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REGULAR ARTICLES

Restoring the black color of alpaca fiber

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Abstract
A project to restore the black alpaca population was implemented in 2018 at Pacomarca Scientific Station because demand for natural black alpaca fiber increased. The objectives were: (a) to evaluate the influence of environmental effects on colorimetric values, (b) to analyze Huacaya/Suri segregation in black alpacas, (c) to analyze black color segregation in alpaca population, (d) to evaluate progress in the search for intense black, (e) to analyze fiber diameter (FD) and fleece weight (GFW) in black alpacas, and (f) to estimate the genetic parameters of colorimetry values and their correlation with other textile traits. The pedigree file included 17,184 animals recorded between 1992 and 2025, and 5,091 colorimetric records of lightness (L*), red–green (a*), and yellow–blue (b*) from black alpacas were analyzed. Also, 5,825 FD and 3,467 GFW records from black alpacas, corresponding to 4,565 alpacas, were measured between 2018 and 2024. Coat color group and year significantly affected colorimetric values. Huacaya×Suri mating is not practiced, but 0.91% of newborns were Suri and 7.95% of newborns were Huacaya within the Huacaya and Suri mating groups, respectively. Black alpacas were born mainly from reddish black (41.18%) and from full black (71%) parents. CIELAB values have been reduced in the search for intense black. The mean of GFW of a black alpaca was less than that of a white alpaca. The heritability estimates of colorimetric traits for black alpacas were very low (0.01 to 0.04), and significant correlations were found between FD-L* (-0.55), FD-a* (-0.99), FD-b* (-0.94), and GFW-L* (0.31). Black alpacas offer a commercial opportunity that can support their conservation. Selection for intense black color in alpacas is feasible by using colorimetric values as a criterion, especially L* and b*.

Keywords Black alpaca · Colorimetry · Fiber · Genetic

Introduction

Alpaca fiber–based products are increasingly gaining recognition in niche markets. Consumers are adding alpaca fiber to their wardrobes not only for its textile properties, such as softness and fineness, but also for its contribution to the sustainability of Andean culture and ecosystems. In parallel, the alpaca population has expanded not only in South America but also worldwide. According to MIDAGRI (2019), the global alpaca population is estimated at approximately 6.07 million heads. Peru, which accounted for 86.9% of the world's alpacas in 1999 (3.03 million heads), represented 71.7% in 2019 with 4.35 million heads, followed by Bolivia (8.6%), Australia (8.2%), the United States (5.8%), several European countries (2.5% collectively), and about 50 other countries each holding less than 1% of the global alpaca population.

Based on fiber classification reports from the alpaca textile industry, approximately 80% of alpaca fiber corresponds to white fleece, while the remaining proportion is distributed across different colored groups. According to the Peruvian Technical Standard NTP 231.301 (2014), fleece colors are categorized as basic or combined. Cruz (2017) also described these colors. Black represents less than 1%, according to data from the fiber classification carried out by

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Inca Tops, which reports that only 0.07–0.4% of black fiber is recovered from national production of color fiber (Burgos et al. 2023).

In 2018, a program, "Yanapaco (black alpaca in Quechua and Aymara languages)" began at Pacomarca Scientific Station to conserve and promote black alpacas. Alongside the conservation effort, the project produced dark-colored fiber without chemical dyes; 100% pure alpaca fiber in a natural black color was offered to luxury alpaca commercial niches and was well received in the market (Burgos et al. 2023). The commercial term *Black Alpaca was thus coined to designate alpacas with dark fleeces*, *including the black and reddish-black* colors, hereafter referred to collectively as *Black Alpaca*.

Black alpaca fiber is classified into four color subgroups: two can be directly used as pure natural fibers for garments and textile products, while two reddish subtypes are commonly blended with other colors and/or fiber types to create shades distinct from pure black. The darker the alpaca fiber, the higher its commercial value, which has driven selection based on color intensity to produce intense black fleeces.

Two methodologies has been used to distinguish the color in alpacas and llamas: (a) **animal color**, which refers to the variation in tones across the body surface and is used to assign a color of the animal, as described by Frank et al. (2006), and (b) **fleece color**, which specifically refers to the coat color as expressed in the shorn fiber, a trait directly relevant to textile processing (Cruz et al. 2021). This study focuses on fleece color.

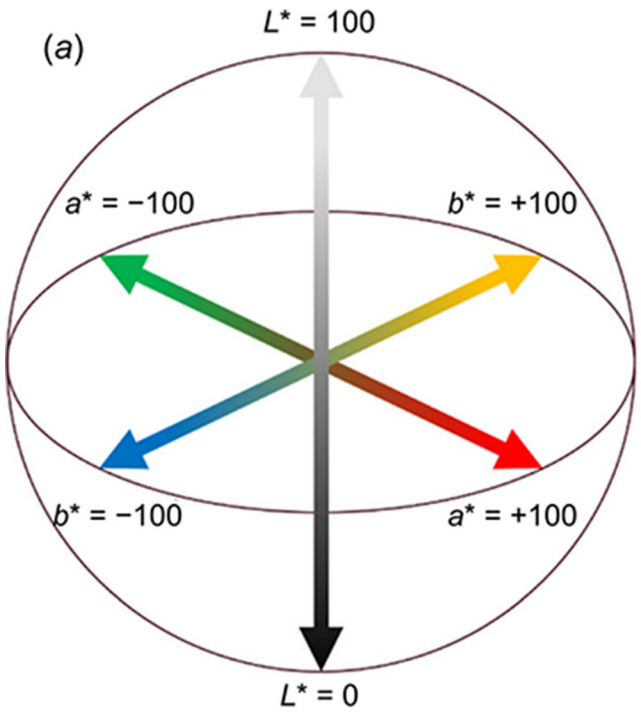


Fig. 1 Three-dimensional color space, L*= Lightness, a*= axis red-green, b*= axis yellow-blue

The most widely used method for measuring color is the chromatic model shown in Fig. 1, proposed by the Commission Internationale de l'éclairage (CIE), which represents color in a three-dimensional space known as the CIELAB system (Fairchild 2005). Researchers have also applied this model to describe fiber color in alpacas (Bartolomé et al. 2009; Cruz et al. 2021; Gray et al. 2023; Pinares et al. 2021).

