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Genetic parameters of fiber density traits and their relationship with textile traits in alpacas

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HIGHLIGHTS

- Reducing fiber diameter (FD) and increasing fleece weight(FW) are breeding goals for alpaca.
- FD and FW have unfavorable genetic correlation.
- Fiber density can be objectively measured by the number of hair ducts/mm^2(HD), total fibers/mm^2 (TF) and the ratio TF/HD (RT).
- TF have high heritability and its genetic correlation with FW and DF are moderate.
- TF is a selection criterion for improving simultaneously fiber diameter and fleece weight in alpacas.

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ABSTRACT

Genetic improvement programs for alpacas that focus on reducing fiber diameter have succeeded in enhancing fiber quality but they have also decreased fleece weight. Fiber diameter and fleece weight have an unfavorable genetic correlation, which makes it difficult to improve both traits simultaneously. This study aimed to estimate the genetic parameters of fiber density traits, and their genetic correlations with fleece weight (FW), fiber diameter (FD), density score (DS) and percentage of medullation (PM), as well as to evaluate their incorporation as selection criteria to increase fleece weight. The density traits were the number of hair ducts per mm^2(HD), number of fibers per mm^2 (NF) and the NF/HD ratio (RT). Fiber density traits were objectively measured by using high-resolution skin images taken from 402 Huacaya alpacas. Animal model was used to estimate genetic parameters. Pedigree (15,360 alpacas) and phenotype records for FW (11,271), DS (5,752), FD (8,763) and PM (8,763) were retrieved from the Pacomarca database. The heritability was 0.40±0.05, 0.47±0.03, 0.37±0.05, 0.34±0.02, 0.31±0.01, 0.28±0.01 and 0.16±0.01 for HD, NF, RT, DS, FD, PM and FW respectively. Favorable genetic correlations were found between NF-FW, NF-FD and DS-FW, with values of 0.36, -0.50 and 0.50, respectively. However, unfavorable genetic correlations were also found between FD-FW and PM-FW, with values of 0.35 and 0.24 respectively. NF is an appropriate selection criterion for improving fiber diameter, percentage of medullation and fleece weight simultaneously in Huacaya alpacas.

1. Introduction

Alpaca breeding programs will focus on the reduction of fiber diameter, increasing the fleece weight (Gutiérrez et al., 2009), and the reduction of the percentage of medullated fiber (Cruz et al., 2019; Pinares et al., 2018; Quispe et al., 2022a). These traits are the main textile characteristics that give commercial value to the alpaca yarns and garments.

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In Peru, alpaca fleeces are sold in two types of markets, in the first the price is based on a combination of fleece weight (quantity) and fiber fineness (quality a priori), available only to some producers; and in the second the price is based only on the fleece weight (Allain and Renieri, 2010). Since the second type of market is the predominant one, there is little incentive to run a genetic improvement program for alpaca fiber quality in Peru.

Alpaca Genetic improvement programs aim to enhance fiber quality by reducing the average fiber diameter. However, this approach may also result in a decrease in fleece weight, as has been observed in alpacas (More et al., 2017; Quispe et al., 2023; Wuliji, 2017), sheep (Notter and Hough, 1997; Safari et al., 2005) and goats (Allain and Roguet, 2003; Taddeo et al., 1998).

Fleece weight depends mainly on the following factors: a) the fiber density, which is determined by the quantity of fiber produced per animal, b) the staple length, which is influenced by the interval between shearing and the fiber growth rate, and c) the amount of skin surface on which the fiber grows (McFadden and Neale, 1954). However, the genetic relationship between fiber quality traits, fleece weight and fiber density are not well understood. This information is needed to enhance fiber diameter and fleece weight simultaneously.

Animal fibers originate from primary and secondary hair follicles that are organized in follicular groups in sheep (Chapman, 1971), alpacas (Moore et al., 2015) and llamas (Atlee et al., 1997). Similarly, the diameter of the fibers has an inverse correlation with the follicular density and the secondary/primary follicle ratio (Ferguson et al., 2012; Scobie and Young, 2000). Therefore, hair follicle density traits could be used as selection criteria to improve the quality of animal fibers (Galbraith, 2010). However, the current methodology for obtaining skin samples to measure hair follicles is invasive. Furthermore, additional procedures, including cross and longitudinal cuts and staining protocols, are currently required to differentiate between the various follicular groups (Vélez et al., 2016). On the other hand, follicular density represents an indirect measure of fiber density, it should be noted that not all hair follicles are associated with a fiber bundle. However, some ducts can transport a considerable number of primary and secondary follicle fiber bundles to the surface of the skin (Nagorcka et al., 1995; 1998).

