibre length, fibre cross-sectional shape, and linear density. Moreover, the process is affected by the number of fibre ends, yarn twist, and fabric structure. Generally, longer staple fibres lead to less pilling, as fewer fibre ends protrude from the fabric surface per unit area. Coarser fibres tend to pill less due to their greater stiffness. Furthermore, fibres with an irregular cross-section are less prone to pilling because of the difficulty in bringing fibres to the surface, resulting in greater friction due to the irregular cross-section [34].

Siiri Nool [9] has compared different wool yarns manufactured in Estonian wool mills for producing a knitted felted product. Natural white SW and W yarns made from local wool were used. The knitted materials were felted in a washing machine. Nool evaluated the felting tendency of different yarns by measuring the dimensional changes of the samples after felting. Five SW and four W yarns were tested. She observed that materials knitted and felted from native sheep SW yarns felt more. These samples lost approximately 35% in height and 20% in width after felting. Wool yarn samples shrank by 22% in height and 11% in width. The sample that felted the least was made from EV and Texel crossbreed sheep wool [9].

At the Textile Department of Pallas University of Applied Sciences, research was conducted on the effects of wool sorting and processing on the properties of yarns and fabrics, using EML wool as an example. It was found that SW yarn produced more pills than W yarn made from the same wool. However, the thickness of yarns varied. Additionally, in the case of knitted materials, yarns made from finer, high-crimp fibres exhibited better abrasion resistance [7].

As part of the Estonia–Norway project, both knitted and knitted felted materials were studied. The mass per unit area of the fabrics was measured, and felting shrinkage was calculated as follows: 17.6% for ET, 23.56% for EV, and 17.18% for KML. The air permeability of these materials was also tested, and the reduction in air permeability due to felting was found to be 39.5% for ET, 37.1% for EV, and 52.8% for KML [8]. Abrasion and pilling resistance were also evaluated. For the knitted and the knitted felted materials, the average abrasion resistance was as follows: ET – 80 000 and 41 133 rubs, EV – 78 333 and 70 000 rubs, and KML – 60 000 and 65 000 rubs [8], respectively. It was stated that the knitted felted fabrics had less pilling than the knitted fabrics [8,35].

1.5. Felting tendency of wool fibres, yarn, and textile

Felting is a unique property of various animal fibres, including sheep wool. The basic mechanism behind felting in wool is thought to be the directional frictional effect (DFE) [36]. In addition to DFE, several fibre properties influence the felting process [26,36–39]. Furthermore, felting is affected by external conditions, such as felting duration, medium parameters, and material properties and structure [37,38].

Unal and Atav [26] have noted that fibre properties such as fineness, length, cuticular height, and cuticle scale frequency affect felting tendency. The combination of properties determines the felting tendency of certain wool types. Generally, it is accepted that finer wool fibres felt more than coarser fibres [26,39]. This is due to the higher bending rigidity of coarser fibres. However, many researchers have found that fibre length has an even greater effect on felting [26,38,39]. Additionally, greater cuticle scale height and scale frequency tend to increase felting tendency [26,27]. Fibre crimp also has a significant impact on felting, particularly when felting is done using wool batts. Many researchers have found that lower crimp increases the felting rate [22–24].

Many authors have determined that yarn twist, density of the woven cloth, and tightness of the knit greatly affect shrinkage of wool fabrics. Bogaty et al. [40] have stated that yarns with a higher twist exhibit a lower shrinkage rate, while plying has no significant effect. Moreover, it was determined that the denser the knitted material the more shrink resistant it is [40]. The same applies to woven cloth [41]. Van der Vegt [38] further observed that yarns with lower twist require less mechanical action to start felting. This suggests that increasing tension within a yarn or a yarn component (sliver or slubbing) reduces the rate of felting. Additionally, it has been found that SW yarns felt more readily than W yarns. This is because in SW and WR yarns, fibre crimp has largely been removed through gilling and combing. In contrast, W yarns retain more fibre crimp due to their bulkiness and the less aligned arrangement of fibres [37].

2. Materials and methods

2.1. Materials

In this study, wool fibres from three Estonian local sheep breeds were studied – Estonian Darkhead (ET), Estonian Whitehead (EV), Kihnu Native (KML) – and compared to those of a fourth breed, the locally grown *Mérinos d'Arles* (MRA). All abbreviations are listed in Table 1.

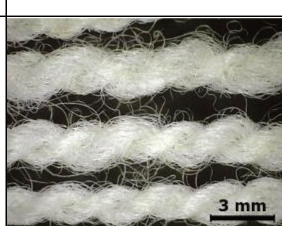
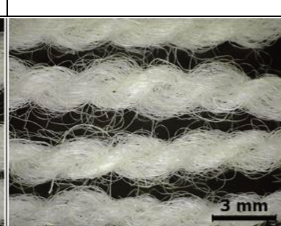
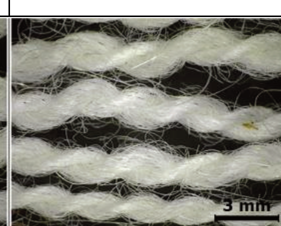
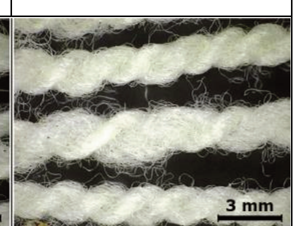
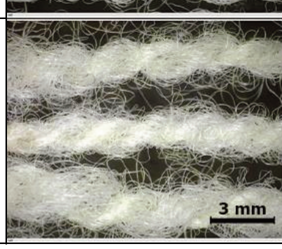
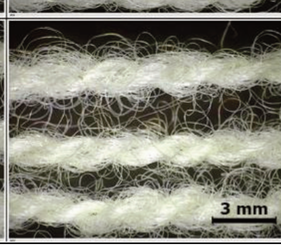
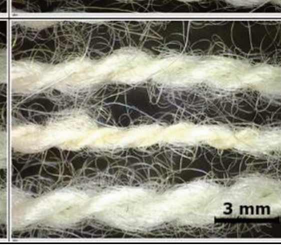
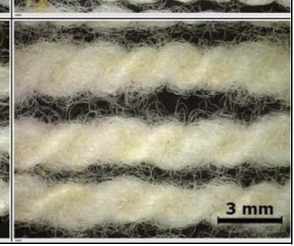
The aim was to give an overview of the properties of the selected wool types as fibres, yarns, and textiles, and to analyse how fibre properties affect textile properties. For testing, fibres per breed were obtained from a single herd. Therefore, the results do not give an overview of the average wool properties of each breed. Wool was collected from the following farms in Estonia: ET – Sireli farm, EV – Murese farm, KML – Õnnekivi farm, and MRA – Ala-Mähkli farm. All wool used in the experiments was white and scoured in Viljandi Vilma Wool Laboratory prior to testing. Approximately 10 kg of wool was collected from each farm. In all cases, the wool had not been sorted by quality. It was scoured to yield at least 5 kg of usable fibre for textile production. Wool was scoured in a semi-industrial washing machine Electrolux W5105S, using special wool scouring programmes. Scouring contained a rinsing and a washing cycle. The detergent 'Pro-fit Wool' by Cole & Wilson was used. ET, EV, and KML fibres were rinsed for 15 min in 60 °C water using 25 ml of detergent per 1 kg of wool. For MRA fibres with clean fibre bundle ends, the rinsing programme was the same, but 50 ml of detergent per 1 kg of wool was used. MRA wool with dirty fibre bundle ends was rinsed and soaked by hand three times for a total of 20 min in 40 °C water using 30 ml of detergent per 1 kg of wool. Washing was conducted at 60 °C for 75 min with 50 ml of detergent per 1 kg of wool.

A total of eight yarn types were produced. From each wool type (ET, EV, KML, MRA), two yarn types were spun – a W and a SW yarn. The photos are shown in Table 2. WR yarns were not produced, as no WR mills operate in Estonia. Yarn thickness was selected based on the most commonly produced size in Estonian wool mills: 8/2 yarn (com-

Table 1. Abbreviations for wool types, yarn production methods, and yarn types

Wool type by sheep breed	Abbreviation	Yarn production method	Abbreviation	Abbreviations for yarn types
Mérinos d'Arles sheep	MRA	semi-worsted	SW	SW_MRA
				SW_ET
Estonian Darkhead sheep	ET			SW_EV
				SW_KML
Estonian Whitehead sheep	EV	woollen	W	W_MRA
				W_ET
Kihnu Native sheep	KML			W_EV
				W_KML

Table 2. Produced yarns by wool type and yarn type; photos by digital microscope Dino-Lite, magnification 30x

Wool type → Yarn type ↓	ET	EV	KML	MRA
SW				
W				

mercial value) was manufactured. Analysing the same wool types as different yarns aided in understanding which yarn and material properties were affected either by the fibre properties or by the yarn structure. W yarns were produced in Süvahavva wool mill (an old mule spinning machine park from 1890), and SW yarns were spun in Vilma wool laboratory (machine park by Ramella). All yarns were held in skeins prior to testing to avoid stretching.

Plain knit specimens from each yarn type were produced using a Nika KH-868 knitting machine, class 5. Yarn tension was adjusted to suit the yarn thickness; stitch tension was set to the lowest possible level for knitting each yarn type – '10'. The appropriate felting method was determined by reviewing various studies [9,42–44] and conducting preliminary experiments. The selected felting method, detailed in Table 3, was suitable for felting small specimens. The knitted materials made from W and SW yarns of each wool type were felted together in a domestic washing machine (Samsung WF0600NCW) using the same amount of detergent during each washing cycle (W yarns contained some carding oil even after the initial yarn scouring). Photos of the knitted and knitted felted materials are shown in Table 4.

2.2. Methods

The standard test methods used in this study are presented in Table 5.

All tests – except for fibre diameter, cuticle scale frequency, and scale height – were conducted in the standard atmosphere for conditioning and testing, at 20.0 ± 2.0 °C and 65.0 ± 4.0% relative humidity, in accordance with EVS-EN ISO 139:2005/A1:2011. Sampling followed EVS-EN 12751:2000. For fibre tests, a 50 g laboratory sample was taken from each wool type, from which a 1 mg test sample was obtained through mixing and halving.

Fibre properties were assessed to evaluate both the felting behaviour and the mechanical properties of the yarn and the material.

Fibre diameter was measured from 60 individual fibres per wool type. Fibres were cut to a suitable length, spread on a slide and examined under an optical microscope (Axioskop 2 by Zeiss).