Producing dark-colored fiber, and particularly intense black, still faces multiple challenges. The colored population is small and widely dispersed across the Andes and other parts of the world (Baxter et al. 2025; Burgos et al. 2023; MIDAGRI 2019), with exceptions in a few small communities where the proportion of colored alpacas exceeds the national average (Oria et al. 2009). Moreover, alpacas have a long generation interval (about 7 years), a gestation period of about 11 months, and generally produce only one offspring per year (Cruz et al. 2015). In addition, two black alpacas do not always produce black offspring, and black color intensity varies substantially (Cruz et al. 2021). Technological challenges also remain; for example, before 2018, measuring fiber diameter in dark-colored alpacas resulted in errors (Quispe et al. 2018), as available equipment was not calibrated for dark fibers. Limitations also persist in measuring the percentage and type of medullation in dark fibers (Bartl et al. 2023; Cruz et al. 2019, 2024). Although researchers have attempted to bleach fibers to assess medullation (Lozano et al. 2023), this process damages the medullated structure and may lead to inaccurate results. Furthermore, reproductive biotechnologies such as artificial insemination and embryo transfer require improvements in fertility rates (Adams et al. 2009; Vaughan et al. 2013), before they can be widely implemented in extensive camelid breeding systems. In addition to producing intense black, the black alpaca program must address these challenges.

The Inca Group, through its Pacomarca Scientific Station, has undertaken the conservation and promotion of black alpaca by implementing both commercial and productive strategies. These strategies aim not only to produce intense black fleeces but also to conserve other alpaca colors, using the CIELAB methodology as a tool for color selection. Consequently, conserving black alpacas requires an analysis of the underlying genetic background. Based on this, the following objectives were established: (a) to evaluate the influence of environmental effects on colorimetric values, (b) to analyze Huacaya/Suri segregation in black alpacas, (c) to analyze black color segregation in alpaca population, (d) to evaluate progress in the search for intense black, (e) to analyze fiber diameter and fleece weight in black alpacas, and (f) to estimate the genetic parameters of colorimetric traits

and their correlation with the main textile traits of economic interest in black alpacas.

Materials and methods

Animal population, phenotypes, and datasets

The dataset analyzed was obtained from PacoProWeb at the Pacomarca Scientific Station, including both Huacaya and Suri types, grouped into nine basic fleece color categories: white (W), light fawn intensity X, Y, Z (LFX, LFY, LFZ), light brown (LB), dark brown (DB), dark brown–black or reddish- black (RB), black (B), and the different shades of grey (G) as reported by Cruz (2017) and NTP.231.301 (2014).

Colorimetric records were collected between 2018 and 2024. Approximately 10 g of fiber was sampled from the mid-side of each animal. Samples were properly labeled, washed with neutral detergent, and dried at room temperature. Color measurements were then obtained using a colorimeter on the CIELAB scale, which represents color in a three-dimensional space defined by Lightness (L*), the red–green axis (a*), and the yellow–blue axis (b*), as described by Martínez (2001).

The pedigree file included 17,184 animals recorded between 1992 and 2025. A total of 11,663 colorimetric records were analyzed, including all colors. The number of records for Black alpacas was 5,091, 5825, and 3464 for colorimetric values, FD, and GFW, respectively, corresponding to 4,565 black alpacas and the period between 2018 and 2024. Animal age ranged from 0.1 to 15.3 years.

Influence of environmental effects on colorimetry

To analyze the environmental effects on colorimetry, a multifactorial linear model was applied. Fisher's Least Significant Difference (LSD) methodology was used for mean comparisons to evaluate differences in the effects of sex (2 levels: male and female), alpaca type (2 levels: Huacaya and Suri), fleece color (2 levels: RB, and B), and sampling year (7 levels: 2018–2024) on CIELAB values (L*, a*, and b*). For statistical analysis, the *agricolae* package was used, while graphical outputs were generated with the *ggplot2*, *colourpicker*, *plotly*, and *rgl* packages in R (R Core Team 2020).

Segregation of Huacaya and Suri phenotypes in black alpacas

A total of 2,284 birth records of alpacas from 2018 to 2024 were analyzed, including 2,196 records from Huacaya × Huacaya matings and 88 records from Suri × Suri matings. The analysis used pivot tables in Microsoft Excel to compare segregation between Huacaya × Huacaya and Suri × Suri matings.

Color segregation in Huacaya alpacas

To analyze fleece color segregation, the dataset included animals with recorded and measured fleece color under colorimetry. Two types of analyses were performed using pivot tables in Microsoft Excel:

a) A total of 12,977 birth records of alpacas of all fleece colors were used to compare parental fleece color and the corresponding offspring between 2018 and 2024. Notably, this is the only section of the study in which all fleece colors were included for analysis.
b) A total of 2,196 birth records of black Huacaya alpacas from the black alpaca program, born between 2018 and 2024, were also independently analyzed to evaluate segregation by parental lines. The distribution of CIELAB values (Fig. 2) shows the L*, a* and b* colorimetry traits distribution of black alpacas regarding the age of the animals.

Phenotypic progress of black alpaca

To evaluate the evolution of colorimetric values in the offspring, 1,205 records of black Huacaya alpacas, born between 2018 and 2024, were collected at one year old. Data visualization was performed using the *ggplot2* package in the R language (R Core Team 2020).

Fiber diameter and fleece weight analysis in black alpacas

Samples were evaluated for fiber diameter (FD) following the methodology described by Gutiérrez et al. (2009). Measurements of black fiber were obtained using the *Small Fiber EC*, an instrument specifically developed for assessing fiber diameter in dark-colored fleeces (Quispe et al. 2018). The average fiber diameter tended to increase with the age of the animal (Fig. 3). Additionally, fleece weight (GFW) was recorded, also following Gutiérrez et al. (2009), for alpacas included in the black alpaca program. A comparison of GFW with white alpacas was performed using reference values reported by Cruz et al. (2025).