Recently, a novel method for measuring fiber density has been developed. The method is non-invasive and involves the utilization of a modified microscope, designated the 'Fiber-Den', for the purpose of capturing images of alpaca skin (Quispe et al., 2023). Images were used by specialized software to measure fiber density traits as the number of hair ducts/mm^2, the total number of fibers/mm^2, and the ratio of the number of total fibers to the number of hair ducts (Quispe and Quispe, 2019). Furthermore, fiber density traits had moderate heritability estimates and favorable genetic correlation with fiber diameter and fleece weight (Flores et al., 2023) to allow simultaneously improvement of the latest traits (Quispe et al., 2023).

The determination of additional genetic parameters and genetic correlations of fiber density is a necessary step in the prediction of genetic progress in the quality and quantity of alpaca fiber. For this reason, this study aimed to: a) estimate phenotypic and the genetic parameters of the number of ducts/mm^2, number of fibers/mm^2, and fiber/duct ratio; b) to investigate the genetic relationship of these traits with fiber diameter, percentage of medullation, fleece weight, and the density score; and c) to evaluate the incorporation of some density traits as possible selection criterion for improving fiber diameter and fleece weight simultaneously.

2. Material and methods

2.1. Animal population, phenotypes and datasets

The fiber density traits were the number of hair ducts per mm^2(HD), number of fibers per mm^2 (NF) and the NF/HD ratio (RT). Fiber density traits were measured in 402 Huacaya alpaca aged between 1 and 15 years, with an average age of 6.4 years. Fiber density traits were measured (Quispe and Quispe, 2019) as follows: a) A representative area of the alpaca's middle ribs was shaved, b) this shaved area was dyed to pigment the protruding fibers, c) after 40 minutes, the skin was rinsed to remove excess dye, d) five high-resolution images per skin area were taken by the Fiber-Den equipment and e) these images were analyzed by specialized software to calculate the number of hair ducts/mm^2 (HD), the number of fibers/mm^2 (NF) and NF/HD ratio (RT).

The textile traits were the fiber diameter (FD), fleece weight (FW) as described by Gutiérrez et al. (2009) and percentage of medullation (PM) as described by Cruz et al. (2019). Also, the density score (DS) was evaluated subjectively using a scale of 1 to 5 as described by Cervantes et al. (2010). The descriptive statistics for these traits are shown in Table 1. These textile traits were obtained from the PacoPro v5.10 database of the Pacomarca Scientific Station (Grupo Inca), located in the southeast of Peru. The pedigree file contained 15,360 animals registered from 1992 to 2023.

2.2. Statistical analyses and models

Fisheŕs least square difference was used for assessing the effect of the coat color and sex on the HD, NF and their RT. Subsequently, two models were used for variance components estimation:

- The model fitted for HD, NF, RT and DS was $\boldsymbol{y} = \boldsymbol{Xb} + \boldsymbol{Zu} + \boldsymbol{e}$
- The model fitted for FD, PM and FW was: $\boldsymbol{y} = \boldsymbol{Xb} + \boldsymbol{Zu} + \boldsymbol{Pp} + \boldsymbol{e}$

with, $\begin{pmatrix} u \\ p \\ e \end{pmatrix} \sim N\left(\begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} A \otimes G_0 & 0 & 0 \\ 0 & I_p \otimes P_0 & 0 \\ 0 & 0 & I_e \otimes R_0 \end{bmatrix}\right)$

Where, **y** is the vector of observations, **b** is the vector of fixed effects, **u** is the vector representing the additive genetic effects, **p** corresponds to the vector of permanent environments of individuals for fiber traits, **e** is the vector of residuals; **X, Z**, and **P** are the incidence matrices for fixed, direct genetic and permanent environmental effects respectively. $\mathbf{I_e}$ is the identity matrix of equal order to the number of records, $\mathbf{I_p}$ is the identity matrix of equal order to the number of permanent environmental subclasses, **A** is the numerator relationship matrix, $\mathbf{R_0}$ the residual covariance matrix among measurements on the same animal, $\mathbf{G_0}$ the covariance matrix for additive genetic effects, $\mathbf{P_0}$ the covariance matrix for permanent environmental effects and $\otimes$ the Kronecker product.

The fixed effects for all traits were: color with 2 levels (white and light fawn); sex with 2 levels (male and female), except for FD, SD, PM as combined effect of sex and lactation (Cruz et al., 2017) with 3 levels (male, lactating female, non-lactating female); year of recording as contemporary group with 17 levels (2007 to 2023) and age as linear and quadratic covariate in days.