Fibre length was measured from a total of 150 individual fibres per wool type. A single fibre was measured between forceps. The fibre was extended to remove crimp without stretching.

Table 3. Felting parameters

Felting parameters	First felting cycle	Second felting cycle
Temperature, °C	40	40
Time, min	65	65
Centrifuge, rev/min	1000	1000
Wool shampoo by Orto, ml per 100 g of material	15	0

Table 4. Photos of the knitted and knitted felted materials

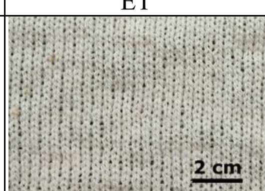
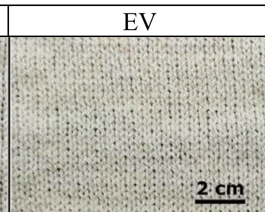
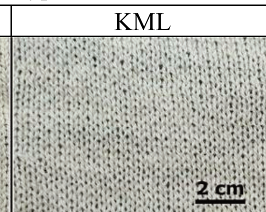
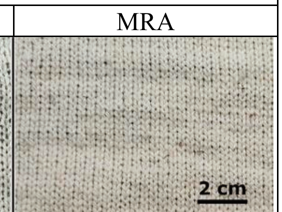
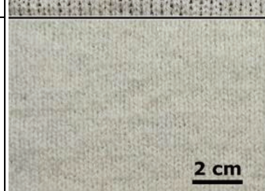
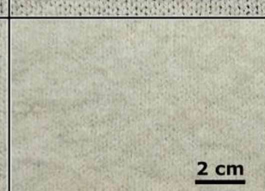
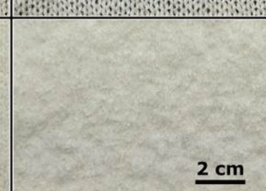
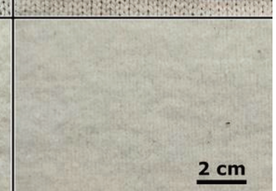
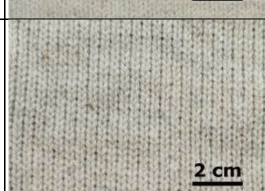
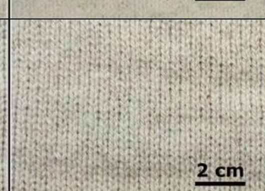
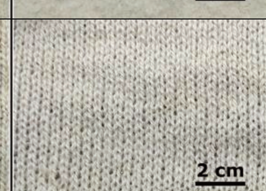
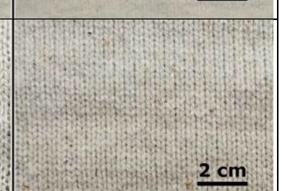
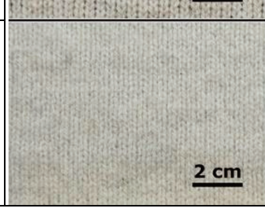
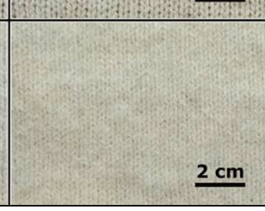
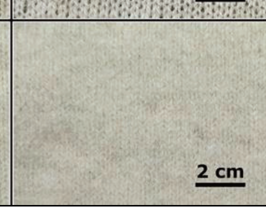
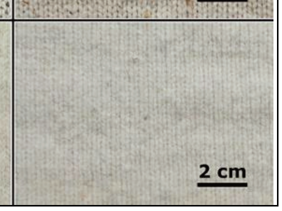
Yarn type	Material type	Wool type			
		ET	EV	KML	MRA
SW	Knitted material				
	Knitted felted material				
W	Knitted material				
	Knitted felted material				

Table 5. Standard test methods

Textile material	Parameter	Standard test method
Fibre	Diameter	Microscopic observation
	Length	ASTM D5103-07(2018) – Standard test method for length and length distribution of manufactured staple fibers (single-fiber test) [45]
	Linear density	EVS-EN ISO 1973:2021 – Textile fibres – Determination of linear density – Gravimetric method and vibroscope method [46]
	Cuticle scale frequency	Microscopic observation
	Cuticle scale height	Microscopic observation
Yarn	Linear density	EVS-EN ISO 2060:2000 – Textiles – Yarn from packages – Determination of linear density (mass per unit length) by the skein method; options 1 and 4 [47]
	Twist	EVS-EN ISO 2061:2015 – Textiles – Determination of twist in yarns – Direct counting method [48]
	Tenacity and elongation	EVS-EN ISO 2062:2010 – Textiles – Yarns from packages – Determination of single-end breaking force and elongation at break using constant rate of extension (CRE) tester; method C [49]
	Yarn evenness	Testing: ASTM D2255-02 – Standard test method for grading spun yarns for appearance Grading: CSN 80 0704:1973 – Determination of thread appearance [50]
Knitted / knitted felted material	Mass per unit area	EVS-EN 12127:2000 – Textiles – Fabrics – Determination of mass per unit area using small samples [51]
	Air permeability	EVS-EN ISO 9237:2000 – Textiles – Determination of permeability of fabrics to air [52]
	Thickness	EVS-EN ISO 5084:2000 – Textiles – Determination of thickness of textiles and textile products [53]
	Pilling resistance	EVS-EN ISO 12945-2:2020 – Textiles – Determination of fabric propensity to surface pilling, fuzzing or matting – Part 2: Modified Martindale method [54,55]
	Abrasion resistance	EVS-EN ISO 12947-2:2016 – Textiles – Determination of the abrasion resistance of fabrics by the Martindale method – Part 2: Determination of specimen breakdown [56]

Fibre linear density was measured from 100 fibres per wool type. A single fibre was fixed to a vibroscope (Vibroskop by Lenzing) under a suitable tensioning force using tensioning force clips.

Fibre cuticle scale frequency and scale height were measured by scanning electron microscopy (SEM). Microscopic observation was based on established techniques used in previous studies [26–29]. Five fibres were analysed per wool type. Prior to imaging, the fibres were prepared by removing the crimp without stretching them. The specimens were coated with a gold-palladium layer using a Jeol Fine Coat Ion Sputter JFC-1100, with a coating time of 2 min 30 s. SEM imaging was performed using a Thermo Scientific Phenom XL scanning electron microscope at an accelerating voltage of 5 kV. Scale frequency was measured from one position on each fibre (Fig. 2a). For this, the number of scales per 100 µm fibre length was counted – fully visible scales were counted as 1.0, partially visible ones as 0.5. The fibre diameter at the measured position was also recorded. For comparison, the estimated number of scales per 10 000 µm² was calculated. Scale height was determined from two scales per fibre with a total of 10 measurements (Fig. 2b).

Yarn properties were assessed to characterise material performance and felting behaviour. W yarns contained carding oils and required washing prior to use, unlike SW yarns.

Yarn linear density was measured from 10 skeins per yarn type, skein length being 10.000 ± 0.0025 m. Each conditioned test skein was weighed using a Mettler AE 200 balance. The linear density Tt_c was then calculated using Eq. (1):

$$Tt_c = \frac{m_c \times 10^3}{L}, \quad (1)$$

where Tt_c is the linear density (tex), m_c is the mass of the conditioned test skein (g), and L is the length of the skein (m) [47].

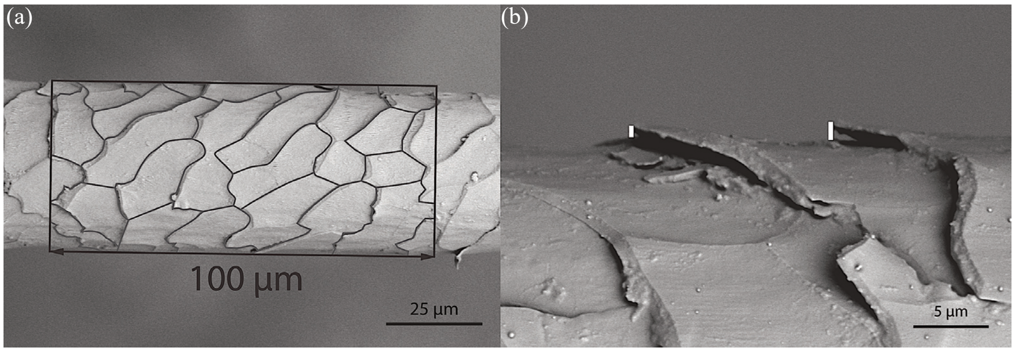


Fig. 2. SEM images: measuring the number of scales per 100 µm fibre length (a) and measuring scale height (b).

Yarn twist was determined from 10 specimens with a length of 60 cm from each yarn type. A specimen was fixed between the clamps of a twist counter, with a gauge length set to 500.0 ± 0.5 mm. The twist was removed and counted by turning a rotatable clamp. The average twist per test specimen t_x was calculated using Eq. (2):

$$t_x = \frac{1000\,x}{l}, \tag{2}$$

where t_x is the average twist (turns/m), l is the length of the test specimen before untwisting (mm), and x is the total number of turns observed in the test specimen [48].

Yarn tensile properties were tested on 10 specimens per yarn type. The gauge length of the tensile testing machine Instron 5866 was set to 500 ± 2 mm, and the length of the specimens was at least 100 mm longer. The specimen was clamped between the parallelly aligned test machine jaws with a pretension of 0.5 ± 0.1 cN/tex. Each specimen was extended until rupture. The extension rate of the moving clamp was set to 500 mm/min. A load cell with a maximum capacity of 500 N was used. Breaking force and elongation at break were recorded using the Instron Bluehill software. Breaking tenacity, expressed in centinewtons per tex, was calculated using Eq. (3):

$$B = \frac{F}{T}, \tag{3}$$

where B is the tenacity (cN/tex), F is the breaking force (cN), and T is the linear density (tex) [49].

Elongation at break, expressed as a percentage, was calculated using Eq. (4):

$$\varepsilon = \frac{\Delta l}{l_0} \times 100\%, \tag{4}$$

where ε is the elongation (%), Δl is the elongation at break (cm), and l_0 is the initial length of the specimen under pretension at the beginning of the test (cm) [49].

Yarn evenness was tested in accordance with the standards aimed for testing single spun cotton yarns but were deemed suitable for assessing wool yarns. Yarn boards (standard reference photos) were used for evaluation, graded from A (even yarn) to F (uneven yarn) [50]. For evaluation, the specimens were wrapped around a black surface in equally spaced turns. One specimen from each yarn type was assessed from both sides of the board in a VeriVide colour assessment cabinet under the artificial daylight D65. Bunches, covers, fuzz, neps, slubs, and thick and thin places were assessed. If the two sides of a specimen differed in appearance, the lower grade was assigned according to the standard.

