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Effect of dehairing on llama fibre aiming to improve its homogeneity and textile quality

Abstract

The aim of this work was to demonstrate the effect of dehairing on the content of objectionable fibres and fibre length, in relation to different fleece types of Llama fibre, evaluating the degree of improvement regarding the homogeneity and general textile quality. Sixteen (16) llama fleeces of different fleece types where analysed while being processed by the AM2 dehairing technology. The analysis was implemented regarding fibre groups (FGs) as well as regarding fibre types. The total mean fibre diameter of the dehairing product (TMDnd) of all fleeces of 29.3 µm at the beginning was reduced to 25.9 µm after the first 3 passes through the AM2. With the successive passes, the TMDnd is further reduced, reaching 24.9 µm after the tenth pass, with a total reduction of 4,4 µm. The study with respect to the dehairing process reaffirmed a favourable modification implying an improvement with respect to the textile quality of the fibre. It was confirmed that, firstly, this is due to the separation of the coarse fibres, which are included in the subproduct and, at the same time, it is due to the increase of the relative weight of fine fibres (FG3) in the dehairing product, thus reducing the TMDnd of this product as well as the prickle effect due to the reduction of objectionable fibres. However, it arises the need to consider the existing context of fibre production which includes fleeces of varied textile value, including coarse fleeces whose fine fibres are not fine enough. It was therefore concluded that, for the production of fine textiles, dehairing alone cannot guarantee a sufficiently fine dehairing product, but it must be implemented after the fleeces have been classified regarding fineness. Also, classification regarding fleece type (FT) was found to be fundamental in order to obtain homogenous raw material for the textile industry. It was confirmed, that dehairing reduces the mean fibre diameter, and this is due to the separation of the coarse fibres out of the dehairing product, while the diameter of the fine fibres stays the same. With respect to the objectionable fibres, which are represented by the coarse fibre group (FG1), it was revealed that the dehairing process clearly reduces this variable for all dehaired fleece types, but the relative weight is not reduced below the desired threshold of 3% for all of them. In addition, it was noted that the large medullated fibres that are very coarse are separated more effectively, whereas coarse continuous medullated fibres are more problematic in this respect and it was also noted that further trials need to be undertaken to address this issue. The fibres belonging to the group of fine fibres (FG3) are the shortest ones, but they remain above 7 cm in the product of dehairing even after the tenth pass.

Keywords: fleece type, dehairing, variability, dissection, classing, objectionable fibres, textile raw material, natural fibre

Volume 10 Issue 6 - 2024

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Received: November 06, 2024 | **Published:** November 19, 2024

Introduction

Nowadays the global environment faces a serious challenge due to microplastic pollution. Trough exploring and promoting natural fibres like wool, cashmere, llama, alpaca, and mohair as alternatives to synthetic fibres utilized in textiles is a significant step to achieve a more sustainable fashion. With a deeper understanding of the properties and benefits of these fibres, a shift towards environmental preservation in the textile industry can be encouraged.[1] Also, new investigation on animal fibre of which only a minority is currently used can add to this issue, such as on dromedary camel fibre.[2] Regarding llama fibre, there is a perspective related to its production due to its excellent textile behaviour. Textile quality is given by the mean diameter and its distribution, by the fleece types that constitute differentiable structures, and, to a lesser extent, by the colour of the fibre.[3]

The price the producer receives per kilogram of fibre is mainly determined by its colour and its mean diameter.[4] This means that, if a producer sells white fleeces, the price they receive per kilogramme is different from the one they receive for coffee-coloured or black fleeces. It also means that if they sell fine fleeces, its price per kilogramme is differential, because the fibre is of better textile quality. According to McGregor,[5,6] a small total mean fibre diameter is the most important factor regarding the market value of alpaca fleeces in Australia. On the other hand, since a fibre producer sells the fibre in kilogrammes, this logically means that, depending on the amount of fibre sold, the producer's income varies. However, the price does not vary regarding the amount of fibre sold. This is because, for example, a producer who sells 10 kg of fibre of a certain quality obtains the same price (pesos/kg or dollars/kg) as a producer who sells 100 kg of fibre of the same quality.

In short, producers can improve their incomes by producing and selling more quantity and, at the same time, by improving the quality of the fibre. The latter one, as long as the better quality is reflected in a higher price. Undoubtedly, better fibre quality leads to a higher value for the consumer of a textile clothing, but this value does not automatically translate into a higher price for the raw material. In the practice of fibre production, this is reflected in the fact that a fleece from a young animal of superfine fibre can weigh between 1.5 and 1.7 kg approximately; while a fleece from an old animal of very coarse fibre can weigh 3 kg or more. Thus, if an animal produces a heavy fleece, on the one hand, this has the potential to increase the producer's income by selling more kilogrammes, but, on the other hand, if the fleece is heavy because it is coarse fibre, it may reduce the possibility of income due to obtaining a low price per kilogramme or, directly, not finding a buyer. Therefore, the debate of this research is framed in the dilemma between quantity (kg) and quality (reflected in pesos/kg or dollars/kg) of the fibre.[7,8]

Regarding how to achieve a lower total mean fibre diameter (TMD), there are two main possibilities, the genetic method, on the one hand, and the implementation of the dehairing, on the other hand. The genetic method involves selecting breeding animals by giving priority to animals having fine fleece and a reduced coarsening regarding the increasing age, particularly when selecting the breeder male for mating, and thus reducing the increase in the fibre diameter of the flock as the animals get older. However, for Peruvian alpacas, it was determined that it would be difficult to obtain quickly a better genetics through the selection of animals favouring a reduced micron blowout. The genetic problem of reduced coarsening by age is the low heritability of the trait (0.18) which would imply a very slow response to selection.[9] On the other hand, research on Australian alpacas related to the micron blowout and selection concluded that there is an opportunity to improve the TMD and VC of alpaca fibre by the selection, but without quantifying the method.[10]

However, it should also be considered that the priority for each llama breeder is different and a selection in favour of fine fleece and reduced micron blowout animals may not necessarily be implemented, as the llama is a multi-purpose animal. The llama is described as an important element of cultural identity and main livelihood for small producers in the Central Andes of South America, including Argentina, providing meat, milk, fibre, transport energy and guano.[11] In addition to these traditional purposes, there are more recently developed purposes, such as tourism activities, either as an animal being part of sight-seeing and animal watching or for activities involving trekking and hiking accompanied by llamas, and even as a trained animal for therapeutic activities. Therefore, it is pertinent to investigate solutions to achieve greater fineness regardless of the method related to genetic improvement and to produce the desired raw material from the llama population as it is.

If that is the case, one possible measure to achieve a better textile quality is the implementation of the dehairing, which allows to reduce the content of the so-called objectionable fibres to tolerable levels so as not to cause prickle and to reduce the mean diameter.[12,13] The understanding of the mechanisms at work during the textile process of dehairing that result in the separation of the different fibre types is justified on the basis of the dehairing theory.[14] Dehairing is a production step that is designed to satisfy the need to homogenise animal fibre, particularly in cashmere,[15] but it has not been sufficiently studied in relation to llama fibre.