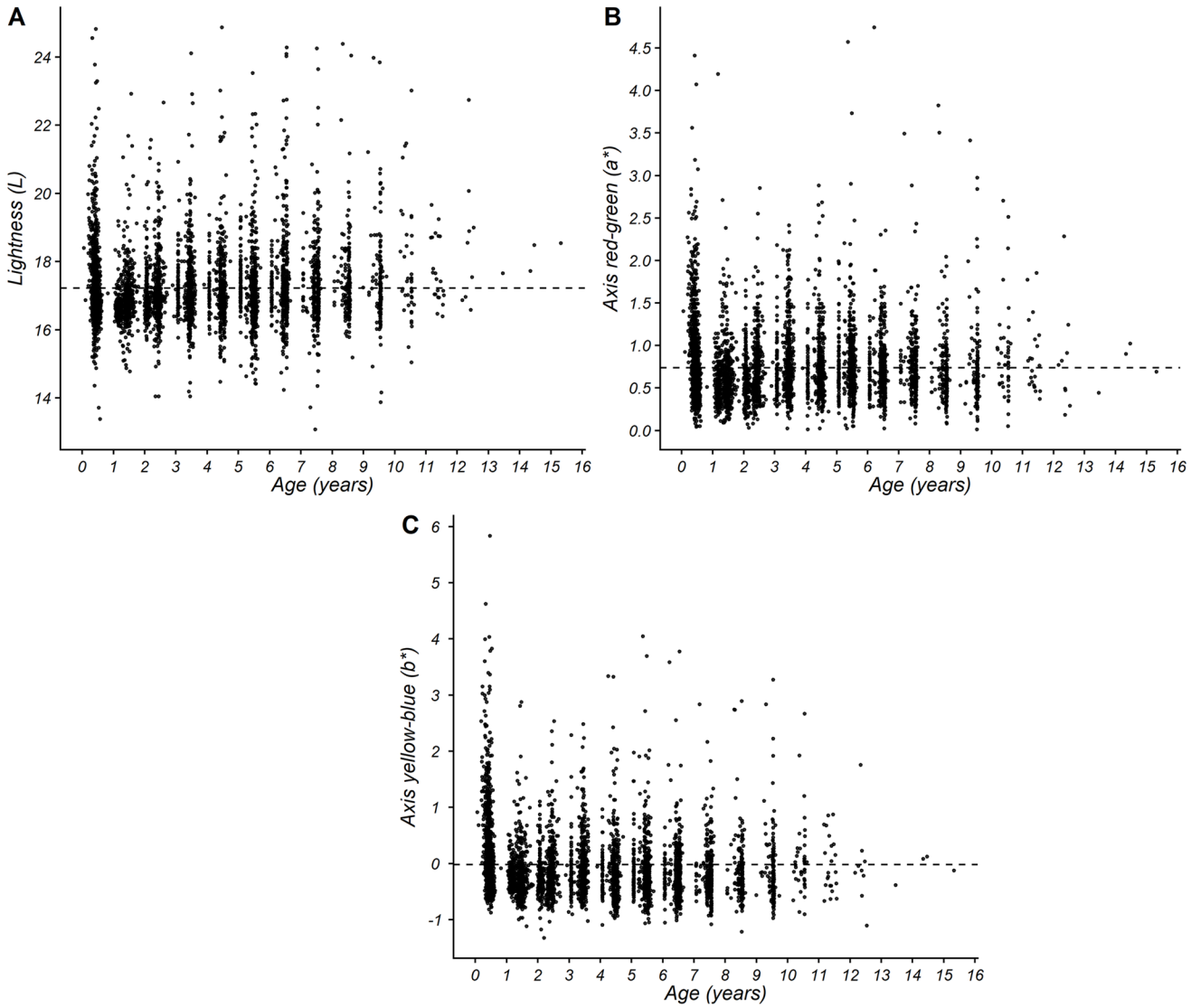


Fig. 2 Distribution of CIELAB values in the Black Alpaca Program. Lightness (**A**), axis red - green (**B**) and axis yellow – blue (**C**)

Estimation of genetic parameters for colorimetry in black alpacas

To estimate variance components of colorimetry traits (L*, a*, and b*) in black alpacas and their genetic relationship with the main textile traits (FD and GFW), a multi-trait animal model with repeated measures was applied, using the restricted maximum likelihood (REML) procedure (Patterson and Thompson 1971). The model fitted for L*, a*, b*, FD, and GFW was: $\boldsymbol{y} = \boldsymbol{Xb} + \boldsymbol{Zu} + \boldsymbol{Pp} + \boldsymbol{e}$

$$\begin{matrix} \text{w} \\ \\ \end{matrix} \quad \begin{matrix} \\ \\ \end{matrix} \quad \begin{matrix} \text{i} \\ \\ \end{matrix} \quad \begin{matrix} \text{t} \\ \\ \end{matrix} \quad \begin{matrix} \\ \text{h} \end{matrix}$$

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

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 ⊗ the Kronecker product.

Fixed effects for all traits included coat color with two levels (RB and B), sex with two levels (male and female), except for fiber diameter where a combined effect of sex × lactation was considered (Cruz et al. 2017), with three levels

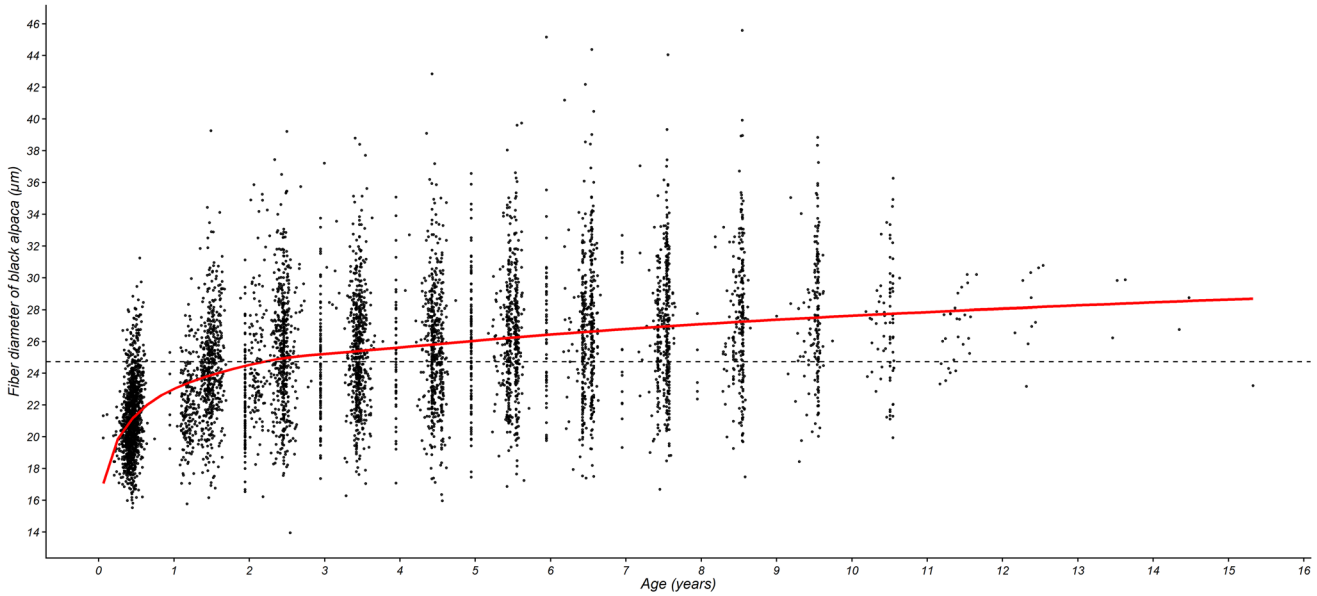


Fig. 3 Distribution of fiber diameter of Huacaya black alpaca according to age, the redline is the second-order polynomial trend and the dotted blackline is the general mean