Material properties – including stitch density, mass per unit area, air permeability, and thickness – were measured to assess felting behaviour. Pilling and abrasion resistance were also evaluated to assess material durability.

Mass per unit area was measured from five specimens per material. For each specimen, three length and three width measurements were recorded, and mean values were calculated. The area of each specimen was then determined from the mean values. Each specimen was weighed using a Mettler AE 200 balance. Mass per unit area M was calculated using Eq. (5):

$$M = \frac{m \times 1000}{A}, \tag{5}$$

where M is the mass per unit area (g/m^2), m is the mass of a test specimen (g), and A is the area of the same test specimen (cm^2) [51].

Air permeability was measured 20 times at different locations on each material using the FX 3340 MiniAir device, with a measuring range of 15–1500 l/m^2/s on a test area of 20 cm^2. A pressure drop of 100 Pa was applied. One side of each specimen was tested.

Thickness was measured from 10 different spots on each material. For testing, the specimen was placed undistorted on the reference plate of a Hans Schmidt & Co GmbH thickness gauge DD-50-T. The presser-foot, applying a pressure of 1 ± 0.01 kPa, was lowered onto the specimen, and the gauge length reading was recorded after 30 ± 5 s.

Pilling resistance was tested on three specimens per material on James Heal 5-position Martindale abrasion testing machine. The test specimen holder, guide spindle, and holder ring had a mass of 155 ± 1 g. The assessment of pilling and fuzzing was performed visually after a defined number of pilling rubs (125, 500, 1000, 2000, 5000, and 7000) and graded from '5' (no change) to '1' (greatest change) [54,55]. Visual assessments were conducted under the artificial daylight D65 in the VeriVide colour assessment cabinet.

Abrasion resistance was tested on three specimens per material on James Heal 5-position Martindale abrasion testing machine. The abrasion load parameters were set according to the apparel fabrics (9 kPa). Foam backings were not used. The test was conducted until 36 000 rub cycles were completed (a premium requirement for outerwear coat fabrics [57]). Visual assessments were done under the artificial daylight D56 in the VeriVide colour assessment cabinet after every 1000 rubs (up to 6000), 2000 rubs (from 6001 to 20 000), and 5000 rubs (from 20 001).

Felting tendency was evaluated by examining the influence of fibre properties on yarn characteristics and by comparing the properties of knitted and knitted felted materials.

3. Results and discussion

3.1. Fibres

3.1.1. Fibre diameter

The average fibre diameters of ET, EV, KML, and MRA wool are presented in Fig. 3. Fibre diameter distributions of ET, EV, KML, and MRA wool are shown in Figs 4–7. MRA wool exhibited the most uniform fibre diameter distribution across the wool batch, indicating consistency both between animals and within individual fleeces. In contrast, the other wool types showed broader distributions with multiple diameter range groups. On average, ET and EV fibres were very coarse, measuring 42.0 ± 8.8 µm and 41.6 ± 8.4 µm, respectively. KML fibres

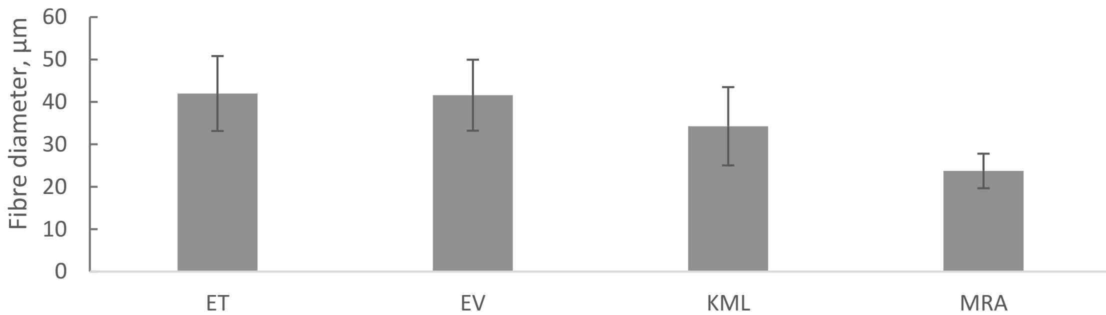


Fig. 3. Average fibre diameter.

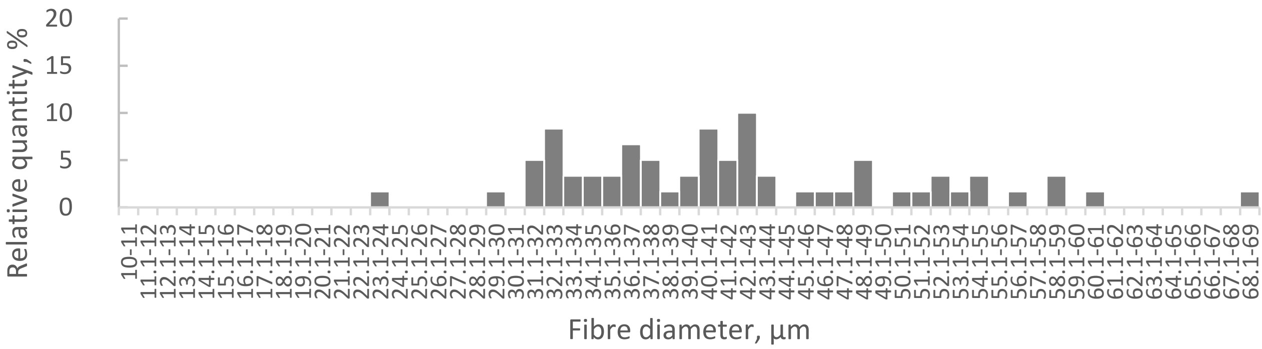


Fig. 4. Fibre diameter distribution of Estonian Darkhead (ET) sheep wool.

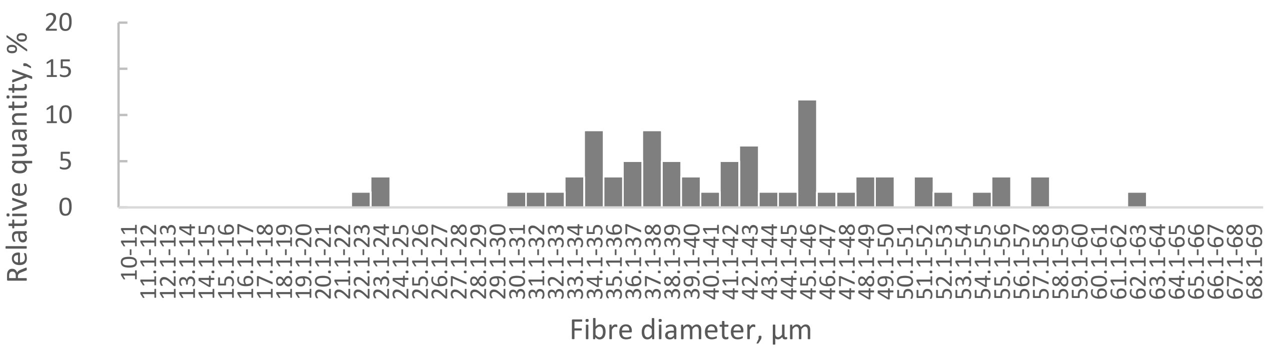


Fig. 5. Fibre diameter distribution of Estonian Whitehead (EV) sheep wool.

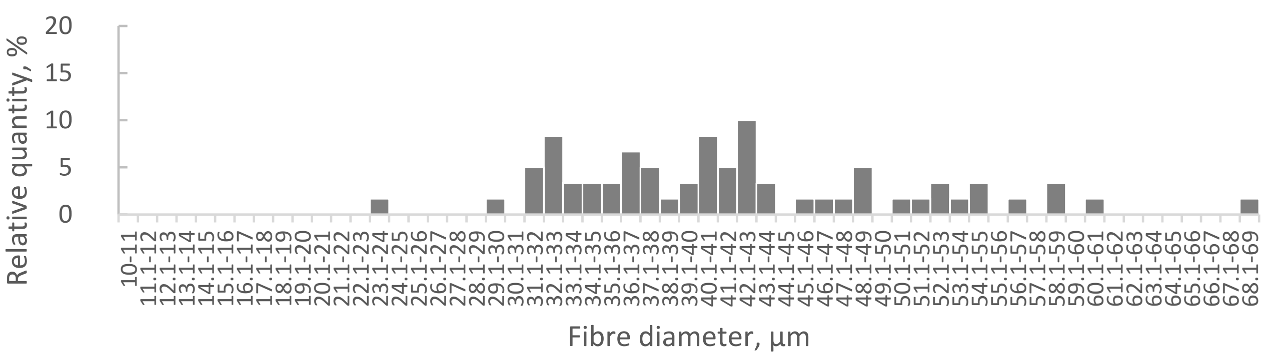


Fig. 6. Fibre diameter distribution of Kihnu Native (KML) sheep wool.

were coarse, with an average diameter of 34.3 ± 9.2 µm. MRA fibres were semi-fine, 23.7 ± 4.1 µm (according to the Soviet time system – fine, < 25.0 µm [16]). Optical microscopy revealed that 16.7% of the measured EV fibres were medullated, which affected the fibre linear density measurements by reducing fibre mass. The high linear density of KML fibres may be attributed to morphological differences, although these were not examined in this study.

The average fibre fineness of ET and EV wool, compared to the results from previous research, was coarser. Respectively, ET and EV average fibre fineness was 13.0 and 12.6 µm coarser compared to the measurements from 1980 [16], and

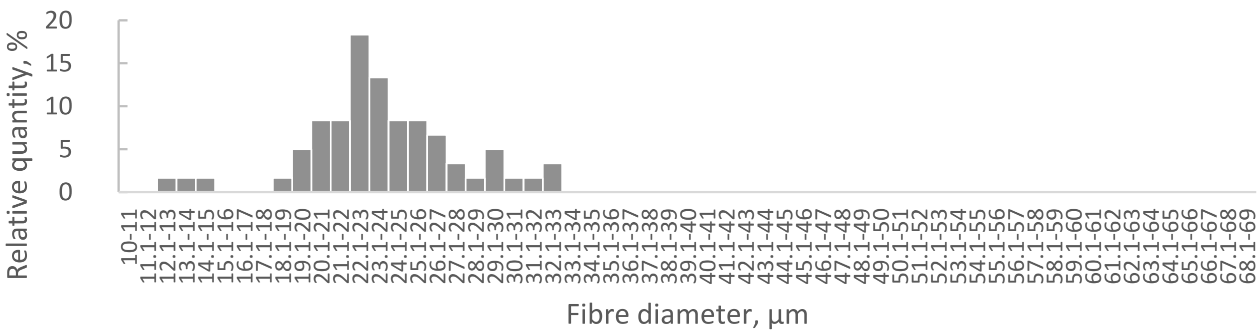


Fig. 7. Fibre diameter distribution of *Mérinos d'Arles* (MRA) sheep wool.