Through a work realized with panellists who sense more or less prickle on the skin coarse fibre measured by weight/fibre total weight of 3.23% was detected in yarn and 4.57% in fabric surface,[12] which leads to a threshold of 3% or less to be reached by dehairing. In this context it is fundamental to explore the sensation of llama fibre textiles on the skin through the assessment of consumers as done by Frank et al.,[16] concluding that the prickle effect detection thresholds in lama fibre fabrics range from 2.36 to 2.42% in coarse fibre differences and from 0.11 to 1.63 microns in fibre difference. Furthermore, a higher percentage of coarse fibres were detected on the surface of yarn than within the yarn.[17] Undoubtedly, there is a need to separate out the coarser or objectionable fibres. This means reducing the variability shown by the llama fibre with respect to its diameter, that is to say, beyond aiming at a reduction of the TMD, it also means achieving a more homogeneous textile material and a MD distribution that does not include fibres of a too high diameter corresponding to the objectionable fibres.

The implementation of the dehairing or purification at the beginning of the textile process results in a structure modification of the fibre as textile raw material since it extracts the coarsest, longest and straightest fibres, the objectionable fibres, what has an effect on the rest of the textile process. The purification yield in Double Coated fleeces is lower due to a high number of coarse fibres. In Double Coated fleeces, the prickle effect was reduced significantly, in Simple Coated fleeces, the reduction was less significant and in Lustre fleeces, no effect was detected. An important implication of these findings is that the classing regarding the fleece type is a fundamental requirement to be performed before, as to say at the beginning of, the textile process since different fleece types require to be treated differently during the purification.[18] Also, the ethno-zootechnical study of llama populations in the province of Jujuy, in Argentina, confirmed the need to carry out a classing process in order to obtain homogeneous commercial lots.[19]

With a new dehairing technology, developed in Argentina which is called AM2, alpaca fibre was successfully dehaired. The reduction of coarse fibres down to the required minimum not to cause prickle was reached at six passes.[20] The efficiency of the AM2 technology was evaluated and was found to be similar in Llama and Alpaca fibre and slightly better than a similar technology used in cashmere fibre in Australia. In general, efficiency fluctuates between 74 and 94%, in terms of desirable fine fibre recovery.[21]

In this research work the Three Group Dissection method has fundamental importance and was used to reveal the characteristics of different fibre groups (FGs), taking the group of fine fibres (FG3) contained in a staple as an indicator of the textile quality. Besides that, the group of coarse fibres (FG1) is composed completely by objectionable fibres and FG2 is the fibre group (FG) of intermediate fibres.[7,8,22]

The aim of this work was to demonstrate the effect of dehairing on the content of objectionable fibres and fibre length, in relation to different fleece types of Llama fibre, evaluating the degree of improvement regarding the homogeneity and general textile quality.

Materials and methods

Llama fleeces utilized for the dehairing trail: The materials used for the industrial dehairing trials were 16 llama fleeces obtained from the shearing of breeding animals from an establishment in Tres Arroyos, Province of Buenos Aires, Argentina. Two of the 16 fleeces belonged to the Double Coated (DC) fleece type, 6 to the Intermediate Coated (IC) one, 6 to the Simple Coated (SC) one and 2 to the Lustre (L) fleece type. The availability of fleeces was limited to the ones the establishment could provide, so actually only one fleece of type L could be provided and also one Hemi Lustre (HL) fleece type was used to represent the lustre fleeces, which is supported by the similarity of HL and L described in Frank et al.[23] Of each fleece type, half had an annual shearing gap and the other half had a biannual shearing gap. Some of the fleeces had felted parts, which were discarded and were not used for the trial.

The method used for the dehairing trial was implemented in the framework of the existing industry in Argentina and it was carried out with an industrial dehairing machine. The process of the fleeces was carried out in the dehairing plant of the textile entrepreneur *Lic.* Diego G. Seghetti Frondizi. This plant is belonging to the SUPPRAD Programme and is equipped with machines for industrial dehairing of animal fibre using AM2 technology.[24]

Each fleece was processed separately. During the trial, the fibre was processed without being pre-washed and was prepared in the same way as commonly done on a daily basis in the plant. First, it is passed through the Fearnaught, which is a process implemented at the beginning of the textile chain and which has the function of opening up the matted and felted parts of a fleece. Therefore, the Fearnaught is also referred to as an "opener". The parts of a fleece that were so matted that they could not be disentangled after the pass through the Fearnaught were set aside and were not dehaired. The fibre was then humidified and during dehairing, an antistatic product was applied to the fibre and a certain humidity was maintained in the air to improve the dehairing process.

The pass named "0" (zero) corresponds to the pass through the Fearnaught, that is to say, the fleece before being dehaired. In order to achieve a complete dehairing, several passes are made through the dehairing machine. The first pass is numbered '1' and the successive passes are numbered '2', '3' and so on. The dehairing trial includes 10 passes altogether, where the fibre is divided into two parts: the dehairing product being the finer and desired fibres as well as the subproduct, which includes the coarser fibres. The dehairing product of each pass is the raw material for the next pass. On the other hand, the subproduct of the successive passes was not processed further, as shown in Figure 1.

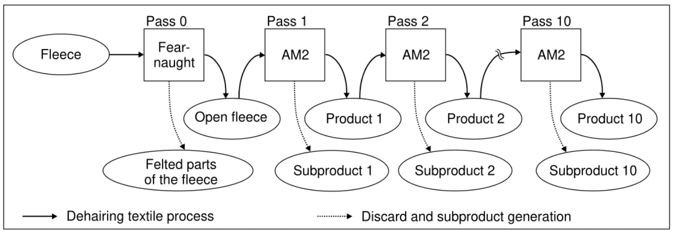

Figure 1 Flow chart of the dehairing trail.

From one pass to the next one, the fibre was left to stand for at least 24 hours in the humidification room. Before and after each pass, the product and the subproduct were weighed. The latter includes vegetable matter, soil dust, etc., which are extracted from the product through the dehairing. The so-called machine "sweeping" was also weighed, including the fibre rest remaining in the pipes, through which the fibre is taken to the AM2. After each pass, all three sections (product, subproduct and sweeping) were removed from the machine to ensure that the fibres from the different fleeces were not mixed. Each sample and section were stored in a nylon bag, identifying the fleece and pass number.

Fibre samples were taken after each step of the textile process. For the sampling, the grid method was used on the extended fibre, obtaining a staple from different sites until the sample was complete, 30 g in total. The grid consists of a plastic object and is shaped like a net, with holes sized approximately 3 cm by 7 cm. Its function is to help during sampling in order to take the sample in a balanced way from different parts of the complete fibre.

The characteristic used to define the yield is the weight of the dehairing product in relation to the weight of the complete fleece.[25]

To the abbreviated denomination of the variables used, a letter "d" was added at the end of it, which stands for "dehairing" and is used for the product. An "s" is used for the "subproduct". The variables corresponding to the "0" (zero) pass also have a "d" added to them even though they do not represent data for a dehaired product, but are still describing the complete fleece. This follows the logic that the fleece, after being opened in the Fearnaught machine, becomes the raw material for the further process in the AM2, just like the product of each pass through the AM2 becomes the raw material for the next pass. That is why, also in the graphs, the data of the "0" pass is always integrated into the smoothed curve of the product which is identified with the letter "d".