Table 1 Least significant difference of the effects on CIELAB Values in Huacaya black alpacas

	L*	a*	b*
Coat color			
Reddish Black	18.10±2.25[a]	1.28±0.95[a]	0.76±1.54[a]
Black	17.25±1.30[b]	0.71±0.48[b]	-0.12±0.62[b]
Sex			
Female	17.30±1.28[a]	0.75±0.48[a]	-0.10±0.61[b]
Male	17.40±1.78[a]	0.78±0.74[a]	0.09±1.15[a]
Year of sampling			
2018	17.49±0.97[ab]	0.91±0.58[a]	0.23±0.82[a]
2019	17.53±1.23[a]	0.90±0.53[a]	0.04±0.71[b]
2020	17.58±1.80[a]	0.90±0.71[a]	0.15±0.98[a]
2021	17.00±1.17[d]	0.70±0.56[b]	-0.18±0.63[c]
2022	17.16±1.33[c]	0.61±0.41[c]	-0.18±0.75[c]
2023	17.25±1.57[bc]	0.63±0.46[c]	-0.17±0.79[c]
2024	17.23±0.94[bc]	0.71±0.35[b]	-0.02±0.46[b]

L*= Lightness, a*=axis red - green, b*= axis yellow - blue. Superscripts ([a], [b], [c] and [d]) indicate which groups are statistically different or equal to each other

Means ± standard deviation

(males, non-lactating females, and lactating females); year of data collection with six levels (2018–2024); and age as linear and quadratic covariates in days.

Pedigree recoding and analysis were performed using Endog v4.8 (Gutierrez and Goyache 2005). Genetic and phenotypic parameters were estimated using VCE 6.0 (Neumaier and Groeneveld 1998).

Results

Influence of environmental effects on colorimetry

The effects of coat color, sex, alpaca type, and year of sampling on CIELAB values were assessed (Table 1). Results showed that sex had no significant influence on L* and a*, but had a significant effect on b* value. A slight effect of alpaca type (Huacaya or Suri) was observed only on Lightness (L*).

Fiber lightness values decreased progressively from white to black, whereas values of the red and yellow axes increased. A closer examination of black alpaca records (RB and B) reveals that animals with the most intense black coloration lose yellow coloration (b* positive as RB), approaching 0, and adopt a bluish coloration (b* negative as B).

Huacaya and Suri segregation in black alpacas

Pedigree information presented in Fig. 4 shows the cross segregation of offspring within the black alpaca program. There were no crossed matings between Huacaya×Suri type animals. Huacaya×Suri mating is not practiced, but 0.91% of newborns were Suri and 7.95% of newborns were Huacaya within the Huacaya and Suri mating groups, respectively. During the first year of the program, from 260 births of Huacaya parents, 5% newborns were of the Suri type, this proportion decreased progressively until reaching 0% in 2024, despite the increasing number of births recorded between 2019 and 2024. Conversely, the same figure shows

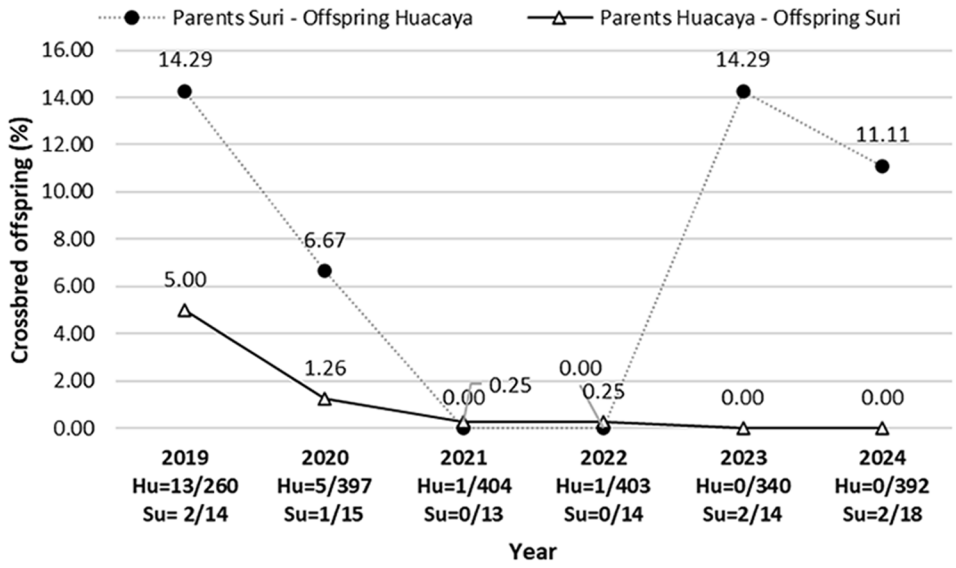


Fig. 4 Percentage of crossbred offspring (number of offspring/total births) of Huacaya (Hu) and Suri (Su) type alpacas from the black alpaca program