6.3 and 11.1 µm coarser compared to the measurements from the 1990s [6]. The fineness of the KML wool measured in this study was broadly consistent with the results from Pallas University of Applied Sciences [7].

3.1.2. Fibre length

The average fibre lengths of ET, EV, KML, and MRA wool are presented in Fig. 8. Fibre length distributions are shown in Figs 9–12. EV and MRA wool exhibited a single prominent peak in their distributions, indicating a relatively uniform fibre length within and between fleeces. The broader distribution observed in EV wool may be attributed to ongoing breeding efforts. In contrast, the fibre length distributions of ET and KML wool displayed multiple peaks, suggesting greater variability within the wool batches. EV wool contained the longest fibres, with an average length of 136 ± 34 mm. The average length of the other fibres was: KML 124 ± 41 mm, ET 121 ± 31 mm, and MRA 102 ± 23 mm. MRA wool was the most uniform. EV and ET wool was not as even, likely due to ongoing breeding – animals with varying wool quality exist within the same herd.

A 1980 study reported the average fibre length of both ET and EV wool as 106 mm [16]. The average fibre lengths measured in the current study were 15 mm and 30 mm longer, respectively. No previous data were available for KML wool.

3.1.3. Linear density of wool fibres

The average fibre linear density of ET, EV, KML, and MRA wool is presented in Fig. 13. Among all the samples, MRA wool exhibited the most uniform linear density. EV fibres were the most uniform among the Estonian breeds, though their distribution was still broader than that of MRA. Similarly to the fibre length results, ET and KML wool fibres showed broader distributions with multiple linear density groups, which once again was probably due to the variety of fibres in the wool batch. Linear density measurements indicated that, on average, KML wool fibres were the coarsest, 19.1 ± 7.4 dtex, followed by ET, 18.7 ± 4.8 dtex, and EV,

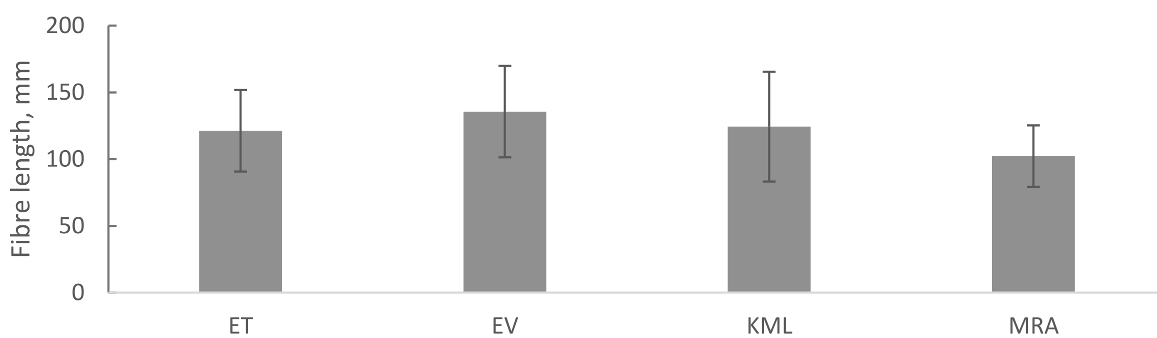


Fig. 8. Average fibre length.

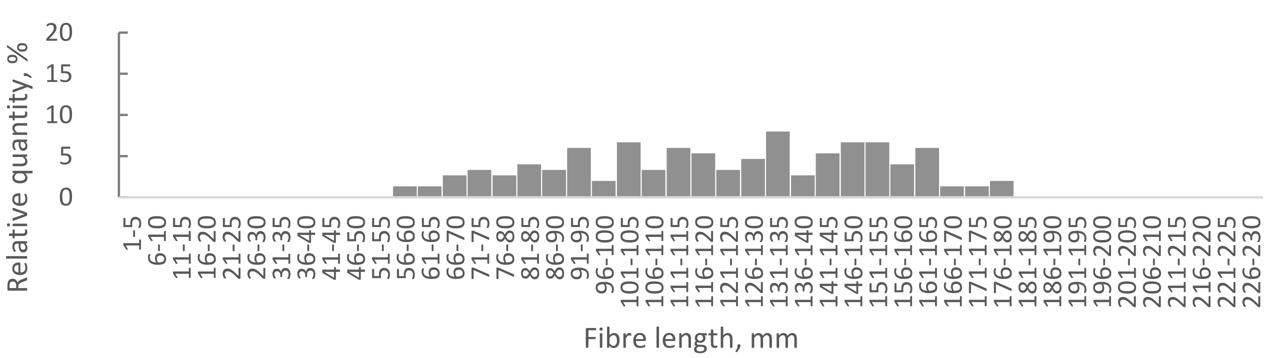


Fig. 9. Fibre length distribution of Estonian Darkhead (ET) sheep wool.

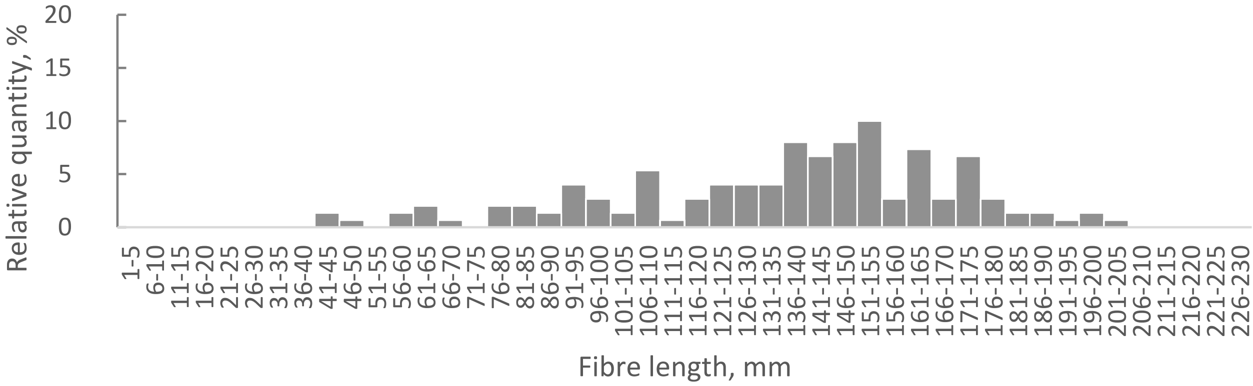


Fig. 10. Fibre length distribution of Estonian Whitehead (EV) sheep wool.

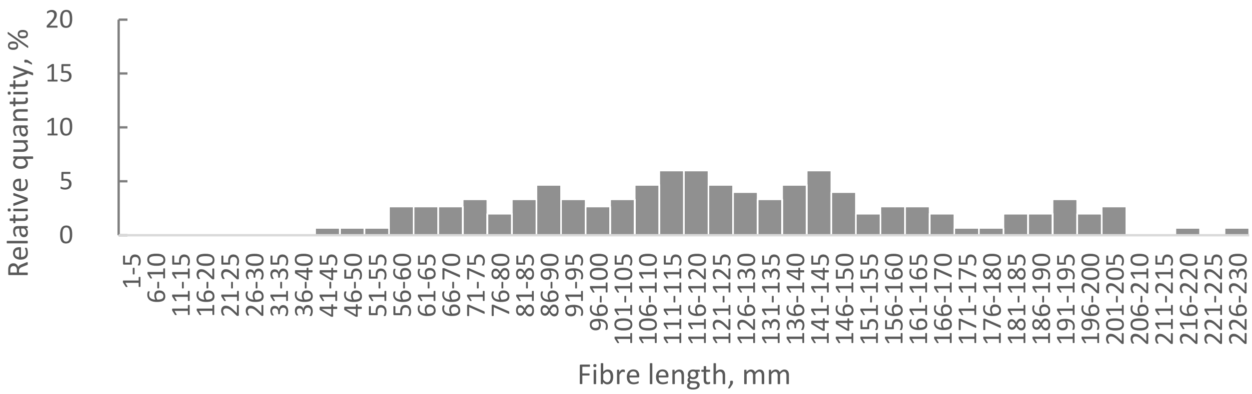


Fig. 11. Fibre length distribution of Kihnu Native (KML) sheep wool.

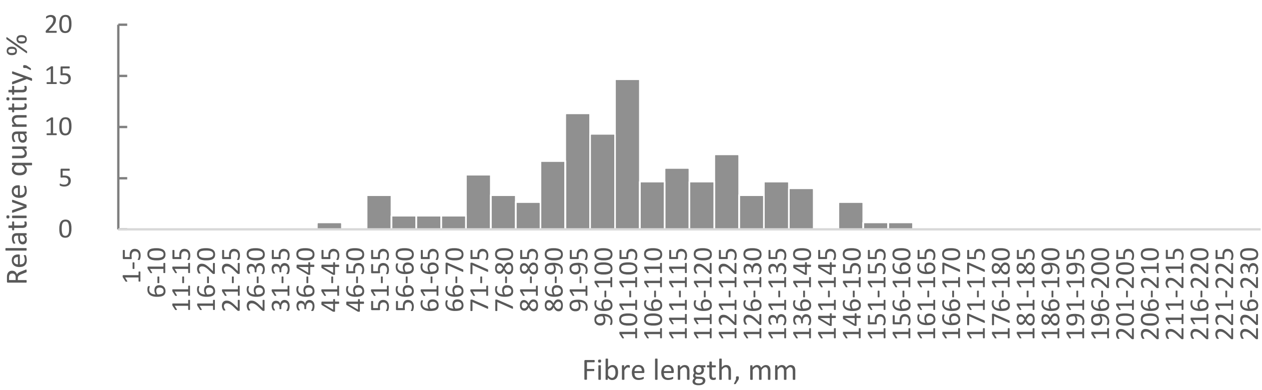


Fig. 12. Fibre length distribution of *Mérinos d'Arles* (MRA) sheep wool.