For the recoding and analysis of the pedigree, the Endog v4.8 software was used (Gutierrez and Goyache, 2005). Genetic parameters were estimated using the VCE 6.0 program (Neumaier and Groeneveld, 1998), phenotypic correlations and statistical analyses were made using the packages *agricolae, ggplot2, ggpubr* of the R language (R Core Team, 2020).

Selection responses of FD, PM and FW under various strategies of weighting textile and density traits were assessed by using selection

Table 1
Descriptive statistic of the main textile traits in Huacaya type alpacas.

Textile traits	Records (n)	Min	Max	Average	Standard deviation
Density score (1 to 5)	5,752	1	5	3.31	0.71
Fiber diameter (μm)	8,763	12	36.3	21.7	3.29
Percentage of medullation (%)	8,763	0	100	32.5	21.1
Fleece weight (kg)	11,271	0.6	10.2	2.52	1.09

Table 2
Selection strategies to improve fiber diameter - FD, percentage of medullation - PM (quality) and fleece weight - FW (quantity) of alpaca fiber.

Selection strategy	Description
Use of relative economics weights (the sum is 100 % in absolute value) to improve the objectives under of the expected genetic responses	Weighting of equivalent economic weights on the selection criteria (NF, DS, FD, PM) to improve of the selection objectives (FD, PM, FW) Scenario 1: FD=-37.5 %, PM=-12.5 %, NF=50 % Scenario 2: FD=-37.5 %, PM=-12.5 %, NF=25 %, DS=25 % Scenario 3: FD=-37.5 %, PM=-12.5 %, DS=50 % Scenario 4: NF=100 % Scenario 5: DS=100 %

NF= number of fibers/mm^2, DS=density score 1 to 5.

index methodology (Table 2). To calculate the expected genetic responses, breeding values were standardized as described by Gutierrez et al. (2014). The direct response to selection ($\boldsymbol{R}$) was calculated using $\boldsymbol{R} = \boldsymbol{h}^2\boldsymbol{i}$, where $\boldsymbol{h}^2$ is the narrow-sense heritability, $\boldsymbol{i}$ is the selection intensity. Thus, the direct response for the trait $\boldsymbol{x}$ was $\boldsymbol{R_x} = \boldsymbol{v_x h_x i}$, being $\boldsymbol{v_x}$ the relative economic weight applied on this trait, and all the correlated responses for any trait $\boldsymbol{y}$ in the index such as the corresponding correlated response in $\boldsymbol{x}$ will be $\boldsymbol{CR_x} = (\boldsymbol{v_y r_{xy} h_y})\boldsymbol{i}$, being $\boldsymbol{r_{xy}}$ the genetic correlation between $\boldsymbol{x}$ and $\boldsymbol{y}$ traits. Then, the total response for trait 1 ($\boldsymbol{TR}_1$) using the data the all traits will be $\boldsymbol{TR}_1 = (\boldsymbol{v}_1\boldsymbol{h}_1 + \boldsymbol{v}_2\boldsymbol{r}_{12}\boldsymbol{h}_2 + \boldsymbol{v}_3\boldsymbol{r}_{13}\boldsymbol{h}_3 + \ldots\boldsymbol{v}_n\boldsymbol{r}_{1n}\boldsymbol{h}_n)\boldsymbol{i}$, and the total response ($\boldsymbol{t}$), expressed in % as proportion of genetic standard deviation for all traits using the all data is represented in the next expression:

$$\boldsymbol{t} = \boldsymbol{v}'\boldsymbol{T}\boldsymbol{i} = \boldsymbol{v}'\begin{bmatrix} h_1 & r_{12}h_1 & r_{13}h_1 & \ldots. & r_{1n}h_1 \\ r_{21}h_2 & h_2 & r_{23}h_2 & \ldots. & r_{2n}h_2 \\ \ldots & \ldots & \ldots & \ldots. & \ldots \\ \ldots & \ldots & \ldots & \ldots. & \ldots \\ r_{n1}h_n & r_{n2}h_n & r_{n3}h_n & \ldots. & h_n \end{bmatrix}\boldsymbol{i}$$

where: $\boldsymbol{v}$ is the vector of relative economics weights used in the selection criteria, $\boldsymbol{h}$ is the squared root of the heritability, $\boldsymbol{v}'$ is the transpose of $\boldsymbol{v}$. Values of $\boldsymbol{v}$ was expressed in % over the sum of their absolute values (Cardellino and Rovira, 1986; Gutiérrez, 2010; Gutierrez et al., 2014).

3. Results

3.1. Statistical analyses

The descriptive statistics of the fiber density traits of alpacas from Pacomarca are shown in Table 3. The average for HD, NF and RT were 32.00±6.00, 9.26±2.20 and 3.52±0.46 respectively. Significance of the age, sex and coat color effects on HD, NF and RT traits are shown in Table 4. Coat color effect did not influence the HD, NF and RT. However, the effects of sex and age had an influence (*p<0.001*) on the three traits of fiber density.