Dissection method: The Three Group Dissection was used as the main method. The fibres are separated into three fibre groups (FGs: FG1, FG2 and FG3). FG1 integrates the coarsest and the most visible fibres, FG2 the intermediate fibres and FG3 the finest ones. It is important to note that in this context "fine" and "coarse" are relative expressions because the finest fibres of a very coarse fleece are not fine. This means that in the Three Group Dissection, the fibres are not separated according to different diameters with absolute values, but according to different fibre diameters relative to each other.[7,22]

Statistical analysis and graph production: Regarding the statistical analysis of the data referring to the mean diameter (MD), it should be taken into account that this is a non-normal variable since the normality and homogeneity of variance of the MD distribution is not stated. The data were processed with Infostat statistical analysis software (Grupo InfoStat, FCA, Universidad Nacional de Córdoba, Argentina) and a Kruskal Wallis test (KW) was used. The KW according to ranges is a non-parametric method to test whether samples originate from the same distribution. It is used to compare two or more independent samples of equal or different size. A significant KW indicates that at least one sample stochastically dominates, at least, one of the other samples.[26] The test does not identify where the stochastic dominance occurs or for how many two-sample groups the stochastic dominance is obtained. Dunn's test helps to analyse two-sample groups specifically in *post hoc* tests.[27]

The determination of the mean fibre diameter (MD) and the counting of the fibre types was done on a sample basis and this estimation can be more or less accurate according to statistical theory if the number of fibres measured per sample is modified. This number (n) was set according to a required amplitude in terms of percentage of the mean of 5%, that is to say, that amplitude would be 1 µm for a mean of 20 µm. The usual equation of $n = \frac{(2*1.96*SD)}{(0.05*MD)}$, was applied where SD is sample standard deviation and MD is mean fibre diameter. This equation is applicable even for approximate variable confidence gaps for the mean of a non-normal random variable distribution, whilst the assumptions of the central limit theorem are met and for a sufficiently large *n*.[28]

Citation: Brodtmann LI, Frondizi DGS, Hick MVH, et al. Effect of dehairing on llama fibre aiming to improve its homogeneity and textile quality. *J Textile Eng Fashion Technol.* 2024;10(6):216–227. DOI: 10.15406/jteft.2024.10.00391

Infostat was used to create the dot plots. The standard error was used to express variation as most of the variables do not have a normal distribution. Smoothing (LOWESS) was implemented for all variables.[29] The bandwidth of the smoothing was set to 50%.

Fleece types (FTs): The identification of fleece types was made according to what was determined in Frank.[30] Furthermore, the differentiation of fleece types is described in Frank et al.,[31] and complemented in Brodtmann et al.[22] and Brodtmann,[7] and through a multivariate statistical analysis.[23]

Fibre types: Fibre types are defined by their medulla, which are differentiated as non-medullated fibres (A, for its acronym in Spanish: fibra amedulada) as well as fragmented (F), interrupted (I), continuous (C) or large, incl. lattice, (G, for its acronym in Spanish: gruesa) medulla fibres.[30] In microscopic observation, the fibre type is in principle determined by the medulla type, as its main morphological characteristic.[30,31]

Different variants to express the mean fibre diameter (MD): After a fibre sample was taken, the Three Group Dissection was implemented. From the three resulting FGs and their weight and fibre frequency, the total mean fibre diameter (TMD) weighted regarding weight or fibre frequency were calculated and are named with a "w" or "n" at the end (TMDw and TMDn).

To measure the mean fibre diameter (MD) a projection microscope method was used, which is based on measuring the diameter of a certain number of fibres and recording the fibre frequency (N) of each fibre type (defined by its medulla type: A, F, I, C, G). N results from the same fibres of which the diameter is measured since the fibres are also counted according to their medulla type at the same time. This is a slightly modified version of the one of the IWTO,[32] a projection microscope method described in Frank et al.[33] which takes into account suggestions for alpacas.[34] By applying this method, the MD is recorded according to the fibre types observed under the microscope (Lanameter), as well as their respective absolute fibre frequencies (NA, NF, NI, NC and NG). The relative fibre frequencies (N%A, N%F, N%I, N%C and N%G) are then calculated, that is to say the percentage value of the number of fibres in relation to the total analysed staple. In this context, fibre type is synonymous with medulla type.

From each fibre sample a bunch of fibres was separated, approximately 0,2 g, for which the measurement of the other two TMD variants arises, both at the same time, TMDw for the relative weight (W%) weighted variable and TMDn for the relative fibre frequency (N%) weighted variable, whereby these variables are given the letters "w" or "n". In the case of TMDw and TMDn, first the MD of each FG (MD1, MD2 and MD3) is measured and W% as well as N% of each FG (W%1, W%2 and W%3; N%1, N%2 and N%3) are recorded. TMDw and TMDn are then weighted using equations 1 and 2.

$$TMDw = \frac{(MD1 \cdot W\%1) + (MD2 \cdot W\%2) + (MD3 \cdot W\%3)}{W\%1 + W\%2 + W\%3} \quad (1)$$

$$TMDn = \frac{(MD1 \cdot N\%1) + (MD2 \cdot N\%2) + (MD3 \cdot N\%3)}{N\%1 + N\%2 + N\%3} \quad (2)$$

The mean diameter of FG1 (MD1 or MD1d) and its standard deviation (SD1) result from the projection microscope method, during which the MDs of each fibre type were measured. For example, the MD of the non-medullated fibres within FG1 is named MDA1. To calculate the MD of the whole FG, then, the measured MDs for each fibre type and their respective N% are used according to the following equation.

$$MD1 = \frac{(MDA1 \cdot N\%A1) + (MDF1 \cdot N\%F1) + (MDI1 \cdot N\%I1) + (MDC1 \cdot N\%C1) + (MDG1 \cdot N\%G1)}{N\%A1 + N\%F1 + N\%I1 + N\%C1 + N\%G1} \quad (3)$$

For the MDs of FG2 and FG3 (MD2 and MD3), and their respective standard deviations (SD2 and SD3), the variable names are analogous to FG1, replacing the digit "1" by "2" and "3" respectively.

The mean diameter measured for different fibre types (defined by its medulla), for instance for FG1 (MDA1, MDF1, MDI1, MDC1 and MDG1) as well as their respective relative fibre frequencies (N%A1, N%F1, N%I1, N%C1 and N%G1), arise from the projection microscope method. For FG2 and FG3, the variable names are analogous to FG1, replacing the digit "1" by "2" and "3" respectively.

The mean diameter of the non-medullated fibres (MDA or MDAd) is weighted from the MD of the non-medullated fibres of each FG (MDA1, MDA2 and MDA3) and the relative fibre frequencies of the non-medullated fibres of each FG (N%A1, N%A2 and N%A3), as shown in Equation 4. For the fibre MD of the other fibre types (MDF, MDI, MDC and MDG), the variable denominations are analogous to the non-medullated fibres, replacing the letter "A" by "F", "I", "C" and "G" respectively.

$$MDA = \frac{(MDA1 \cdot N\%A1) + (MDA2 \cdot N\%A2) + (MDA3 \cdot N\%A3)}{N\%A1 + N\%A2 + N\%A3} \quad (4)$$

Relative fibre frequency (N%): The relative fibre frequency of the non-medullated fibres (N%A) is calculated by weighting the N%A of the three FGs (N%A1, N%A2 and N%A3) according to the relative fibre frequencies of the fibres within each FG (N%1, N%2 and N%3), as shown in Equation 5. For the fibre N% of the other fibre types (N%F, N%I, N%C and N%G), the variable denominations are analogous to the non-medullated fibres, replacing the letter "A" by "F", "I", "C" and "G" respectively.

$$N\%A = \frac{(N\%A1 \cdot N\%1) + (N\%A2 \cdot N\%2) + (N\%A3 \cdot N\%3)}{N\%1 + N\%2 + N\%3} \quad (5)$$

Crimp frequency (CF): The crimp frequency is defined by the number of "valleys" or "summits" shown by the fibre crimp within the length of one centimetre, that is to say, what corresponds to the period of a sinusoidal wave. The measured section within the fibre length is randomly chosen. In the case of the fibres of crimp group 4 (CG4), which are almost straight, a value of 0.5 crimps/cm is recorded as a generic expression for fibres with half a crimp per centimetre or less as well as for fibres including a sharp bend somewhere along their length, but which are otherwise almost straight.