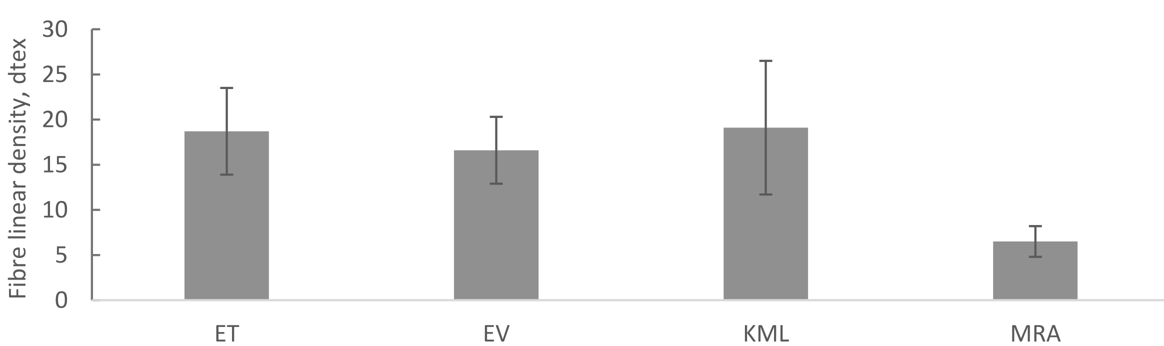


Fig. 13. Average fibre linear density.

16.6 ± 3.7 dtex. The linear density of MRA wool fibres was the lowest and therefore indicated the finest fibres, 6.5 ± 1.7 dtex.

The average linear density values obtained in this study were higher than those reported in the Estonia–Norway co-operation project, which measured unscoured wool [8]. However, the conditioning and testing conditions in that project differed from the standard atmosphere. The average linear density of the ET, EV, and KML wool measured in the current study was 5.39, 0.39, and 6.97 dtex higher, respectively. These differences may result from variations in herds, sampling methods, or testing environments.

3.1.4. Fibre cuticle scale frequency and cuticle scale height

The average fibre cuticle scale frequency and cuticle scale height are summarised in Table 6. These parameters have not previously been measured on Estonian wool. Representative SEM images are presented in Fig. 14. The results indicated that finer fibres generally exhibited a higher scale frequency than coarser ones – with the exception of EV wool. This observation contrasts with the findings of Raja et al. [27], who reported no significant difference between coarse and semi-fine fibres. The estimated average number of scales per 10 000 μm^2 ranged from 37.9 ± 7.0 to 46.4 ± 12.9. The average scale height was greater in finer wool types – again with the exception of EV wool. EV fibres exhibited highly serrated scale edges, distinguishing them from the other wool types. The average cuticular scale height ranged from 0.63 ± 0.18 to 0.88 ± 0.41 μm.

3.2. Yarns

3.2.1. Yarn linear density

The average yarn linear density is summarised in Fig. 15. For SW yarns, the linear density ranged from 346 ± 10 tex to 424 ± 16 tex, and for W yarns, from 460 ± 54 tex to 478 ± 28 tex. W yarns exhibited higher linear density values compared to SW yarns – a difference attributed to the variation in produc-

Table 6. Cuticle scale frequency and scale height

Wool type	Average number of scales per 100 μm fibre length	SD	Average estimated number of scales per 10 000 μm^2	SD	Average scale height, μm	SD, μm
ET	18.0	2.9	37.9	7.0	0.63	0.18
EV	18.1	5.5	39.4	7.9	0.88	0.41
KML	17.2	3.8	39.6	9.5	0.71	0.32
MRA	9.8	2.2	46.4	12.9	0.75	0.18

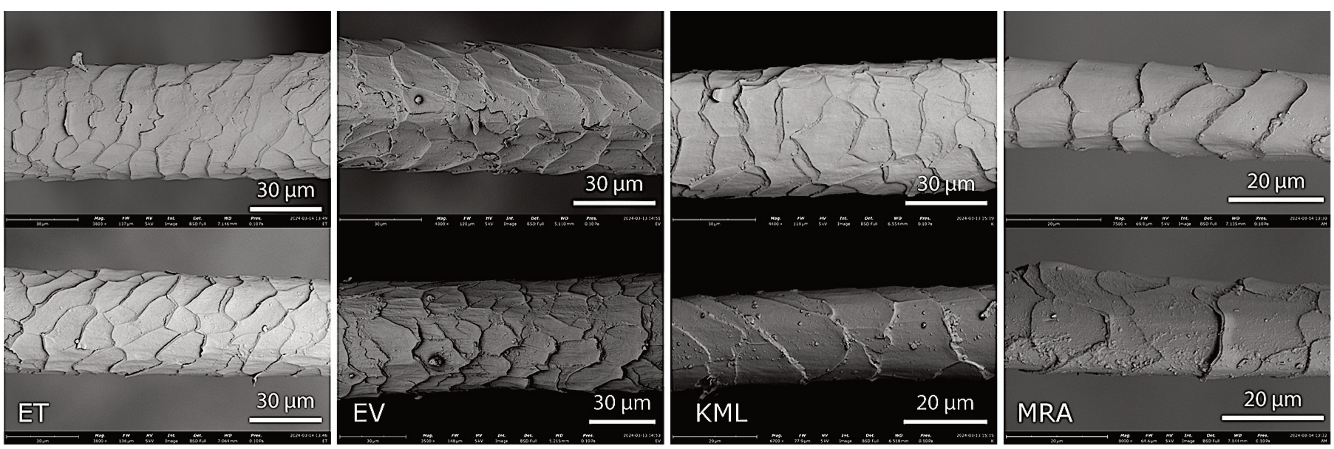


Fig. 14. SEM images of examples of wool fibres.

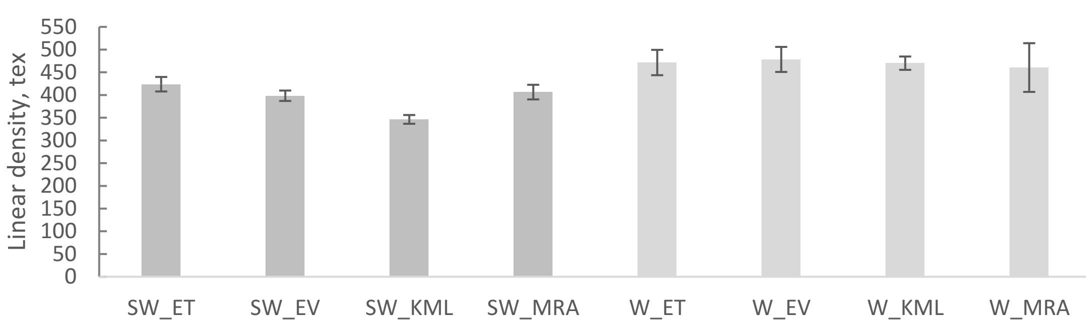


Fig. 15. Linear density of yarns.

tion methods. SW yarns differed between each other; in W yarns differences or irregularities occurred within the yarns themselves.

SW yarns varied due to the following reasons: during pin drafting of the slivers drafting times varied, drafting rate had to be regulated constantly, and sliver breakage occurred occasionally, influencing the consistency of sliver thickness. Consequently, yarn thickness had to be adjusted and compared visually during spinning, causing differences between yarns. In W yarns, unevenness mainly occurred due to outdated machinery. The average linear density of W yarns was more similar since the weight of the wool batch (which was similar for all yarns) largely determined yarn thickness. Among all yarns, the SW_KML yarn had the lowest linear density (346 ± 10 tex), while the W_EV yarn had the highest (478 ± 28 tex). In the following figures, a darker shade of grey indicates SW yarns and lighter shade W yarns.

3.2.2. Yarn twist

All the produced yarns exhibited a twist direction of Z (right-hand) in one-ply and S (left-hand) in plied form. The mean twist of different yarn types is presented in Fig. 16. The average yarn twist ranged from 146.5 ± 5.2 to 178.0 ± 10.7 turns/m for SW yarns and 163.8 ± 11.3 to 179.8 ± 11.6 turns/m for W yarns. Variability among SW yarns occurred between different yarn types, whereas in W yarns, irregularities were observed within individual yarns. When comparing the yarns by wool type, the average twist was similar between the two production methods, with W yarns exhibiting slightly higher twist values. The yarn with the lowest twist was SW_KML (146.5 ± 5.2 turns/m), while the highest twist was observed in W_MRA (179.8 ± 11.6 turns/m).

3.2.3. Yarn tensile properties

The average breaking tenacity of yarns (Fig. 17) ranged from 4.6 ± 0.2 to 6.4 ± 0.7 cN/tex in SW and 2.3 ± 0.3 to 4.2 ± 0.2 cN/tex in W yarns. Tenacity was higher in SW yarns, since parallelly aligned fibres are harder to pull out of a yarn. For both SW and W yarns, the tenacity values followed the same order by wool type, suggesting correlation with fibre properties. No correlation was found between wool fibre diameter and yarn tenacity, contrary to findings by Bouagga et al. [31]. The absence of correlation may be attributed to the high variance in fibre diameter.

Yarn tenacity was influenced by fibre length and crimp (visual assessment). Yarns produced from KML fibres exhibited the highest average tenacity within both production categories (SW_KML 6.4 ± 0.7 cN/tex and W_KML 4.2 ± 0.2 cN/tex). KML fibres were the second longest and contained few medullated fibres. In contrast, MRA yarns showed the lowest tenacity values (SW_MRA 4.6 ± 0.2 cN/tex and W_MRA 2.3 ± 0.3 cN/tex). Additionally, MRA average fibre length was the shortest. Moreover, fibre crimp influenced tenacity. KML fibres had the lowest and MRA fibres the highest crimp. Decrease in length and increase in fibre crimp reduced the strength of a yarn. The same was stated by Barach and Rainard [21].