Fig. 1 illustrates the distribution of HD, NTF and RT among different age groups of Huacaya alpacas, revealing variability across the age groups. Fig.s 1A and 1B show that HD and NF decreased with age, while RT increases (Fig. 1C).

Table 3
Statistic descriptive of the number of hair ducts/mm^2, number of total fibers/mm^2 and ratio number of fibers/number of hair ducts in Huacaya type alpacas.

Density traits	Records (n)	Min	Max	Average	Standard deviation
Number of hair ducts/mm^2 (NF)	402	4.40	19.80	9.26	2.20
Number of fibers/mm^2 (HD)	402	15.00	52.80	32.00	6.00
Ratio NF/HD	402	2.18	4.92	3.52	0.46

Table 4
Significance of the effects influencing the fiber density traits in Huacaya type alpacas.

Effects	Hair ducts/mm^2 (HD)	Number of fibers/mm^2 (NF)	Ratio NF/HD
Coat color	ns	ns	ns
Sex	***	***	***
Coat color*sex	ns	*	*
Age	***	***	***

(ns): non significant
* $p < 0.05$
*** $p < 0.001$.

Similarly, Fig. 2 shows how fleece weight changes with the age in Huacaya alpacas, considering one shearing per year. Fleece weight did not increase linearly with age. It increased exponentially during the first five years, after which it reached a maximum and remained stable until around eight years of age. After this point, performance began to decline, primarily due to the shorter fibers of adult animals.

The scatterplots of HD and NF with main textile traits (FD, PM, FW) are shown in Fig. 3. The HD and the NF had a similar trend with the textile traits, observing that they did not have a linear relationship but rather tended to increase exponentially when the diameter decreased below 21μm, the medullation below 40 % and the fleece weight below 3 kg.

3.2. Genetic parameters

The estimates of heritability, permanent environmental and repeatability of density traits, and genetic and phenotypic correlations with the main textile traits are shown in Table 5. The heritability was low to moderate between 0.16 to 0.47. The genetic correlations were low to high between 0.01 to 0.75 in absolute value. The genetic correlations between density traits ranged from moderate to high, with a particularly high correlation between HD and NF (0.75). Regarding the correlation of fiber density traits with textile traits, both HD and NF had an identical favorable value of -0.50 with FD, as an increase in both fiber density traits reduces FD. However, both HD and NF did not have relevant correlation with PM, and only NF had a favorable correlation with FW. Likewise, the phenotypic correlation was low to high between 0.01 to 0.80 in absolute value. Most phenotypic correlations were similar to the genetic ones, except for RT and DS traits. Instead, the repeatabilities were moderate between 0.31 to 0.49.

3.3. Selection strategies

Fig. 4 shows the improvement in the expected genetic responses of traits included in the breeding goal, regarding the equivalent economic weights for FD, PM, NF and DS. Very different responses were found among the five scenarios. When the first three scenarios were compared, it was predicted that FW would increase by around +4 % in all cases. However, when 50 % of the weighting was applied to NF, the expected response for the FD and PM decreased by -34 % and -15 % respectively. These correlated responses were lower when only DS were included: -21 % and -9 % for FD and PM respectively. When NF and DS were weighted at 25 %, the expected responses were -28 % and -12 % for FD and PM respectively.

Conversely, when all weight was placed on the density traits (100 % for NF or DS), a better expected response for FW was observed than in the other scenarios. When NF was the only selection criterion, a better expected response was found for FD, PM and FW (-24 %, -5 % and +17 %, respectively) than when DS was the only selection criterion. Here, the expected responses were +3 %, +6 % and +17 % for FD, PM and FW