Crimp groups (CGs): The crimp type is determined by comparing each individual fibre with the Llama Fibre Crimp Chart (modified from Frank,[30]; Brodtmann et al.,[22]; Brodtmann,[7]). In Frank,[30] 23 different crimp types are distinguished while, with the Three Group Dissection, this is simplified by assigning these crimp types to seven different crimp groups (CG1 to CG7). Fibres within one of these groups show a similar pattern regarding their crimp. To form the crimp groups, the follicles are not taken into account. This modification is made taking into account what is defined by McGregor[35] for cashmere fibre crimp. Here, crimp groups were established according to typical crimp patterns of different fibres.

Fibre length (L): The fibre length is measured by placing the fibre along a straight line, allowing the fibre to lie in its natural shape, without stretching it.

Results and discussion

Total mean diameter and mean diameter according to fibre groups

Within the textile context, the expression "soft" is commonly recognised as the tactile sensation or handle, and combines in itself information related to several characteristics at once: skin comfort (prickle), stiffness, smoothness, softness.[12,36] The term "prickle", which implies itching or pruritus, is only applied to garments used in contact with the skin, directly or indirectly, and it has become increasingly significant. Several studies have shown that the prickle sensation comes from the coarse fibres of the right end of the diameter distribution, the so-called "coarse edge".[37,38] The prickle is produced because the fibres push on the skin's surface with so much force as to activate nerve cells.[39] Naylor[38] has determined that the percentage of fibres coarser than 30 µm is a good predictor of prickle sensation in knitted fabrics and much more accurate in plain-weave fabrics. However, this 30 µm cut-off point can be argued because it can be altered by several factors and it could be said to fluctuate between 26 and 35 µm, for which further experimental evidence is required.[40]

If the "coarse edge" in the diameter distribution is what causes the prickle effect problem, two possible solutions can be thought of: reduce the mean diameter (shift to the left of the normal curve with the corresponding "coarse edge") or decrease the range in fibre diameter (shift to the left only the "coarse edge", leaving the mean unchanged).[41] This could be achieved either by dehairing or by genetic selection. Anecdotal information exists for the first situation and experimental information for the second one.[40]

Figure 2 shows the dehairing effect that leads to the reduction of the total mean diameter (TMD) achieved through the dehairing process, represented by the weight-weighted TMD (TMDwd) and the fibre frequency-weighted TMD (TMDnd) of the dehairing product. All 16 fleeces as if having been processed as one fibre lot, have a TMDnd of 29.3 µm at the beginning and a TMDnd of 25.9 µm is achieved after the first 3 passes through the AM2, reaching the 26 µm threshold. With the successive passes, the TMDnd is further reduced, reaching 24.9 µm after the tenth pass, with a total reduction of 4,4 µm. The TMD of the subproduct (TMDns) is significantly higher (Figure 3).

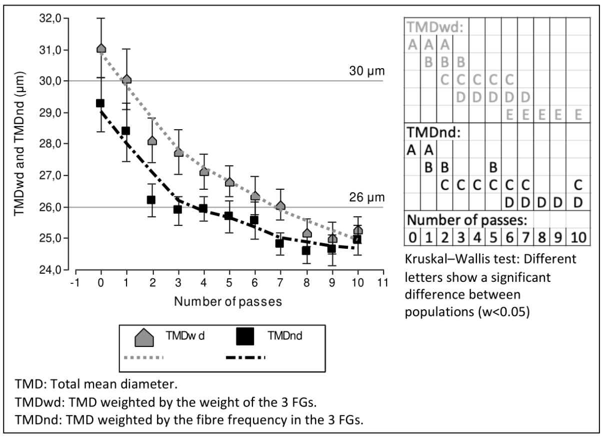

Figure 2 Modification of TMDwd and TMDnd regarding the successive passes.

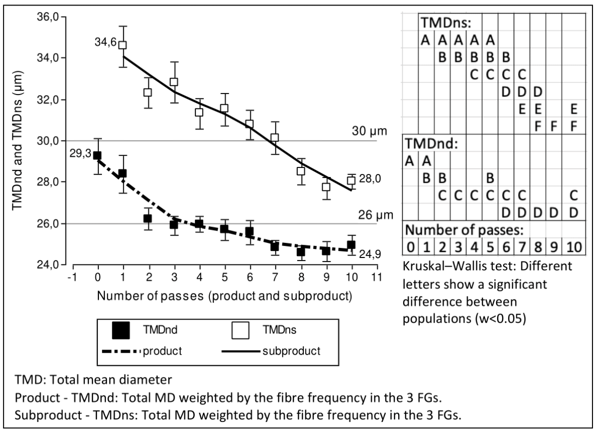

Figure 3 Modification of TMDnd and TMDns regarding the successive passes – product and subproduct.

The product TMD curves (TMDnd and TMDwd) represent the actual dehairing process together with its successive passes, as the product of one pass through the dehairing machine (AM2) is the raw material for the next pass. In the Figure 1 flow chart, this is represented by the arrows showing the dehairing process. The process starts with the whole fleece, which passes through the AM2 forming Product 1, passes through the AM2 again, etc. and ends at Product 10.

In Figure 4 the TMDnd curve is repeated and it shows how the TMDnd can be broken down into the MD curves for each of the 3 FGs of the product (MD1d, MD2d and MD3d).

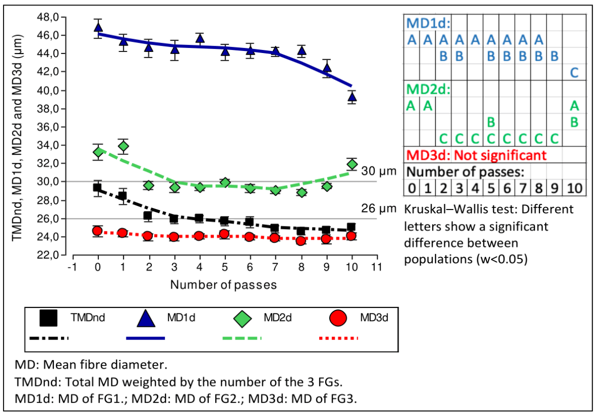

Figure 4 Modification of MD, according to FG, and TMDn regarding the successive passes.