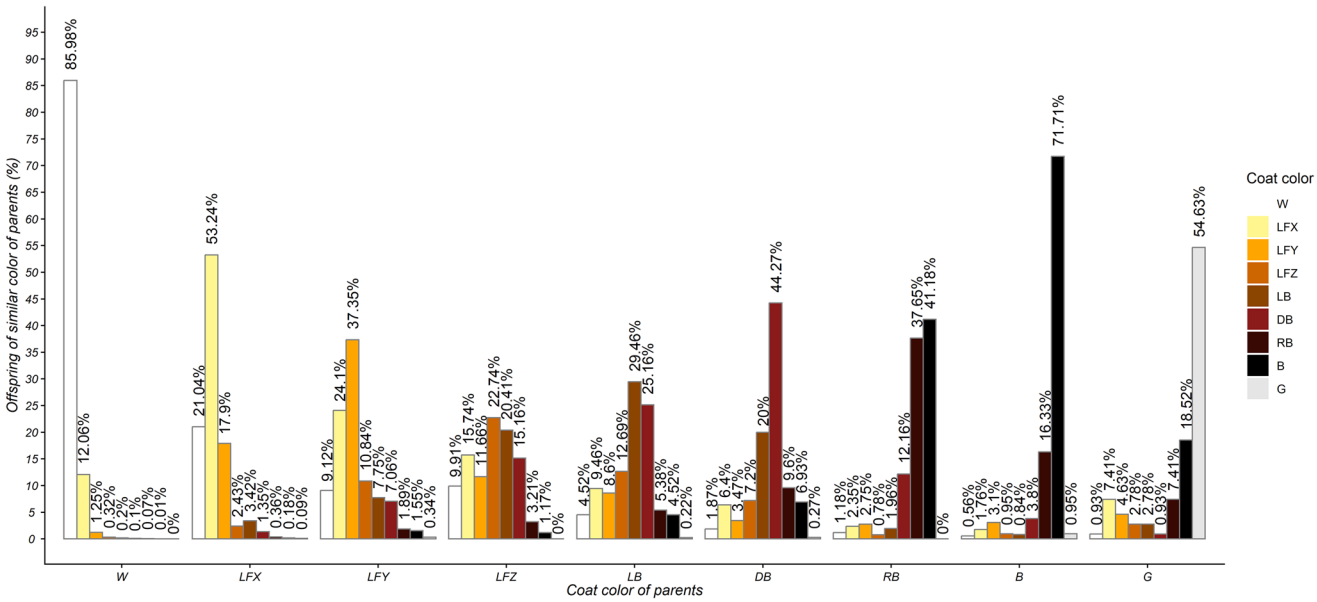


Fig. 5 Coat color segregation (%) according to the coat color of the Huacaya parents, W= White, LFX, LFY y LFZ= light Fawn intensity X, Y and Z, LB= light brown, DB= dark brown, RB= reddish black, B= black and G = all variants of gray, ratios in historical birth data (2001–2024)

that between 2019 and 2024, Suri Black parents produced only up to 2 Huacaya-type offspring, representing 14.29%, although the number of births per year was much lower than for Huacaya (only 13 to 18 per year).

Fleece color segregation

Fleece color segregation in the offspring was evaluated based on the fleece color of the parental lines, using the complete pedigree, taking into account that matings were always carried out between animals of the same color. Figure 5 shows that white-coated parents produced 85.98% of offspring with the same color (white), followed by black-coated parents with 71.71%. In contrast, the remaining colors exhibited much lower segregation percentages for the same fleece color, ranging from 22.74% (LFZ) to 54.63% (Gray). Furthermore, a general trend was observed: darker-colored parents produced fewer light-colored offspring, and vice versa, except for RB, where parents of this color produced a few RB offspring (37.65%) and B offspring (41.18%) in nearly equal proportions.

A comprehensive analysis of the offspring of the Huacaya black alpaca program from 2019 to 2024 is shown in Fig. 6. In 2019, Black Huacaya parents produced 48.08% of offspring the same color as their parents (B), but this percentage increased to 82.91% in 2024. In contrast, the

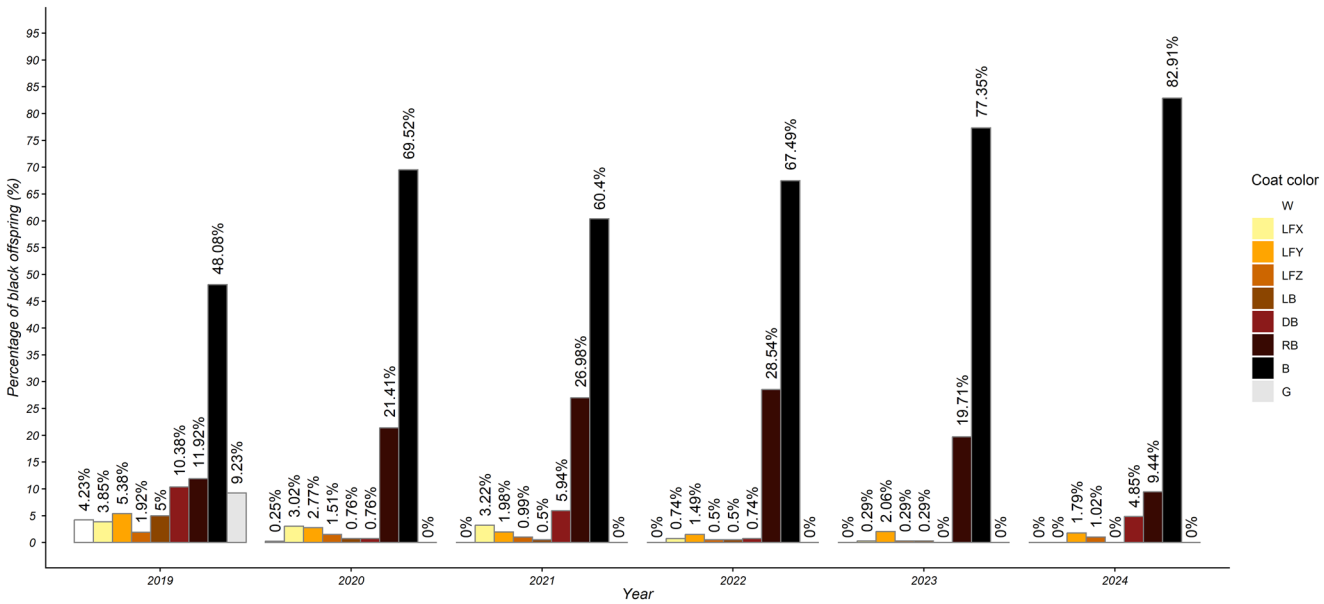


Fig. 6 Coat color segregation of offspring from Huacaya black alpaca program, W= White, LFX, LFY y LFZ= light Fawn intensity X, Y and Z, LB= light brown, DB= dark brown, RB= reddish black, B= black and G = all variants of gray

percentage of births of light colors such as B, LFX, and LFY has decreased, reaching a point where they no longer segregated from black alpaca parental lines over the years. A particularity was observed in the segregation of the grey color, where only in the first year did the black alpaca parents segregated the grey color in its various shades (9.23%).