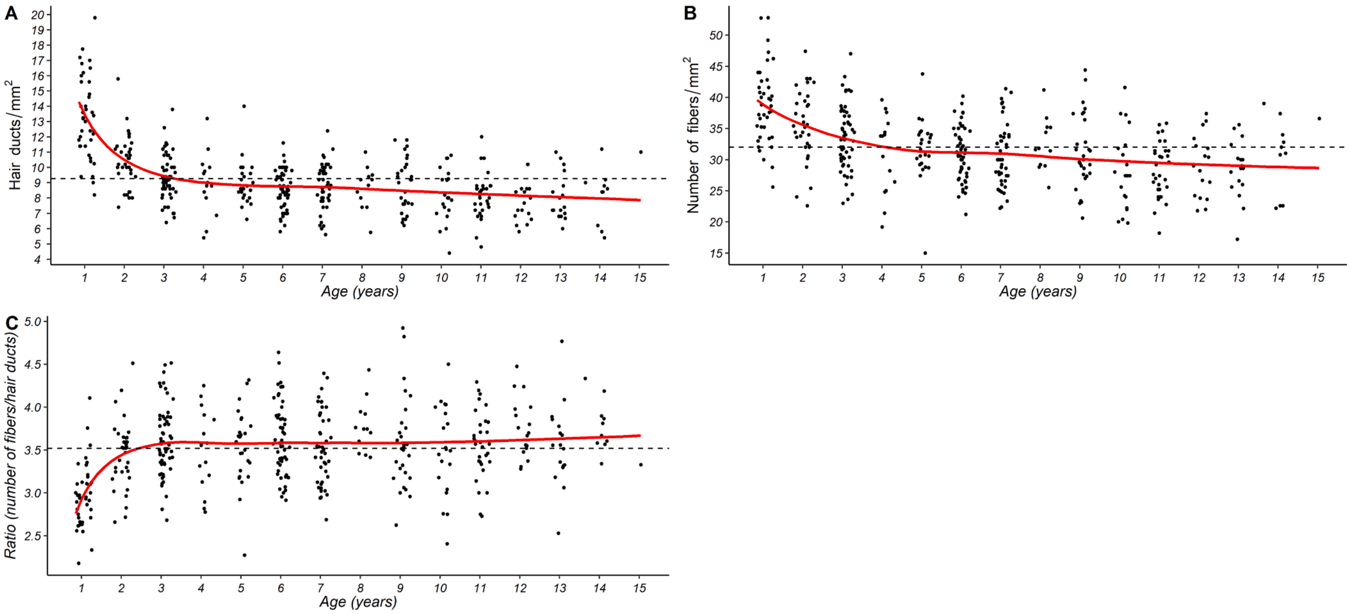

Fig. 1. Distribution of the number of hair ducts/mm^2 (A), number of fibers /mm^2 (B) and ratio number of fibers/hair ducts (C) according to age in Huacaya type alpacas; the dotted line represent the general mean and the redline represent the trend.

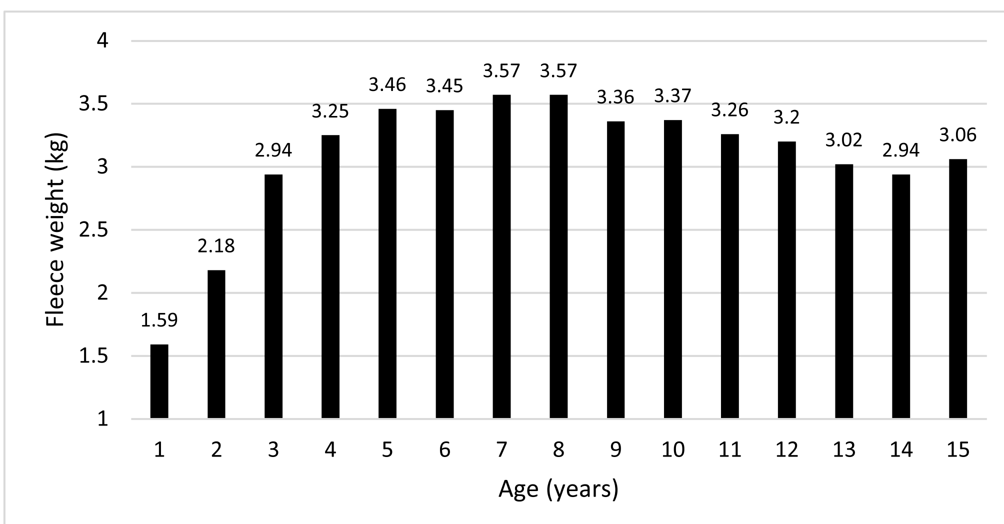

Fig. 2. Histogram of the average of the fleece weight according to age in Huacaya type alpacas.

respectively.

4. Discussion

4.1. Statistical analyses

Compared with Arequipa group, the mean of the density traits in Pacomarca were higher. Flores et al. (2022,; 2023) reported means of 7.83 for HD, 24.7 for NF and 3.25 for a RT in the Arequipa group. The higher fiber density of Pacomarca's alpaca population may be due to the fact that, since 2006, Pacomarca has used the predicted breeding values of fiber diameter (FD) to select animals. In addition, density score is recorded routinely at weaning, and alpacas with very low values are culled.