The dehairing effect is produced by separating the whole fleece into product and subproduct. For example, for the coarse fibre group (FG1), the MD of the whole fleece (MD1d: 46.7 µm) is separated into two MDs: on the one hand, the product MD is reduced (MD1d: 45.2 µm) and, on the other hand, the subproduct MD is increased (MD1s: 49.1 µm).[7]

This MD difference between the product and the subproduct is accompanied by a difference in the relative fibre frequency of the product and subproduct. It decreases from the whole fleece value (N%1d: 17%, Figure 6) to a lower value after the first pass for the product (N%1d: 14%, Figure 6) and increases for the subproduct (N%1s: 36%). With each pass through the AM2, what was described for the first pass, is repeated leaving it open to evaluate how many passes are required to achieve the desired product.

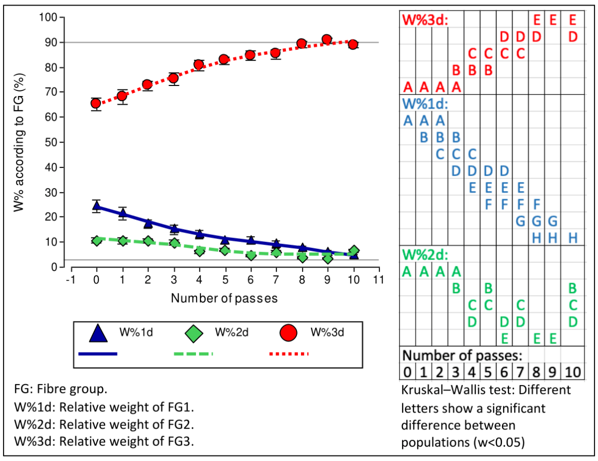

Figure 5 Modification of the relative weight regarding the successive passes, according to FG.

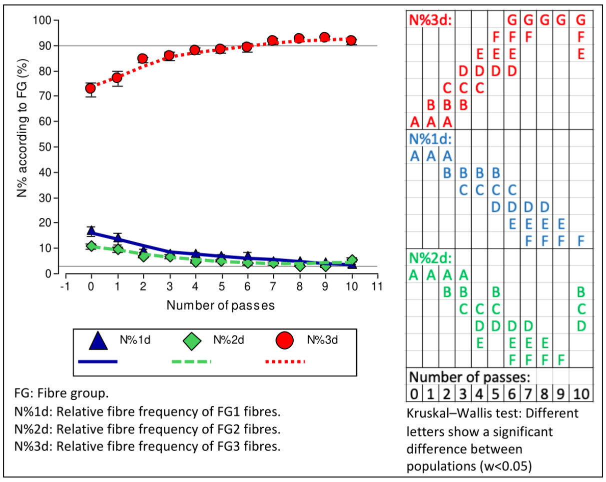

Figure 6 Modification of relative fibre frequency regarding the successive passes, according to FG.

In the case of knitted garments, there is the reference of the 3% coarse fibre threshold expressed in weight/weight (coarse fibre weight/total fibre weight).[12] In this discussion the same threshold is taken into account regarding the relative fibre frequency. Regarding fleece types, the FG1 relative weight of the product (W%1d) shows a relatively similar behaviour for the DC, IC and SC fleeces, with a close approach up to the 3 % threshold after the tenth pass, while the 2 lustre fleece types have a higher W%1d and until the tenth pass do not manage to approach the 3% threshold. The relative frequency of FG1 of the product (N%1d) show a similar behaviour.[7]

The essential aspect to determine is how the dehairing product is modified after each pass and how many passes are needed to achieve a product of the desired quality. At the same time, it is necessary to verify how many passes are indicated to achieve a satisfactory removal of objectionable fibres.[25,42] In Brodtmann[7] the quantity of passes necessary to reach a minimum of coarse fibres in the product (W%1 and N%1) was estimated through a polynomial equation used to describe the reduction of coarse fibres within the product as successive passes are carried out. The results of this trial show a different behaviour depending on the fleece type. The minimum estimation for the coarse fibre group expressed in relative weight and relative fibre frequency (W%1d and N%1d) is reached at passes 12 and 10 for DC fleeces, passes 10 and 8 for IC fleeces, passes 11 and 9 for SC fleeces and passes 15 and 9 for Lustre fleeces, which means that it is confirmed that DC, IC and SC fleeces show a similar behaviour with respect to the relative weight of the coarse fibre group (W%1) and the number of passes needed to reach the minimum, while Lustre fleece behaves differently and needs more passes for that purpose. This confirms that, for the dehairing process, it is detrimental to mix lustre fleeces with the other fleece types. Therefore, in order to achieve an optimal process performance, it is advisable to process DC, IC and SC fleeces together, and lustre fleeces separately. According to industrial assessment, lustre fleeces can be dehaired *at infinitum* (Seghetti Frondizi, D.G., personal communication.).[24] Thus, it is necessary to implement a classing regarding fleece type before starting the dehairing process.[43] The dehairing processes carried out in cashmere show a similar quantity of passes to reach that level of coarse fibres, 9 for Singh[14] and from 9 to 12 for McGregor.[15]

Mean diameter according to fibre type

Figure 7 shows that the non-medullated fibres (MDAd) do not reduce their MD through the dehairing, but they remain around 22 µm (ranging from 21.9 to 22.5 µm). The MD of fragmented medullated fibres (MDFd) is not reduced either, but it remains around 26 µm (ranging from 25.7 to 26.4 µm). That is to say that no dehairing effect is observed on these two variables. This implies that if a superfine or fine dehairing product is required, it is necessary to provide, for the dehairing, fleeces containing fibres of the desired fineness. Furthermore, the almost constant MDAd and MDFd values confirm that the method used in this research work, whereby each sample is first dissected into 3 fibre groups and then the MD of a fibre type is weighted from the MD and the frequency of each FG (Equation 4), provides consistent results, since by measuring always the same fibres, the same result is reached.

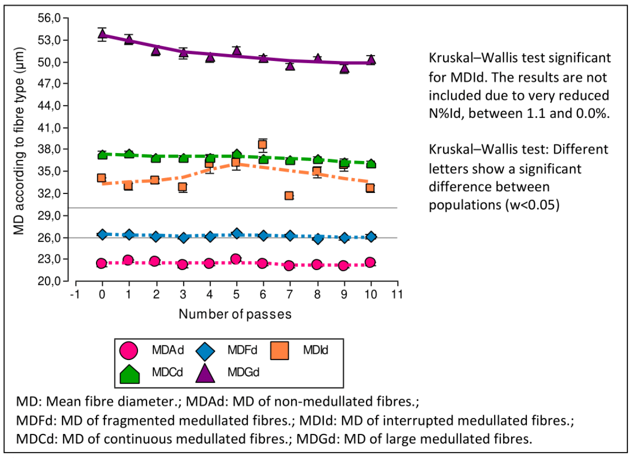

Figure 7 Modification of MD regarding the successive passes, according to fibre type.

Figure 8 shows the dehairing effect on the relative frequency of non-medullated and fragmented medullated fibres (N%Ad and N%Fd). Non-medullated fibres, which are the desired fibres having the highest textile value, clearly increase their presence (N%Ad) within the product, which is confirmed by the significant KW results. This confirms an improvement in the textile quality through the dehairing process. The frequency of fragmented medullated fibres (N%F), which are also desired fibres within the product, remains high throughout the successive passes.