Phenotypic progress toward intense black

The trend of colorimetric traits in the offspring of the Huacaya black alpaca is shown in Fig. 7. The results illustrate the phenotypic progress toward intense black by using colorimetric traits as a selection criterion. Starting in 2018, when animals were incorporated into the program, the graph shows that the first babies born in 2019 represented a setback in the search for intense black. From that point onward, however, selection success has progressively improved in subsequent years.

Fiber diameter and fleece weight in black alpacas

The average of fiber diameter in black alpaca (B and RB) was 24.73 µm (Fig. 3), coarser than the white alpacas. While the Fig. 8 shows the fleece weight of black and white alpacas across years of age, based on data adapted from Cruz et al. (2025). Fleece weight in black alpacas was lower than in white alpacas from the first year of age. The average fleece weight of a black alpaca is 2.49 kg/animal, but overall, the cumulative difference was 6.63 kg less than that of a white alpaca over eleven years of production.

Heritabilities, genetic and phenotypic correlations of colorimetry and textile traits in black alpacas

Heritabilities, genetic and phenotypic correlations of fiber and colorimetry traits were estimated (Table 2). Heritability estimates for CIELAB values were very low (0.01 to 0.04), whereas FD and GFW showed moderate heritability (0.48 and 0.31). Similarly, the ratio of permanent environmental variance was very low to low across all traits (0.01 to 0.19). However, repeatability estimates were low for L* and b*, moderate for a* and GFW, and high for FD.

Discussion

The global alpaca population has been steadily increasing (MIDAGRI 2019), along with improvements in fiber quality (Burgos et al. 2023; Cruz et al. 2020, 2024). However, the proportion of colored animals, particularly black alpacas, has drastically declined (MIDAGRI 2019). This reduction is largely attributable to the industrialization of alpaca fiber, which over the past 60 to 80 years has predominantly relied on white fiber for the production of textiles through dyeing, while sidelining naturally pigmented fibers. Nevertheless, given the current trend toward environmental protection, natural colors have considerable potential for use in undyed products (Burgos et al. 2023), provided adequate strategies are developed to strengthen their production and commercialization.

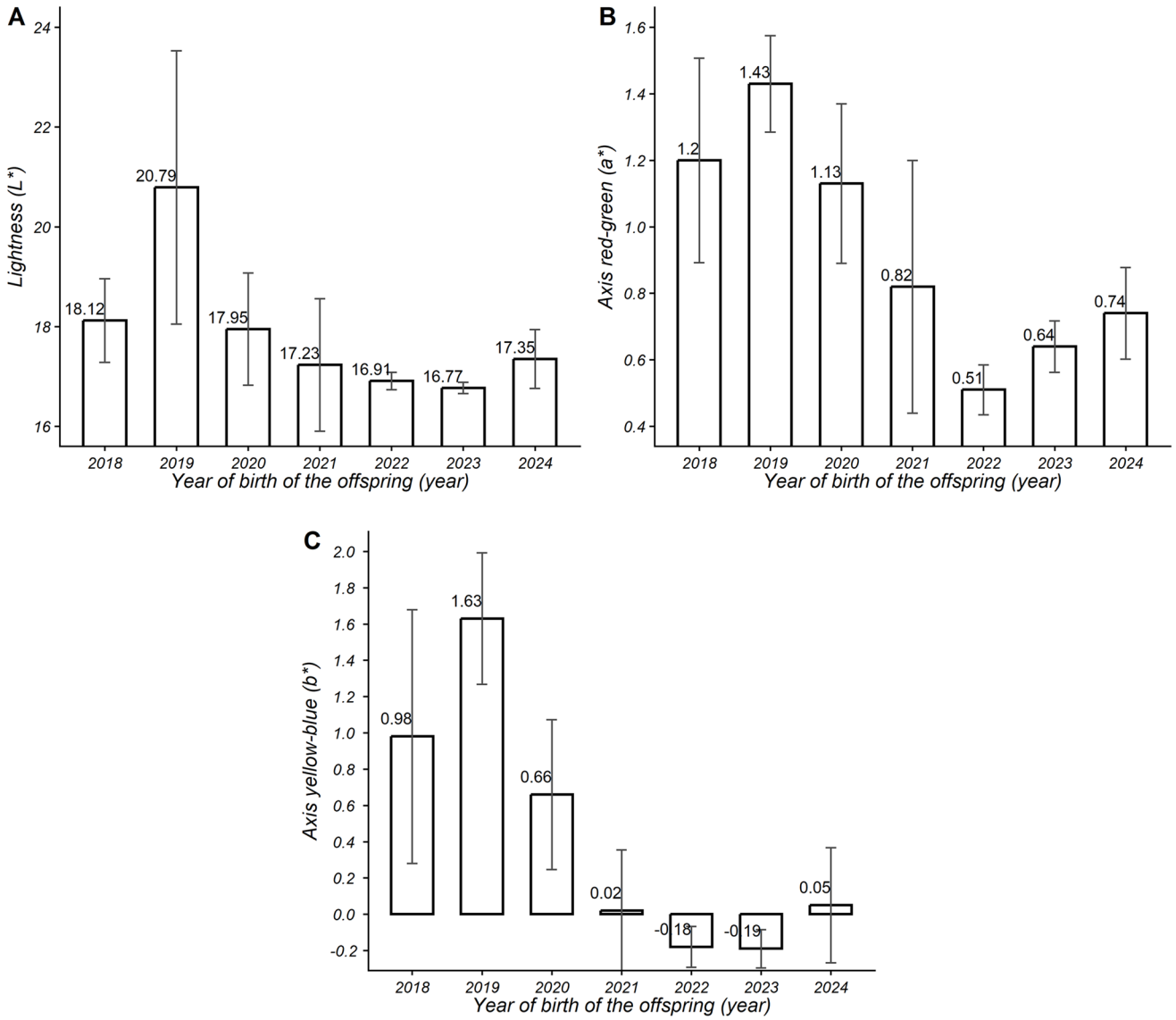


Fig. 7 Trend of the CIELAB values of the offspring born between 2018 to 2024. Lightness (**A**), axis red - green (**B**) and axis yellow - blue (**C**). Means with their respective standard errors