Elongation at break of the different yarn types (Fig. 18) did not follow a clear pattern. The average elongation at break ranged from 23 ± 3% to 31 ± 5% in SW and from 24 ± 3% to 27 ± 3% in W yarns. Nevertheless, the order by wool type was consistent in both production methods: yarns made from KML fibres had the highest elongation at break (SW_KML 31 ± 5% and W_KML 27 ± 2%), followed by MRA, EV, and finally ET yarns. The reason, once again, could have been

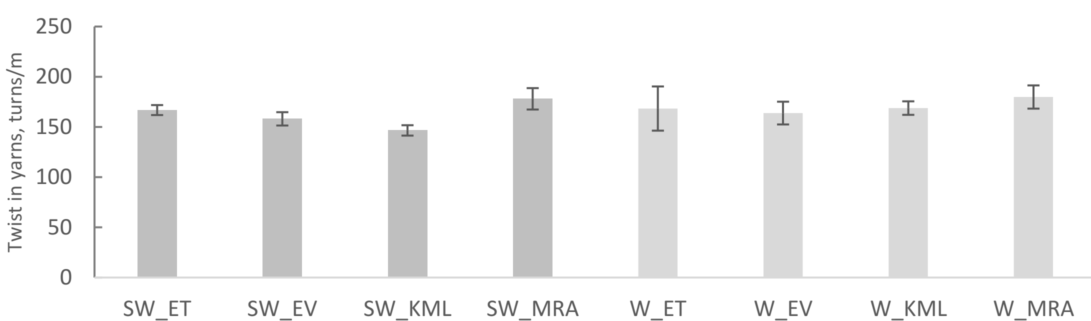


Fig. 16. Twist in yarns.

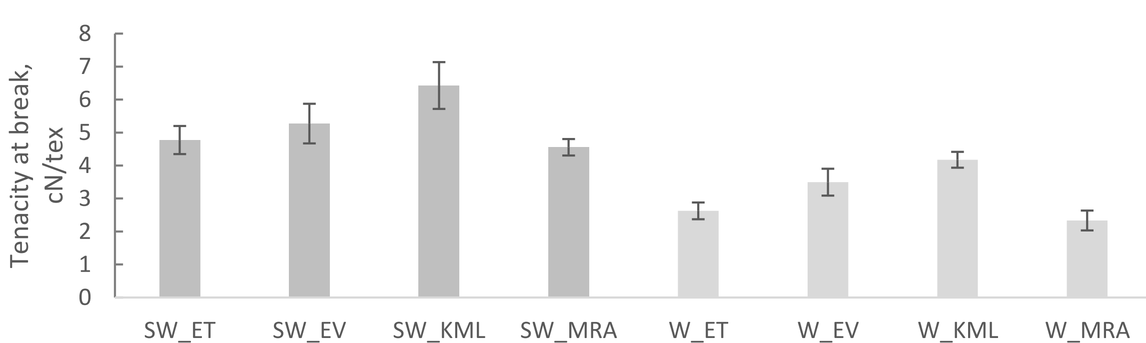


Fig. 17. Yarn breaking tenacity.

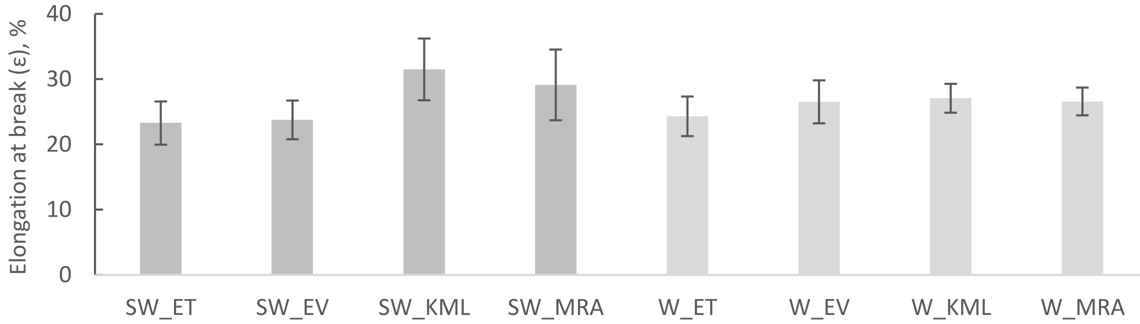


Fig. 18. Elongation at break of yarns.

fibre morphology. To make further conclusions regarding elongation and tenacity, broken specimen ends and morphological properties of fibres should be assessed. In both yarn production categories, KML yarns demonstrated the highest values of both tenacity and elongation at break.

Yarn tensile properties (maximum force and elongation) have previously been studied in the Estonia–Norway cooperation project [8]. Compared to the current research, the order of data by fibre type for average elongation at break was similar – native sheep yarn was the strongest and exhibited the greatest elongation. ET and EV results were similar to one another, yet the yarns were not as strong and elongated less. However, the results themselves differed – in the current study, maximum force was recorded to be lower and elongation much higher. This discrepancy is likely due to differences in testing and conditioning environments. The Estonia–Norway project employed higher temperature and lower humidity levels compared to the standard atmosphere. When humidity is higher (as in the standard atmosphere), then the strength of wool decreases and elongation increases.

3.2.4. Evenness of yarns – grading yarns for appearance

Grades for yarn evenness are summarised in Table 7. Overall, W yarns were more uneven, primarily due to the production process – in W yarns, fibres were not aligned along the yarn axis through a dedicated alignment process, which can lead to fibre reversals and, consequently, irregularities in the yarn structure. In SW yarns, fibres were aligned by a separate gilling process, thereby reducing irregularities inside yarns. Among the SW yarns, the one produced from MRA fibres was the most uneven, likely due to difficulties encountered during processing.

3.3. Fabrics

3.3.1. Mass per unit area of knitted and knitted felted materials

As a result of felting, the material becomes thicker and denser, leading to an increase in mass per unit area. Consequently, the area of the specimen decreases during felting. Dimensional change of the specimens is presented in Figs 19 and 20. Due to the felting process, the properties of knitted felted materials differ from knitted materials. Therefore, they can be used to assess felting shrinkage. Felting shrinkage is further discussed in Subsection 3.3.6.

The results of mass per unit area are presented in Fig. 21. The average mass per unit area ranged from 400 ± 14 to 600 ± 41 g/m^2 in the knitted and 555 to 1186 g/m^2 in the knitted felted materials. As SW yarns had a lower linear

Table 7. Yarn evenness graded from two sides of a yarn board, from A (even) to F (uneven)

Side No.	Grade by yarn type							
	SW_ET	SW_EV	SW_KML	SW_MRA	W_ET	W_EV	W_KML	W_MRA
1	B	C	C	E	D	D	C	D
2	C	D	B	D	D	D	C	D
Overall grade	C	D	C	E	D	D	C	D

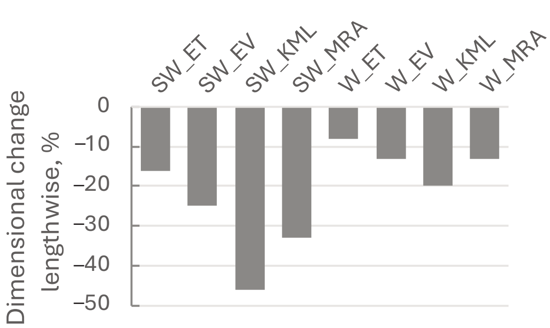


Fig. 19. Dimensional change of the knitted and knitted felted materials after felting, lengthwise (a single large specimen was felted).

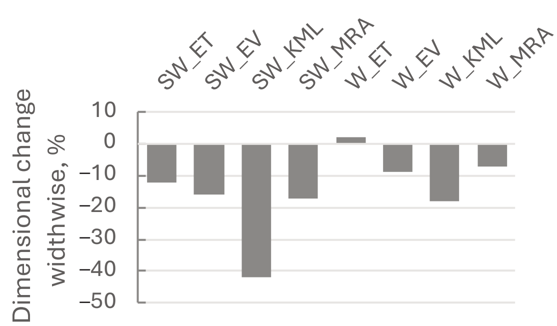


Fig. 20. Dimensional change of the knitted and knitted felted materials after felting, widthwise (a single large specimen was felted).

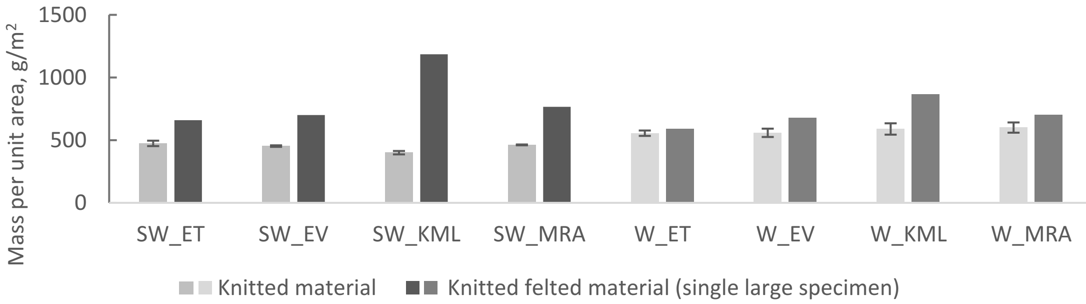


Fig. 21. Mass per unit area results of the knitted and knitted felted materials. In the case of the knitted felted materials, a single specimen was felted and therefore the standard deviation cannot be shown.

density, the knitted fabrics produced from these yarns were lighter. The knitted materials made from W yarns were heavier. Additionally, the evenness of yarns influenced the uniformity of the knitted material. In all the cases, mass per unit area increased after felting. The knitted felted materials made from SW yarns exhibited higher mass per unit area compared to those made from W yarns of the same wool type. The knitted felted materials produced from KML fibres had the highest mass per unit area – 1186 g/m^2 for SW_KML and 863 g/m^2 for W_KML. The knitted felted materials produced from ET fibres had the lowest mass per unit area – 659 g/m^2 for SW_ET and 589 g/m^2 for W_ET. Change in mass per unit area and dimensional change due to felting are further discussed in Subsection 3.3.6.

3.3.2. Air permeability of knitted and knitted felted materials

The results of air permeability of both the knitted and the knitted felted materials are presented in Fig. 22. The average air permeability ranged from 612 ± 88 to >1500 l/m^2/s in the knitted and from 294 ± 13 to 979 ± 67 l/m^2/s in the knitted felted materials. As all the yarns were knitted using the same stitch dial density to enable comparison after felting and fulling, air permeability in the knitted state was primarily influenced by yarn thickness and the evenness of the yarns. The materials produced from thinner yarns exhibited higher air permeability. The knitted materials made from SW_K and SW_EV yarns exceeded the measuring range of the device 15–1500 l/m^2/s.