Citation: Brodtmann LI, Frondizi DGS, Hick MVH, et al. Effect of dehairing on llama fibre aiming to improve its homogeneity and textile quality. *J Textile Eng Fashion Technol.* 2024;10(6):216–227. DOI: 10.15406/jteft.2024.10.00391

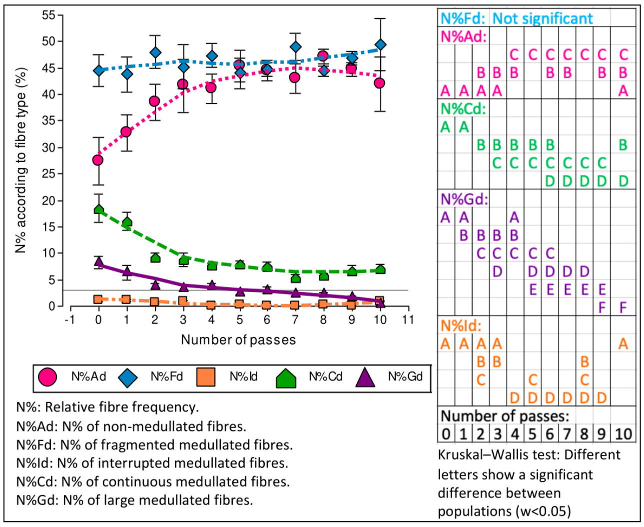

Figure 8 Modification of the N% regarding the successive passes, according to fibre type.

In Figure 7 and Figure 8, it can be seen that the fibre structure does not change much with respect to the MD of the different fibre types. Instead, the dehairing effect and, thus, the modification of the fibre structure is mainly determined by a change in the relative weight and relative fibre frequency (W% and N%) of the three FGs. Further details are revealed in Brodtmann[7] and confirm that FG3 is composed of the non-medullated and fragmented medullated fibres and this remains the case throughout the dehairing process. FG2 contains mostly continuous and fragmented medullated fibres. Finally, FG1 is composed of continuous and large medullated fibres and this composition is kept throughout the dehairing process.

The MD curve of the interrupted medullated fibres (MDId in Figure 7) shows an inconsistent behaviour along the successive passes, but its presence is so low (N%Id in Figure 8) that further discussion is not considered necessary. A dehairing effect is reported for the MD of the continuous and large medullated fibres (MDCd and MDGd in Figure 7) as there is a slight downward trend of the MD. However, the comparison made by the KW test shows no significance. The MDCd drops from 37.3 to 36.1 µm, so it decreases 1.2 µm, and MDGd drops from 53.7 to 50.3 µm, decreasing 3.4 µm over the ten passes. This value of a reduction of only a few microns is consistent with the TMDn reduction value of 4.4 µm (Figure 3).

Figure 8 shows the dehairing effect on the relative frequency of continuous and large medullated fibres (N%Cd and N%Gd) with a clear trend to be reduced, which is confirmed by the significant KW results. This implies a strong modification of the fibre structure and an improvement of the textile quality. According to the KW results, the reduction of the N% for continuous medullated fibres (N%Cd) stabilises from the sixth pass onwards, while it shows a significant difference until the last two passes for large medullated fibres (N%Gd). In this respect, the continuous medullated fibres could be a problem because they seem to be still present in the product even after more passes.

The percentage of large medullated fibres alone is 2.6% at the end of the fifth pass (N%Gd in Figure 8), that is to say that they are already below the 3% threshold, and from the seventh pass onwards, it remains clearly below this threshold. It is interesting to verify that large medullated fibres are noticeably thicker than continuous medullated fibres: the MD of large medullated fibres is 53.8 µm before the dehairing process and decreases up to around 50 µm at the end of dehairing, while the MD of continuous medullated fibres is 40.2 µm before the dehairing process and 38.0 µm at the end of it. Evidently, the increased coarseness of large medullated fibres helps them to be separated more quickly, whereas continuous medullated fibres could be a problem in this respect.

In relation to the dehairing and the behaviour of different types of mohair, alpaca and Angora fibre, McGregor[44] comments that it is highly likely that methods that result in reducing the TMD in alpaca fibre lead directly to a reduction in the incidence of medullated fibre, in the same way it was seen in mohair fibre. In Lupton et al.,[45] it was reported on 20 µm mohair without medullation. However, in Australian alpaca fibre with an TMD measured at an average flank height of 20 µm, the medullated fibres represent a 10% in relation to fibre frequency and these have a MD of 30 µm. This incidence of medullated fibre in Australian alpacas corresponds exactly to the quantity of skin follicles of 9 secondary follicles per each primary follicle. Specifically, the ratio of secondary/primary follicles in alpacas was less than 9:1,[46] what implies that all primary follicles and some of the secondary follicles are producing medullated fibres.[44] For high quality dehaired cashmere, the incidence of medullated fibre should be <0.2%.[47–49]

Crimp frequency (CF)

The 3 FGs show a clear differentiation according to their CF. The results of dehairing do not indicate a clear trend related to an increase or lowering of the CF. The few coarse or objectionable fibres that remain within the product after successive passes keep the low CF and the fine fibres keep the high CF. No clear effect on this fibre characteristic is observed due to the dehairing process.

Crimp groups (CGs)

The Llama Fibre Crimp Chart (modified from Frank,[30]; Brodtmann et al.,[22]; Brodtmann,[7]), shows fibres drawn in size one by one. A typical pattern of a llama fibre can be a short, regular crimp (typically FG3 fibres) as well as a long, irregular crimp (typically FG1 fibres). It may also include curled fibres showing a three-dimensional (3D) shape. CG1 fibres are always very fine, those belonging to CG2 and CG3 increase in diameter. CG4 fibres, in general, are coarse or very coarse, excepted for fibres from Lustre and HL fleece types which may have fine CG4 fibres. CG5, CG6 and CG7 fibres may have different diameters. Fibres which form a marked loop at a certain point along their length are included in CG7.

For 100% of the fibres analysed which belonged to the coarse fibre group (FG1), the crimp group belongs to the CG4. Table 1 shows that this is true for all fleece types and does not change with the successive passes. With respect to CG2 and CG3, the CG of the different fleece types are similar, except for a trend towards a CG with lower CF for the Lustre fleece type. Due to the fact that only one of the dehaired fleeces was of the Lustre fleece type, but the other one was a HL fleece, the difference in relation to the CG in respect to DC, IC and SC fleeces is not so noticeable. In Brodtmann[7] it was shown that Lustre fleeces typically contain more CG4 fibres in FG2 and even in FG3 fibres of CG4 are present.