Influence of environmental effects on colorimetric values

The assignment of fleece color in Pacomarca follows the Peruvian Technical Standard, as reported by Cruz (2017), to ensure comparability. The significance test (Table 1) showed that fleece color and year of sampling had an effect on colorimetric values. The year suggests a selection effect, but since genetic effects may explain part of it, environmental influences may also play a role; no other reports were found on the influence of these factors on such traits. Nevertheless, the CIELAB values were similar to those previously reported by Cruz et al. (2021). For RB and B colors, the difference can be attributed to genetic control of pigmentation, mainly regulated by the MC1R and ASIP genes (Anello et al. 2022b; Baxter et al. 2025; Pinares et al. 2021). The segregation of pheomelanin genes (associated with brown or reddish phenotypes) is reflected in RB colors, as also reported in Australian and North American alpacas (Baxter et al. 2025; Paul 2014). Although RB and B share similar luminosity values, differences were observed in the a* and b* axes, where RB tends to exhibit a pheomelanic phenotype. Regarding the year of sampling, the influence on CIELAB values is largely due to the program's selection process. Selection initially aimed to intensify reproduction in black alpacas and, to a lesser extent, RB, by using culling as a selection strategy (Calsamiglia et al. 2015; Mehrabani-Yeganeh et al. 1999). In this scheme, all selected males were

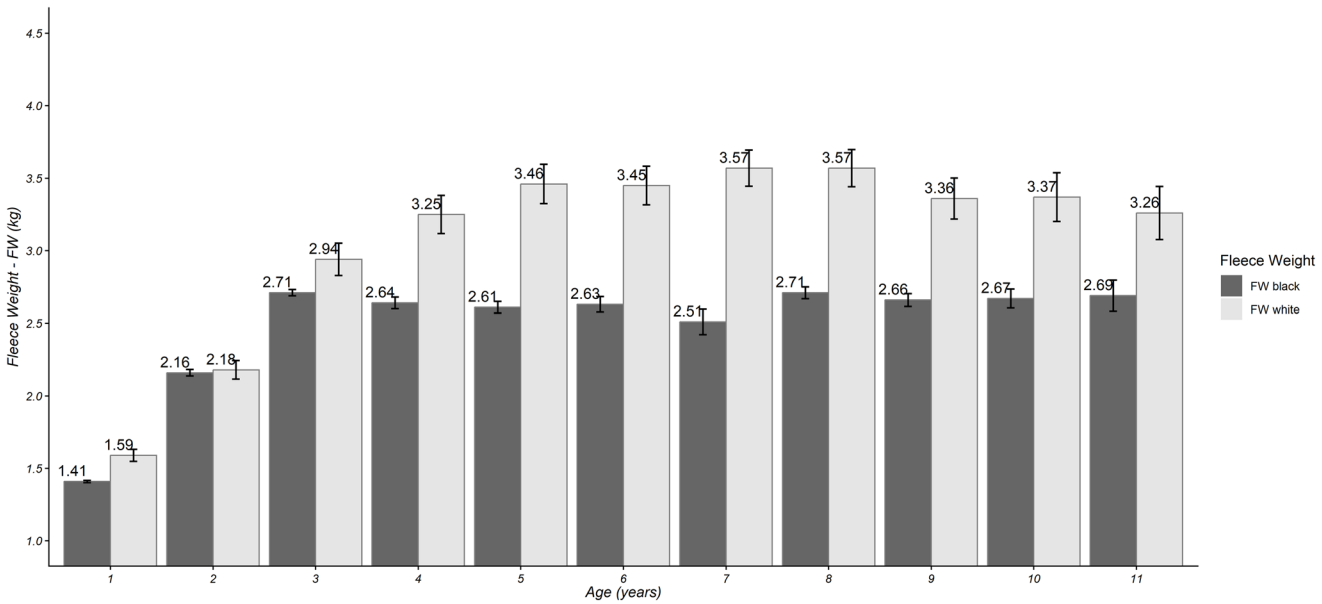


Fig. 8 Comparison of fleece weight (GFW) of black and white Huacaya type alpacas according to age. Means with their respective standard errors

Table 2 Heritability (in the diagonal), genetic correlations (above the diagonal), permanent environmental variances ratio (c^2), and their corresponding standard errors (in brackets), repeatability (R), phenotypic correlations (below the diagonal) for CIELAB values, fiber diameter (FD) and greasy fleece weight (GFW) in Huacaya black alpacas

	L*	a*	b*	FD	GFW
L*	0.01 (0.01)	**0.66** (0.07)	**0.80** (0.07)	**-0.55** (0.02)	**0.31** (0.03)
a*	**0.37**	0.04 (0.01)	**0.98** (0.02)	**-0.99** (0.01)	-0.23 (0.09)
b*	**0.43**	**0.83**	0.03 (0.01)	**-0.94** (0.04)	-0.10 (0.12)
FD	-0.04	-0.19	-0.28	**0.48** (0.02)	**0.33** (0.04)
GFW	-0.02	-0.08	-0.17	**0.43**	**0.31** (0.03)
c^2	0.01 (0.01)	0.19 (0.02)	0.09 (0.01)	0.12 (0.02)	0.06 (0.02)
R	0.02	0.23	0.12	**0.60**	**0.37**

L*= Lightness, a*= axis red - green, b*= axis yellow - blue. All values higher than 0.30 in absolute value are in bold

obligate B, while females could be either B or RB. This also may explain the observed effect of sex on b* values.

Concerning the influence of type (Huacaya vs. Suri) on the L*, this could be attributed to differences in cuticle scale distribution and length between the two fleece types, which may refract light differently during colorimetric measurements (Atav and Türkmen 2015; Shim and Jakes 2006). However, a report on colorimetric values in a reduced sample of white alpacas found no significant differences in any CIELAB values between Huacaya and Suri types (Lozano et al. 2024). However, both studies were inconclusive due to the small Suri alpaca populations recorded.

Huacaya and Suri segregation

The black alpaca program is primarily focused on the Huacaya type. However, some Huacaya alpacas produced Suri offspring and vice versa. Although breeding and maiting is conducted separately, it is important to consider this segregation in order to identify parental animals that generate cross-type progeny. Crossbreeding Huacaya×Suri or vice versa was not practiced.