Likewise, Flores et al. (2022) and Flores et al. (2023) found that sex and age influenced HD and NF, but only age influenced RT. It should be noted that the alpaca groups in these studies had different age group definition: the Huancavelica group was 1-2 years old, while the Arequipa group was 2-8 years old. On the other hand, the effect of age on density traits could be explained by the maturation of follicles. On the other hand, the effect of age on density traits could be explained by the maturation of new follicles, mainly secondary, which increases the number of fibers during the first year. The following years, the skin expand without the appearance of new fibers, leading to a decrease in fiber density (Quispe et al., 2022b).

The trends of the density traits with respect to age for HD and NF are the opposite of those reported for fiber diameter (Burgos et al., 2023; Gutierrez et al., 2011). This is probably due to skin expansion, and the possible dysfunction of many hair follicles caused by ageing (Quispe et al., 2022b).

The influence of the age on the fleece weight was similar to that reported by Burgos et al. (2023), increasing during the first five years of age. In addition, fleece weight can vary considerably within the shearing period, which occurs mainly between September and March, coinciding

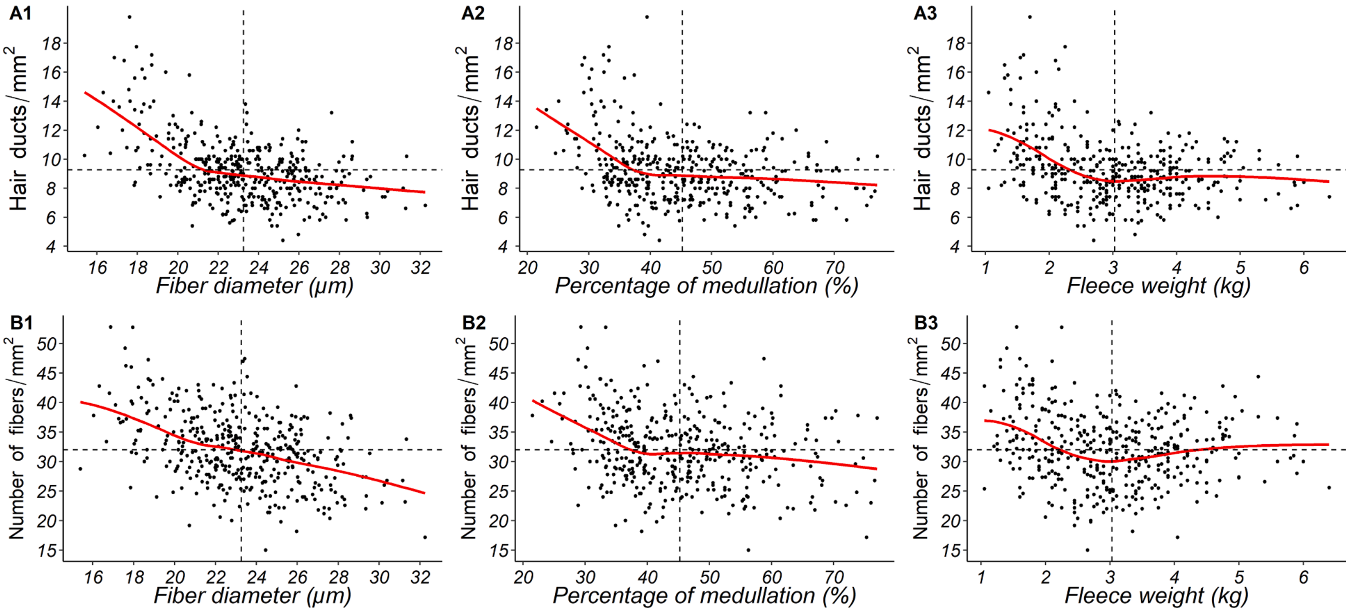

Fig. 3. Scatterplots between the number of hair ducts and fiber diameter (A1), percentage of medullation (A2) and fleece weight (A3) and between the number of fiber and fiber diameter (B1), percentage of medullation (B2) and fleece weight (B3) in Huacaya type alpacas, the redline represent the second-order polynomic trend, and dotted line represent the general mean for each trait.

Table 5
Heritabilities (in the diagonal), genetic correlations (above diagonal), phenotypic correlations (below diagonal), permanent environmental variances ratio (c^2), repeatability (R) and their corresponding standard errors (in brackets) between the density traits and the main textile traits in Huacaya type alpacas.