Table 1 Crimp groups (CGs) according to FG for each FT

	1	2	3	4	5	6
	Product: Modification of the presence of a certain CG implementing dehairing.					
	FG1		**FG2**		**FG3**	
	CG	Modification	CG	Modification	CG	Modification
DC	Only CG4	No modification	A lot of CG3, some of CG4.	CG3 increases	CG2 and CG3, more of CG2.	No modification
IC	Only CG4	No modification	A lot of CG3, some of CG4.	CG3 increases	CG2 and CG3, more of CG2.	CG2 increases
SC	Only CG4	No modification	A lot of CG3, some of CG4.	CG3 increases	A lot of CG2, some of CG3.	CG2 increases
Lustre	Only CG4	No modification	CG3 and CG4, more of CG3.	No modification	CG2 and CG3, more of CG3.	No modification
	Subproduct: Modification of the presence of a certain CG implementing dehairing.					
	FG1		**FG2**		**FG3**	
	CG	Modification	CG	Modification	CG	Modification
DC	Only CG4	No modification	A lot of CG4, some of CG3.	Only CG4	A lot of CG3, some of CG2.	Only CG3
IC	Only CG4	No modification	Almost only CG4, a few of CG3.	No modification	Almost only CG3, a few of CG2 and CG3.	No modification
SC	Only CG4	No modification	Almost only CG4, a few of CG3.	No modification	Almost only CG3, a few of CG4.	No modification
Lustre	Only CG4	No modification	Almost only CG4, a few of CG3.	Only CG4	Almost only CG3, a few of CG2 and CG3.	Only CG3

When comparing the CGs of the product and the subproduct (upper and lower parts of Table 1 respectively), the modification that the dehairing produced in a fibre lot is observed because, for all FTs, the table shows a clearly higher presence of CG4 fibres in the subproduct than in the product. CG4 is the typical CG composed of objectionable fibres and the fact that more of this CG is found in the subproduct indicates the effectiveness of the dehairing process. This would happen due to the higher elasticity of the crimpier fine fibres, and the stiffness and straightness of the coarse fibres.[14]

Furthermore, in the case of showing a modification (column 4 with respect to column 3 as well as column 6 with respect to column 5), this is, for the product, towards a CG that is usually of finer fibres and, for the subproduct, towards a CG that is usually of coarser fibres. This can be observed due to a modification towards a CG of higher crimp in the case of the product and a CG of lower crimp in the case of the subproduct.

With respect to the modification of the fleece structure throughout the successive passes, a modification occurs for DC, IC and SC fleeces towards CGs of higher CF, that is to say, from CG4 to CG3 and from CG3 to CG2. In contrast to this result, no modification occurs for the Lustre fleece, which confirms a different behaviour. This can be explained by the low crimp frequency and the long shape of the crimp of the fine fibres that conform this fleece type.[31] It can be concluded that it is not advisable to process all fleece types together, but rather to implement a classing regarding fleece type before dehairing and to join DC, IC and SC fleeces, on the one hand, and the lustre fleece types (HL and Lustre), on the other hand. Similar characteristics of the processed fibres guarantee a similar behaviour during the dehairing process and thus a more feasible adjustment of the dehairing machine, leading to a better performance of the dehairing as well as of the subsequent production process.[18,24,31]

Fibre length (L)

The dehairing effect shows a shortening of the fibres. FG1 fibres start with an average of approximately 13 cm and are reduced to about 10 cm in the product of the tenth pass. FG3 fibres start with almost 10 cm of length, which is reduced during the dehairing. Clearly, the fibres belonging to FG3 are the shortest ones, but they remain above 7 cm in the product of dehairing even after the tenth pass.[7] This length is appropriate for spinning the fibre by a worsted process.[50] FG2 fibres have a length in-between the other two FGs. Within each one of the passes through the AM2, the shorter fibres are included in the subproduct.

Final evaluation

The dehairing effect can be observed by a cross-sectional reading of all fibre characteristics with respect to the initial fleece structure (pass 0) and the modification observed in the fibre structure of the dehairing product (passes from 1 to 10). A cross-sectional look at the group of fine fibres (FG3) allows the textile quality of the raw material to be assessed before the dehairing (pass 0) since the fibres of this FG are the ones that should be gathered in the dehairing product. It is revealed that for the fleeces utilized during this dehairing trail, FG3 is composed of fine fibres (fine: 22 – 24.9[30]) with a MD of 24.6 µm (MD3d in Figure 4), 36% of which are non-medullated and 58% of which are fragmented medullated fibres, making 94%. These fibres are 9.7 cm long, have a high crimp frequency of 3.8 crimps/cm and represent the 65% of the staple weight (W%3d in Figure 5). Besides that, the weight of the intermediate and coarse fibres of the fleece before the process is 11% and 24% respectively (W%2d and W%1d in Figure 5).

Already after the first pass, the modification of the fibre structure can be observed, which keeps changing with each pass. At the end of the first pass, a relative weight of fine, intermediate and coarse fibres of 68%, 11% and 21% respectively is recorded, which changes to 83%, 7% and 10% respectively at the end of the fifth pass, and to 89%, 5% and 7% respectively after the tenth pass (Figure 5). Fibre length is 8.5; 10.3 and 12.0 cm respectively after the first pass, it is reduced to 7.8; 9.3 and 10.8 cm respectively after the fifth pass and then stabilised for FG2 and FG1, while it is still slightly reduced with respect to FG3, not significantly, however, according to KW. As to say, a significant modification is observed in relation to these variables, while the MD only modifies with a clear trend for FG1, reducing itself (Figure 4), and the modification of the CF does not show a clear trend either.

In other words, the results confirm a modification of the fibre structure through the dehairing, which means an improvement in the textile quality, mainly due to the effective separation of the coarse fibres from the product, with the greatest impact being achieved during the first few passes. At the same time, a limitation is observed, which is given by the fact that the quantity of coarse fibres weight/weight, despite being very close to the 3% threshold, does not manage to decrease below this threshold.

Furthermore, it was confirmed that it is not advisable to implement the dehairing for fleeces whose fine fibres have too high a MD since it was shown that the dehairing effect has a limitation with respect to the ability to reduce the MD of fine fibres. It was also verified that different fleece types respond differently to the dehairing process. To summarise, it can be said that, in order to achieve an improvement in the textile quality, the dehairing is a fundamental component of the solution, but it is limited when implemented on its own since its effectiveness is conditioned by the raw material that is provided to the dehairing. As an additional measure to be evaluated, the classing of fleeces regarding fineness and/or fleece type is fundamental. The need to implement the classing with respect to specific criteria for developing an industry based on animal fibre is in line with what was concluded in Frank et al.[51] in relation to Patagonian cashmere. It was also confirmed that, it is essential to implement a prior classing regarding fleece type for processing llama fibre since different fleece types do not behave in the same way during the process.[18]

Differentiation of fibre groups according to opposite characteristics

The conceptual description of the five llama fleece types was realized by means of opposites in relation to certain fleece characteristics. These are high versus low fibre crimp frequency, on the one hand, as well as double coated versus simple coated, on the other hand. Here, a conceptual approach is implemented and, in this case, "double or simple coated" is related to the visual appreciation of a fleece or a staple, not the inherent nature of a llama fleece, which always has the two coats which are build up from primary and secondary fibres respectively.[7,22]

This idea can be taken further and the position of the three fibre groups that are formed through the Three Group Dissection can be differentiated according to the same concept. Therefore, in Figure 9, in addition to the position of the whole staple in the graph, also the groups of the coarse fibres (FG1) as well as the fine fibres (FG3) are included. Again, the conceptual description of this idea is important, because, in this case, the crimp frequency (CF) is not meant to be thought of mathematically, but is combined with the typical crimp groups (CGs) and the resulting loose versus compact staple structure. The group of the intermediate fibres (FG2) is not included in this graph, because the two main FGs, which are those influencing the fibre structure of a staple, are the other two FGs.[7] If the FG2 would be included in Figure 9, its position would be on an intermediate height, somewhere between FG1 and FG3.