Air permeability was also measured to characterise the felting properties of the fibres and yarns. In all the cases, felting reduced air permeability. A greater decrease in air permeability occurred when the specimens' mass per unit area had increased more (specimen had felted more). The lowest air permeability values were recorded for the knitted felted materials made from MRA fibres: 294 ± 13 l/m^2/s for knitted felted material produced from SW_MRA yarn and 368 ± 26 l/m^2/s for that produced from W_MRA yarn. This was likely due to the finer fibre diameter, which resulted in smaller voids and thus reduced air flow. Change in air permeability due to felting is further discussed in Subsection 3.3.6.

3.3.3. Thickness of knitted and knitted felted materials

Thickness of the knitted materials is summarised in Fig. 23. The average thickness ranged from 2.85 ± 0.07 mm to 4.46 ± 0.12 mm in the knitted and from 5.28 ± 0.23 to 8.18 ± 0.11 mm in the knitted felted materials. Yarn linear density influenced the thickness of the knitted materials. In the knitted felted materials, thickness was primarily affected by felting shrinkage. Increase in thickness during felting was greater in the materials made from SW yarns. Among the knitted felted samples, those made from KML yarns were the thickest – 8.18 ± 0.11 mm for SW_KML and 6.72 ± 0.16 mm for W_KML. The knitted felted materials produced from ET fibres were the thinnest – 5.31 ± 0.07 mm for SW_ET and 5.57 ± 0.07 mm for W_ET. Change in thickness is further discussed in Subsection 3.3.6.

3.3.4. Pilling resistance of knitted and knitted felted materials

The average results for the propensity to pilling of the knitted and knitted felted materials are presented in Table 8. All materials met the premium requirements specified for knitted materials in *Ecodesign criteria for consumer textiles*, 2021 edition [57] – grade 3–4 after 2000 pilling rubs and grade 2–3 after 7000 pilling rubs.

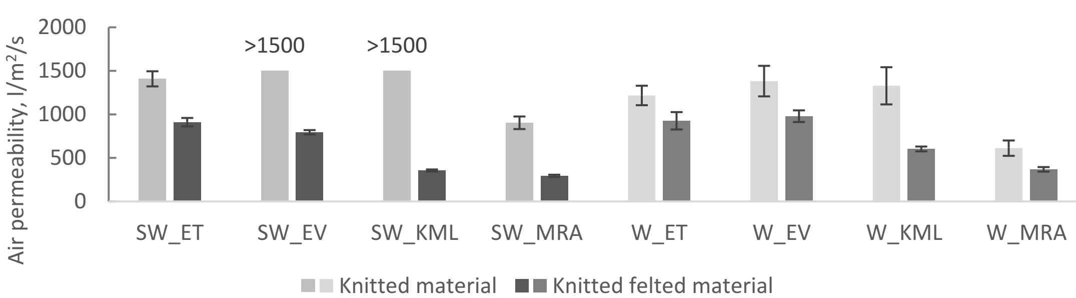


Fig. 22. Air permeability results of the knitted and knitted felted materials.

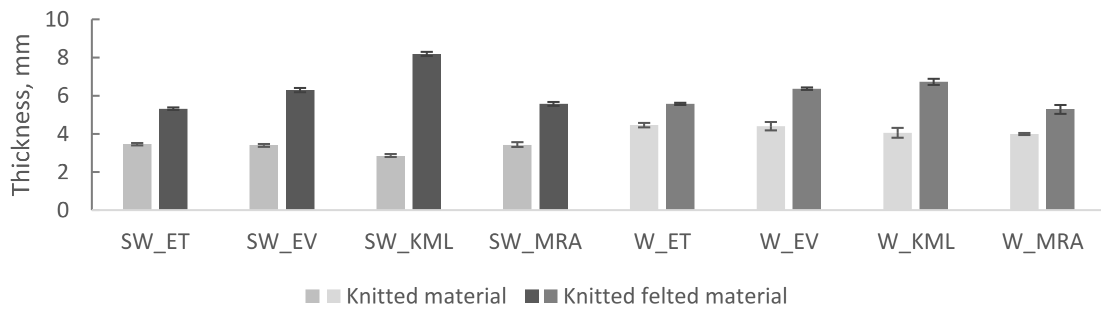


Fig 23. Thickness results of the knitted and knitted felted materials.

Table 8. Knitted and knitted felted material average pilling results, graded from 5 (no change) to 1 (severe change)

No. of pilling rubs	Knitted material average pilling results								Knitted felted material average pilling results							
	Grades by yarn type								Grades by yarn type							
	SW_ ET	SW_ EV	SW_ KML	SW_ MRA	W_ ET	W_ EV	W_ KML	W_ MRA	SW_ ET	SW_ EV	SW_ KML	SW_ MRA	W_ ET	W_ EV	W_ KML	W_ MRA
125	5	5	5	5	5	5	5	5	5	5	5	4	5	5	5	4
500	5	5	5	4	5	5	5	5	5	5	5	3	5	5	5	4
1000	5	5	4	4	5	5	5	4	4	5	5	3	5	5	5	3
2000	5	4	4	4	5	5	5	4	4	4	4	3	5	5	4	3
5000	4	4	3	3	4	5	5	4	3	4	4	3	4	5	4	3
7000	4	4	3	3	4	4	4	4	3	4	4	3	4	4	4	3

W yarns demonstrated better pilling resistance. This may be attributed to their higher linear density, which contributed to a denser structure in the knitted materials. Among W yarns, which were more similar in the average linear density and twist, the yarns containing longer fibres had higher pilling resistance (W_EV, W_KML). These yarns (fibres) also had higher tenacity. The yarns made of finer fibres produced most pills (MRA yarns). Moreover, soft-twist yarns (SW_KML) or the yarns containing un-spun regions (SW_MRA, W_MRA) exhibited lower pilling resistance compared to the yarns with higher twist. In these yarns, fibres were not tightly bound within the yarn structure, which favoured pilling.

During the felting process, lanolin and residual oils from the yarn production were washed off. This resulted in a hairier fabric surface, which overall favoured pilling slightly more. An exception was observed with the SW yarn produced from KML fibres – in this case, felting compensated for the yarn's softer twist, leading to a felted material with improved pilling resistance.

3.3.5. Abrasion resistance of knitted and knitted felted materials

All the knitted and knitted felted materials exhibited abrasion resistance of ≥36 000 rubs without reaching the endpoint, thereby meeting the premium requirement specified for coat and jacket materials in *Ecodesign criteria for consumer textiles* [57]. During abrasion resistance testing, pilling developed on the specimens. The life of the pills appeared to be influenced by yarn and fibre tenacity, as the order by pill life corresponded to tenacity values. In the knitted material tests, the specimens made from MRA and ET yarns exhibited shorter pill lifespans – these yarns also had lower tenacity values. Conversely, the materials produced from EV and KML fibres showed longer pill lifespans – these yarns additionally had higher tenacity results.

Pilling was present longer on SW yarns compared to W yarns. This can be explained by the more parallel alignment of fibres in SW yarns, which are therefore harder to pull out of the yarn. As a result, the phase where open fibre ends are pulled out of the yarn lasts longer, which lengthens the pilling phase and also the life cycle of the material. On the knitted materials made from SW_EV, SW_KML, and W_KML yarns, pills remained visible for 36 000 rubs. On the knitted felted materials, pilling was present longer compared to the knitted ones, and the pills were larger. Few pills were present at 36 000 rubs on all materials. However, in all the cases, the fibres protruding from the fuzzy felted surfaces were eventually abraded away.

3.3.6. Felting shrinkage of knitted and knitted felted materials

Materials knitted from W yarns might have felted less due to fibre crimp present in the bulkier W yarns. Additionally, SW yarns likely felted more as a result of their slightly lower twist, lower linear density of yarns, and a less dense material structure (especially SW_KML), all of which have been associated with increased shrinkage, as noted by Bogaty et al. [40]. In W_MRA yarn, the dense structure might have prevented high felting. Furthermore, the results suggested that felting was influenced by fibre properties, as the felting order by wool types was the same or similar across both production methods. KML fibres demonstrated the greatest felting tendency, followed by MRA and EV fibres, with ET fibres exhibiting the lowest tendency to felt.

Felting tendency was affected by fibre property combinations specific to each wool type. KML fibres displayed the lowest crimp, were among the longest by average fibre length, contained the longest fibre group, and by fineness were in between the researched wool types – in reality classified as coarse. These properties, except for coarseness, have been found to enhance felting, including greater fibre length [26,38,39] and lower crimp [22–24]. Fine fibres have been stated to felt more [26,39]. Moreover, KML fibres exhibited the second highest fibre scale frequency, and their scale height was moderate, similar to that of MRA wool. Both scale height and cuticle scale frequency have generally been reported to increase felting tendency [26,27].

It is highly probable that the combination of high fibre length, low crimp, and high cuticle scale frequency compensated for fibre coarseness in the case of KML fibres. In contrast, MRA fibres likely exhibited lower felting tendency due to their shorter fibre length and higher crimp, both of which are known to reduce felting. The low crimp and long length of KML fibres may have outweighed the felting potential typically associated with finer fibres. Among the other wool types, EV fibres exhibited a greater felting tendency than ET fibres, with ET fibres felting the least. While EV and ET fibres were similar in terms of diameter (both being very coarse) and crimp (normal), EV fibres were longer on average and had the highest cuticle scale height and greater scale frequency than ET fibres. Both the cuticle scale frequency and height of ET fibres were overall the lowest. These findings further support the conclusion that fibre length, cuticle scale frequency, and cuticle scale height positively influence felting behaviour. Results from all the experiments are presented in Table 9 and Fig. 24.

Within the SW yarn category, the knitted material produced from ET yarn felted the least, whereas the one made from KML fibres felted the most. Therefore, area shrinkage ranged from –27% to –69%, change in mass per unit area from +34% to +206%, change in air permeability from –35% to –76%, and thickness from +54% to +187%. The same pattern was present in the case of W yarns: the knitted material made from ET yarn felted the least and the one made from KML yarn the most, area shrinkage ranged from –6% to –35%, change in mass per unit area from +4% to +43%, change in air permeability from –24% to –55%, and thickness ranged from +25% to +66%.