	HD	NF	RT	DS	FD	PM	FW
HD	**0.40** (0.05)	**0.75** (0.05)	**-0.46** (0.05)	-0.08 (0.02)	**-0.50** (0.05)	-0.09 (0.06)	0.03 (0.06)
NF	**0.80** (0.03)	**0.47** (0.03)	0.24 (0.09)	0.21 (0.04)	**-0.50** (0.04)	-0.11 (0.04)	**0.36** (0.06)
RT	**-0.54** (0.04)	0.04 (0.05)	**0.37** (0.05)	**0.39** (0.08)	0.04 (0.07)	0.01 (0.07)	**0.43** (0.05)
DS	0.06 (0.05)	0.13 (0.05)	0.06 (0.05)	**0.34** (0.02)	0.08 (0.06)	0.19 (0.07)	**0.50** (0.05)
FD	**-0.48** (0.04)	**-0.43** (0.05)	0.17 (0.05)	-0.02(0.05)	**0.31** (0.01)	**0.50** (0.06)	**0.35** (0.05)
PM	**-0.32** (0.05)	-0.25 (0.05)	0.15 (0.05)	0.01(0.05)	**0.77** (0.03)	0.28 (0.01)	0.24 (0.05)
FW	**-0.31** (0.05)	-0.15 (0.05)	**0.31** (0.05)	-0.03(0.05)	**0.48** (0.04)	**0.39** (0.05)	0.16 (0.01)
c^2					0.17 (0.02)	0.21 (0.02)	0.15 (0.01)
R					**0.48**	**0.49**	**0.31**

HD= hair ducts, NF= number of fibers, RT= ratio (NF/HD), DS=density score 1 to 5, FD= fiber diameter, PM= percentage of medullation, FW= fleece weight. Note: Heritability and genetic correlations higher than 0.30 in absolute value are provided in bold.

respectively with the beginning and end of the rainy season. The interval between shearing also plays a role, since not all animals are sheared every year. It has been shown that alpaca fiber can grow around 0.92cm to 1.10 cm/month (Burgos et al., 2023; Quispe-Peña et al., 2014), growing 1.13 cm/month on average in young animals (Quispe-Peña et al., 2014). Other studies report similar fiber growth in sheep around 1.03 cm/month (Quispe et al., 2022b). Given that animals provide fiber of better textile-quality but with lower weight in the early years of age, heavier fleece do not necessary indicate better quality. In addition, animals remain in the farm as breeders, regardless of their fiber yield until around ten years of age (Cruz et al., 2023), conditioning the quality o the fiber produced.

The phenotypic relationship between HD and NF with FD (Fig. 3) were similar to those reported by Quispe et al. (2023), who observed greater amounts of HD and NF when the fiber was finer. However, the phenotypic relationships between HD and NF with FW were different. In this study, it was found that animals with a fleece weight of less than 2 kg tend to have a higher fiber density. From 3 kg onwards, the trend seems to reverse, with a slight increase in FW, HD and NF. These differences could be attributed to sampling effects and differences in the definition of age groups of alpacas in the Huancavelica study (Quispe et al., 2023).

4.1.1. Genetic parameters

The heritability of density traits in alpacas were similar to those reported previously (Flores et al., 2022). The heritability estimates of DS, FD and PM were similar to other values reported for the same herd (Cervantes et al., 2010; Cruz et al., 2019; Cruz et al., 2024). However, the heritability for FW was different compared to other reports in alpacas. For instance, More et al. (2017) estimated a heritability of 0.41 for FW at first shearing in Huacaya alpaca, and Gutiérrez et al. (2009) reported a heritability estimate of 0.10 for FW in a joint analysis of Huacaya and Suri alpacas. In this research, we included one or more shearings records per alpaca in the analysis and only used data from Huacaya alpacas. This explains the difference with the aforementioned studies. In contrast, Cruz et al. (2019) reported a value of 0.23 for Huacaya, which is close to the heritability found for FW.

Additionally, it should be noted that Pacomarca's management system differs from the conventional approach typically employed in alpaca breeding. Initially, Pacomarca's objective was to reduce the fiber diameter; subsequently, they incorporated the percentage of medullation as another breeding goal. To this end, they have been selecting their animals based on genetic merit. By contrast, the alpacas in the other two studies were also selected for reducing fiber diameter, but this was done using morphological and subjective evaluations. This methodological