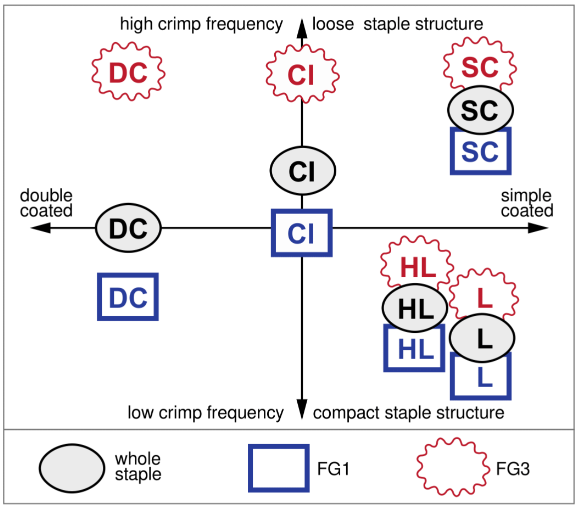

Figure 9 Evaluation of FTs according to opposites in relation to the visual appearance of the fleece coats and the crimp frequency, including FGs.

Fleece types (FTs); DC: Double Coated; IC: Intermediate Coated; SC: Simple Coated; HL: Hemi Lustre; L: Lustre

Fibre groups (FGs) - FG1: group of coarse fibres; FG3: group of fine fibres

It is important to point out that the opposite positions of high versus low crimp frequency of the graph in Figure 9 indicate, at the same time, a loose versus compact staple. This is the case because, for llama fibre, the position of the high frequency is always associated with an irregular crimp which leads to a loose staple structure. Instead, the position of the low crimp frequency, in this graph, is associated with a very regular crimp, which is what allows the typical compact, tight and closed staple structure of the Lustre fleece. That is why the FG1 of the Lustre fleece has the lowest position in this graph. Instead, the FG1 fibres of the DC fleece are positioned higher, because, although its CF is very low too, these fibres have always a very irregular crimp and, therefore, cannot form a compact staple.

When the fibre is obtained from a fleece it shows a certain 'llama fleece structure', consisting of the way in which its fibres are arranged in each staple and, as a whole, in the entire fleece. However, before the textile process begins, the fibres of various fleeces are mixed. Therefore, the fleece as an isolated unit disappears and so does its original structure. 'Llama fibre' is then handled as raw material, that is to say, a fibre lot. And, in the same way that the llama fleece is a set of fibres of different types that are arranged in a specific structure, a specific structure of a set of fibres is also formed when, among many fleeces, a fibre lot is assembled to be used in the textile industry. Thus, it can be said that the set of fibres found within the textile process also has a certain 'structure' or 'fibre structure'. This means that when the term 'fibre structure' is mentioned in this research work, it does not refer to the structure of an individual fibre, but to the structure of a set of fibres included in a fibre lot before or during the textile process. Depending on the fleece types included in a fibre lot and, mixing all of the contained staples, a loose or compact fibre structure is formed, which will have consequences on the efficiency of the dehairing process.

Citation: Brodtmann LI, Frondizi DGS, Hick MVH, et al. Effect of dehairing on llama fibre aiming to improve its homogeneity and textile quality. *J Textile Eng Fashion Technol.* 2024;10(6):216–227. DOI: 10.15406/jteft.2024.10.00391

The FGs of the fine fibres (FG3) of the DC, IC and SC coated fleeces are positioned in the same height within this graph, because all three of them include very crimped fibres and form a loose fibre structure. The different positions within the left and right side of the graph is due to its origin regarding double or simple coated, but the shared position in the upper part shows the common characteristic in respect of a high crimp frequency, a rather irregular crimp and a very loose fibre structure. This gives a clear idea regarding the convenience of joining DC, IC and SC fleece types for textile processing, because, although these are three different fleece types, nevertheless, its group of fine fibres have similar fibre characteristics, as to say the possibility to form, all together, homogeneous raw material, especially if dehaired.

The position of the lustre fleece types in the lower part of Figure 9, with FG1 and FG3 in close positions, is due to the similarity of its characteristics regarding crimp frequency (CF) and crimp groups (CGs). The typical CG of the Lustre fleece type has a low CF and very regular crimp type, which is what allows the fibres to lay close to each other and to form a compact staple structure. It also tends to even have a helicoidal shape, which causes even more difficulties to separate the fibres from each other. The HL fleece has similar characteristics as the Lustre fleece. This confirms the importance of implementing a classing regarding fleece types before the textile process, joining DC, IC and SC fleeces within one fibre lot and separating the HL and L fleeces into another lot.

Conclusion

It was confirmed, that dehairing reduces the mean fibre diameter. This is due to the separation of the coarse fibres out of the dehairing product, while the diameter of the fine fibres stays the same. Thus, it became evident that, in order to achieve a reduced mean fibre diameter within the dehairing product (TMDnd), it is necessary that the fine fibre group (FG3) of the fleeces provided to the dehairing has to have a reduced mean diameter (MD3), that is to say that the dehairing can only provide fine fibres if these fibres are contained in the fleeces before they are dehaired. This means that the dehairing process can be considered a fundamental and important component of the solution, but that the dehairing alone is limited, since its effectiveness is conditioned by the raw material that is provided for the process. Therefore, it was concluded that it is indispensable to avoid the usual practice of gathering raw material as unsorted fibre and providing all fibre together to the dehairing process since, in this case, also fleeces whose FG3 have a too high MD3, are included. Therefore, the need to implement a classing of fleeces regarding fineness as an additional measure prior to the dehairing process was confirmed.

Also, the importance of implementing a classing regarding fleece type before the textile process, joining DC, IC and SC fleeces within one fibre lot and separating the HL and L fleeces into another lot, was confirmed. By joining DC, IC and SC fleece types for textile processing, although these are three different fleece types, nevertheless, its group of fine fibres have similar fibre characteristics, as to say the possibility to form, all together, homogeneous raw material, especially if dehaired.

With respect to the objectionable fibres, which are represented by the coarse fibre group (FG1), it was revealed that the dehairing process clearly reduces this variable for all dehaired fleeces, but the relative weight (W%1d) is not reduced below the desired threshold of 3% for all of them. In addition, it was noted that the large medullated fibres that are very coarse are separated more effectively, whereas coarse continuous medullated fibres are more problematic in this respect and it was also noted that further trials need to be undertaken to address this issue.

In relation to fibre length, it was observed that the dehairing effect shows a shortening of the fibres. Also, a clear trend to include the shorter fibres in the subproduct was observed. In addition, it was verified that the FG3 fibres are the shortest ones, but they maintain their length above 7 cm.

Implications

The adoption of llama fibre dehairing technology by breeders, artisans and the textile industry could significantly enhance the competitiveness of this environmentally-friendly animal fibre. By not requiring prior scouring, it reduces water usage and the emission of the pollutants associated with this process. This approach could also increase the use of natural bio-degradable fibre, reducing the consumption of synthetic microfibres that cause pollution on our planet.

Acknowledgments

None.

Funding

The funding was provided by private activity, by the llama breeder Piedra del Agua Ranch, which is located in the Sierras Centrales of the San Luis Province in Argentina.

Conflicts of interest

The author declares that there is no conflict of interest.

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Citation: Brodtmann LI, Frondizi DGS, Hick MVH, et al. Effect of dehairing on llama fibre aiming to improve its homogeneity and textile quality. *J Textile Eng Fashion Technol.* 2024;10(6):216–227. DOI: 10.15406/jteft.2024.10.00391