The felting shrinkage results obtained in the current study were similar to the ones obtained by Siiri Nool [9]. It was observed that materials made from EML SW yarns felt the most. Additionally, the order of felting shrinkage by wool type in the case of ET and EV wool was consistent with the findings from the Estonia–Norway co-operation project [8]. The materials produced from ET wool felted the least and the ones from EV wool slightly more. The felting shrinkage

Table 9. Felting shrinkage and change in properties of the material after felting

Yarn type	Dimensional change – change in area, %	Change in mass per unit area, %	Change in air permeability, %	Change in thickness, %
SW_ET	–27	+34	–35*	+54
SW_EV	–37	+52	–47*	+85
SW_KML	–69	+206	–76*	+187
SW_MRA	–45	+73	–67	+62
W_ET	–6	+4	–24	+25
W_EV	–21	+19	–29*	+45
W_KML	–35	+43	–55*	+66
W_MRA	–18	+14	–40	+32

* Assessment accuracy was limited because air permeability exceeded the device’s measuring range in a number of samples, resulting in changes greater than the reported values

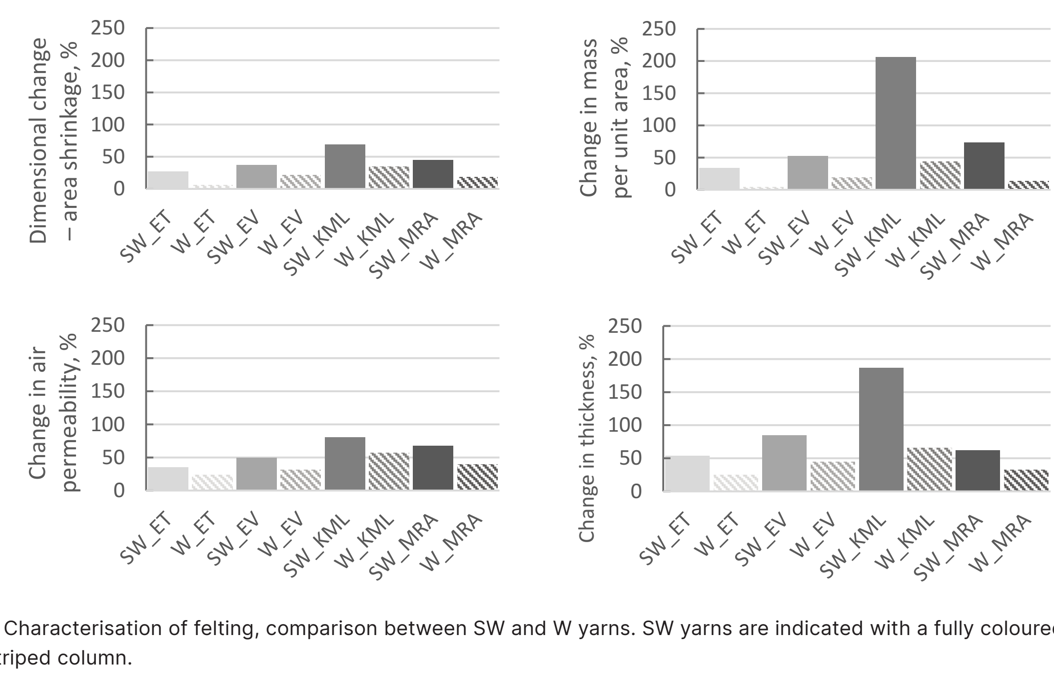


Fig. 24. Characterisation of felting, comparison between SW and W yarns. SW yarns are indicated with a fully coloured column, W yarns with a striped column.

of KML wool was reported to be lower than the one observed in the current study.

4. Conclusions

The studied wool fibres of Estonian breeds were found to be less even compared to the local MRA wool. MRA wool was of better quality. EV wool fibres were the most even from the studied Estonian breeds' wool. Compared to the local MRA wool, Estonian breeds' wool was found to be coarser, longer, and with higher linear density and lower cuticle scale frequency, while cuticle scale height varied. The main difference between Estonian breeds' and Merino wool was fibre fineness (MRA wool was 23.7 ± 4.1 µm on average and Estonian wool on average over 10 µm coarser).

Fibre properties were found to influence yarn performance. SW yarns were stronger compared to W yarns. Yarn tenacity was most affected by fibre length and crimp (visual assessment). The highest tenacity was observed in yarns made from long, low crimp fibres. KML yarns achieved the highest tenacity within both production categories (SW_KML 6.4 ± 0.7 cN/tex and W_KML 4.2 ± 0.2 cN/tex), and KML fibres had the lowest crimp and were among the longest (124 ± 41 mm). On the other hand, MRA yarns exhibited the lowest tenacity (SW_MRA 4.6 ± 0.2 cN/tex and W_MRA 2.3 ± 0.3 cN/tex), and MRA fibres had the highest crimp and were the shortest (102 ± 23 mm).

Material performance and felting were influenced by both fibre and yarn properties. In the pilling resistance test, all the knitted and knitted felted materials met the premium requirements set in the Ecodesign criteria – grade 3–4 after 2000 pilling rubs and grade 2–3 after 7000 pilling rubs. Pilling resistance of the knitted materials was predominantly influenced by linear density of yarn, twist in yarns, and fibre length and diameter. W yarns' pilling resistance was higher due to the higher linear density of the yarns, which produced a slightly denser fabric structure. Yarns made of longer and coarser fibres produced fewer pills. The knitted felted materials generally favoured pilling more – residual carding oils and lanolin were washed off during felting, which made the surface of the material hairy and therefore more prone to pilling.

In abrasion resistance tests, all the materials withstood the premium requirements set in the Ecodesign criteria, which is ≥ 36 000 rubs. The life of pills was associated with yarn and fibre tenacity. On materials made from yarns (fibres) with lower tenacity, life of pills was shorter. Moreover, pilling was present longer on SW than W yarns – fibres in SW yarns are more parallelly aligned and are harder to pull out of the yarn. This lengthens the life cycle of the material. Pilling was present longer on the knitted felted materials compared to the knitted materials, and the pills were larger.

Felting was influenced by fibre and yarn properties, and slightly by material structural differences. Yarn production technology influenced felting – SW yarns generally felted more than W yarns. W yarns might have felted less due to the presence of fibre crimp of bulkier W yarns. Additionally, slightly lower twist, lower linear density of yarns, and less dense structure of the material (especially SW_KML) could have enhanced the felting of SW yarns. Felting was affected by fibre properties – the order by wool types between the two production technologies in many cases was the same or similar. KML fibres had the greatest felting tendency, followed by MRA and EV fibres. ET fibres' felting tendency was the lowest. Fibre properties that enhanced felting were lower crimp, longer fibre length, finer diameter, higher cuticle scale frequency, and higher cuticle scale height.

The findings of the study are essential for

1) establishing a working wool grading system, which is based on the influence of fibre properties on textile material behaviour during use, and
2) finding suitable application for Estonian breeds' wool.

Author contributions

Liisa Torsus: conceptualisation, methodology, validation, research, resources, data curation, writing – original draft preparation, visualisation; **Tiia Plamus**: conceptualisation, methodology, validation, data curation, writing – review and editing, supervision; **Katrin Kabun**: conceptualisation, validation, writing – review and editing, supervision; **Urve Kallavus**: data curation – SEM, writing – review and editing.

Data availability statement

Data are contained within the article.

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Eesti kohaliku lambavilla taasväärtustamine – erinevate villatüüpide mõju tekstiilmaterjali omadustele

Liisa Torsus, Tiia Plamus, Katrin Kabun ja Urve Kallavus

Eesti lambatõugude vill leiab väheldast kasutust. See on väärindamata bioressurss, mis vajab taasväärtustamist. Kohaliku villa kasutuse suurendamiseks on peetud vajalikuks villa käitlemise ja hindamise süsteemi loomist ning villapesula asutamist. Sellise süsteemi loomiseks on vaja teada villakiu omaduste mõju tekstiilmaterjali omadustele. Varasemad kohalikud uuringud on olnud ebapiisavad just kiu omaduste ning silmuskootud materjali ja vanutatud silmuskootud materjali vaheliste seoste uurimisel. Käesolevas artiklis võrreldakse Eesti kohaliku lambavilla kiu, lõnga ja tekstiilmaterjali omadusi ning analüüsitakse kiu omaduste mõju tekstiilmaterjalile. Võrdluse loomiseks kaasati ka kohalik meriinovill, mis on tekstiilitööstuses laialdaselt kasutusel olev villatüüp. Uuringus hinnati villakiu omaduste mõju lõnga, silmuskootud materjali ja vanutatud silmuskootud materjali omadustele. Katsete tulemused võimaldavad leida kohalikule villale erinevaid kasutusvaldkondi ning anda soovitusi villa hindamissüsteemi väljatöötamiseks.

Tulemused näitasid, et Eesti lambatõugude vill on kohaliku meriinovillaga võrreldes pikem, kuid ebaühtlasema pikkusega, jämedam, kohati säsikanaliga ning väiksema soomuste sagedusega ja üldjuhul madalama soomuste kõrgusega. Eesti lambatõugude villast kedratud lõngad osutusid seevastu tugevamaks. Tugevaimates lõngades kasutatud kiud olid pikemad, laugema säbarusega ja vähese säsivillkarvade sisaldusega. Poolkammlõngad olid tugevamad. Pikkade ja jämedate kiudude kasutus ja lõnga suurem keerdumus vähendasid materjali kalduvust topiliseks muutuda. Vanutatud materjalid muutusid topiliseks kergemini kui silmuskootud materjalid, kuid talusid hõõrdumist paremini, kui neis oli kasutatud tugevamaid lõngu.

Viltumisomadusi mõjutasid kiu omadused – laugem säbarus, pikem kiud, väiksem diameeter ning suurem soomuste sagedus ja kõrgus soodustasid viltumist. Villakiu pikkus mõjutas viltumist rohkem kui peenus. Poolkammlõngadest valmistatud materjalid vanusid rohkem. Kiu omaduste erinevused mõjutasid lõnga ja tekstiilmaterjali omadusi ning kvaliteeti, mistõttu on vaja luua villa hindamissüsteem, mis arvestab nii kiu omadusi kui ka villatüüpe. Maalamba vill erines Eesti tumeda- ja valgepealise tõu villast, mis sarnanevad mitme omaduse poolest ja sobivad seetõttu ka segamiseks. Hindamissüsteem peaks arvestama nii villakiu pikkust kui ka läbimõõtu: kiu pikkus mõjutab otseselt tekstiilmaterjali tugevust, peenus aga villase rõiva kandmismugavust. Medullatsioon vähendas villa tugevust. Eesti lambatõugude villa ebaühtlus ei avaldanud lõnga ega materjali omadustele negatiivset mõju võrreldes kohaliku ühtlasema meriinovillaga.