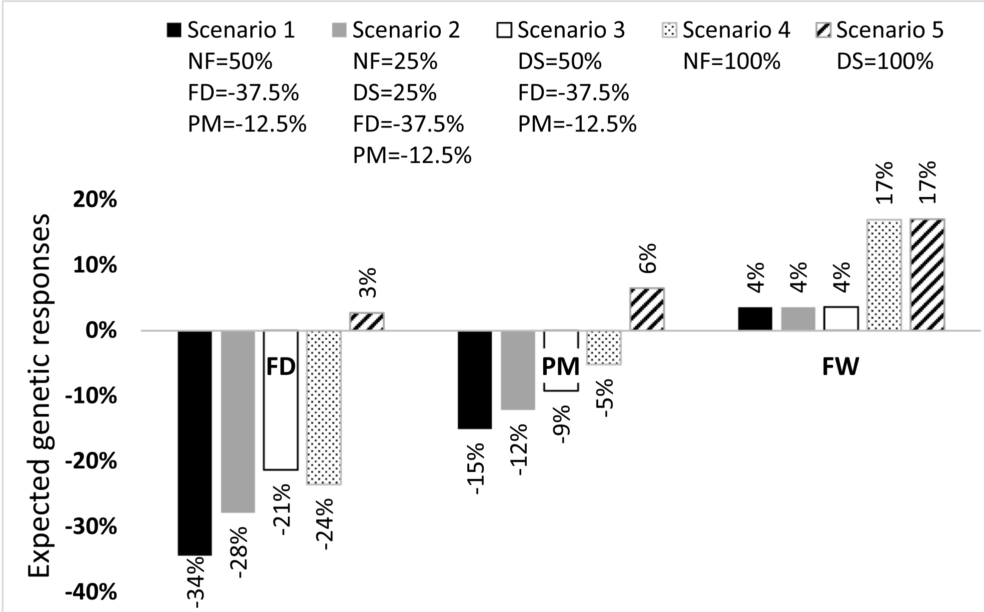

Fig. 4. Weighting of equivalent economic weights on the phenotypes of quality (fiber diameter - FD and percentage of medullation - PM) and quantity (number of fibers - NF and density score - DS) to obtain improvement in the expected genetic responses in the objectives to Huacaya type alpacas.

difference could potentially influence the comparability of the results, although it is important to note that, while conclusive, the results may not be representative of the global alpaca population.

4.2. Selection strategies

Simultaneously improving two unfavorably genetic correlated traits, such as FD and FW, is a concern. However, some strategies can be explored to find an alternative solution.

Exploring the genetic response for each trait according to different weights is an alternative way to predict the effect of the weighted selection (Gutierrez et al., 2014). To improve quality (FD and PM) and quantity (FW) equally, 50 % of the weighting was assigned to both quality and quantity objectives (in absolute values) across three scenarios, and two scenarios more using 100 % on the NF and DS respectively. Appropriate weighting can result in much greater total genetic gain for fiber traits (Cruz et al., 2023).

Although HD, NF, RT and DS are not traits included in the breeding goal, the expected responses for these traits were also considered. However, the responses of FD, PM and FW are the most important. The results suggest that NF is of great importance when weighting the index as it generates a response in quality and quantity. It could even be used as a single trait to improve quantity and slightly improve quality.

Beyond the expected responses obtained using NF, the cost and difficulty of gathering this trait must be taken into account when deciding whether to include it in the selection criteria. For example, many high-resolution pictures are required to measure NF using a specialized camera and software, as well as the necessary preparation of the skin area. On the other hand, directly measuring FW could be more costly and time-consuming than recording NF.

5. Conclusion

Using NF as one of the selection criteria allows to improve FD, PM and FW simultaneously. This Approach will allow us to address the unfavorable genetic correlation between FD-FW and PM-FW. However, there is significant scope to reduce the costs associated with measuring NF, as well as addressing owners' concerns about the time and welfare implications of exposing their animals to this procedure. Similarly, incorporating DS alongside with FD and PM in a selection index will be another cost-effective alternative, albeit with smaller increases in fiber quality and quantity compared to NF.

CRediT authorship contribution statement

Alan Cruz: Writing – original draft, Validation, Investigation, Formal analysis, Conceptualization. **Edgar Quispe:** Writing – review & editing, Investigation, Funding acquisition, Formal analysis. **Alex Yucra:** Data curation. **Renzo Morante:** Writing – review & editing, Data curation. **Alonso Burgos:** Data curation. **Max David Quispe:** Investigation, Funding acquisition. **Juan Pablo Gutiérrez:** Writing – review & editing, Visualization, Validation, Supervision, Methodology. **Gustavo Gutiérrez-Reynoso:** Writing – review & editing, Visualization, Validation, Funding acquisition, Conceptualization.

Declaration of competing interest

We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us.

We confirm that we have given due consideration to the protection of intellectual property associated with this work and that there are no impediments to publication, including the timing of publication, with respect to intellectual property. In so doing we confirm that we have followed the regulations of our institutions concerning intellectual property.

We understand that the Corresponding Author is the sole contact for the Editorial process (including Editorial Manager and direct communications with the office). He is responsible for communicating with the other authors about progress, submissions of revisions and final approval of proofs. We confirm that we have provided a current, correct email address which is accessible by the Corresponding Author and which has been conFig.d to accept email from Gustavo Gutiérrez-Reynoso E-Mail: gustavogr@lamolina.edu.pe

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