Several studies have attempted to explain Huacaya–Suri segregation, but the results remain inconclusive (La Manna et al. 2016). A directed mating experiment proposed by Ponzoni et al. (1997) suggested dominance of the Suri phenotype over Huacaya, controlled by a single gene, in agreement with Sponenberg (2010) and Renieri et al. (2009), who also proposed the action of a single autosomal gene for Suri segregation, although breeding results do not fully support a single-gene model of inheritance for Suri type. On the other hand, another study on Huacaya and Suri segregation in white alpacas suggested incomplete dominance of Suri over Huacaya (Tan et al. 2024), while Pallotti et al. (2024) suggest that the Suri phenotype may arise from a TRPV3 gene variant which may explain some of the Suri fleece characteristics. However, the differences between the Huacaya and Suri phenotypes extend beyond fleece characteristics.

Conversely, Presciuttini et al. (2010) carried out two reciprocal experimental test-crosses; they concluded that

the hypothesis of the control for Suri phenotype under a single gene should be re-analyzed, suggesting that a two-locus model may explain the inheritance of the Suri phenotype, given that their findings showed that 3/4 Suris alpacas have at least one Huacaya offspring. The results of this study (Fig. 4) show higher percentages (7.95%) of offspring with the Huacaya phenotype (from Suri parents) than the percentage (0.91%) of offspring with the Suri phenotype (from Huacaya parents), similar to what was reported by Presciuttini et al. (2010). However, these results cannot be considered entirely conclusive, given that the population of black Suri alpacas is scarce, and no Huacaya×Suri or Suri×Huacaya crosses have been performed within this black alpaca population. The subsequent analyses in the present study were performed using only Huacaya-type alpacas.

Analysis of color segregation

Segregation of black from other colors

Finding black alpacas is a challenge not only in Peru (MIDAGRI 2019), but also abroad. For example, the United States reports less than 1.4% of its alpaca population as black (Baxter et al. 2025). Therefore, starting a recovery program for this alpaca color requires collecting animals from different locations, primarily to avoid inbreeding and its deleterious effects in fiber-producing animals (Matos and Lôbo 2021; Rashidi et al. 2015; Sheikhlou et al. 2020). To address this challenge, in 2018, researchers collected and transferred 452 B and RB alpacas to the Pacomarca Scientific Station, where the population reached about 1,000 live animals in 2024.

Valbonesi et al. (2011) did not report segregation of black from white or brown parental lines; segregation of black was only observed when at least one black parent was involved, reaching up to 10%, but the size of their research population was small. In contrast, Paul (2014) reported that black can segregate from white or other coat colors, consistent with the results found here, where even white × white crosses yielded a small proportion of black offspring (0.01%). Furthermore, as parental lines became darker, the percentage of black segregation increased. The objective of the present study was not to test hypotheses of dominance or recessivity, and matings were performed within the same coat color within the parental lines. In fact, the focus was on understanding segregation to fix the Black color in successive generations.

Segregation of blacks from full-black matings

The concept of black alpaca does not refer to a single color but rather encompasses both RB and B fiber colors. The data support this concept, which includes both RB and B fiber colors (Fig. 5), showing that RB parents produced offspring with B and RB coats (38% and 41%, respectively). Similarly, full black crosses segregated RB and B offspring (16% and 72%, respectively). An experimental mating trial with Peruvian alpacas reported that black × black matings produced only 64% black offspring (Valbonesi et al. 2011). A more detailed study of Australian alpacas by Paul (2014) reported that black × black crosses yielded 84.7% black progeny, values comparable to those observed here for the black alpaca Program (RB and B).

In this context, and with the aim of increasing the population of intense black alpacas, the reproductive strategy employed was to mate B males with both B and RB females (sire B × dam B and sire B × dam RB). This approach yielded satisfactory results (Fig. 6), increasing the proportion of intense black progeny from 48.08% to 82.91% for black alpaca. A concern when implementing the black alpaca program was uncertainty about whether alpaca fiber changes color over time, as natural-colored garments from different years showed slight variation in color intensity. Figure 2 shows the distribution of fleece colorimetry, where, fortunately, coat color remained stable over time. However, garments did present tonal variation from one year to another due to the entry (through birth) and exit (through aging and culling) of animals in the program. Additionally, it should be noted that some animals produce differently colored hairs (graying) as they age. In the case of black alpaca, this manifests mainly as white hairs, which are considered objectionable fibers (Cruz et al. 2024; Frank et al. 2014; McGregor 2006). Unfortunately, there is currently no equipment capable of measuring and/or quantifying the number of colored fibers in alpacas, which limits the possibility of including this parameter in genetic improvement programs.

Phenotypic progress in the pursuit of intense black

The black alpaca program aims to produce fleeces with an intense black. Regarding coat color in alpacas, industry report showed that no single pure color exists, but rather a continuum of shades (Burgos et al. 2023; Cruz et al. 2021), and the B and RB categories are no exception. Including both colors (B and RB) in the program to increase the population of this color type has shown promising results. Nevertheless, the proportion of RB should be reduced, since fiber categorization and classification in manufacturing are strict and leave out less intense colors.

Although coat color, and specifically black, is genetically controlled by the MC1R and ASIP genes (Anello et al. 2022a; Daverio et al. 2016), these genes contain many polymorphisms (Daverio et al. 2016; Pinares et al. 2021). Despite this genetic challenge, progress toward intense

black is showing encouraging outcomes within the program (Fig. 7), and colorimetry enables the use of CIELAB values, particularly L* and b*, to select black males based on the breeding value of L* and b*.

Fiber diameter and fleece weight in black alpacas

Alpaca fiber is classified by quality, including fineness that enables the production of very thin yarns from which lightweight garments can be manufactured (McGregor 2006). Moreover, fiber softness and comfort are critical for garments worn in direct contact with the skin, and this is achieved by reducing the percentage of medullated fibers (Cruz et al. 2019; Pinares et al. 2018, 2019). When combined with the objective of producing natural-colored fiber, as in the black alpaca program, the challenge becomes more complex due to the reduced national black population size, the difficulty of measuring medullation in dark fibers, and the challenge of quantifying objectionable colored fibers. Therefore, the first step is to increase the population of black alpacas, especially those producing intense black. Once achieved, additional selection criteria can be implemented to improve fineness and comfort, as has been done in white alpacas at Pacomarca (Cruz et al. 2020; Gutierrez et al. 2023; Gutiérrez et al. 2009).

The mean fiber diameter of black alpacas of Pacomarca (24.73 µm) is lower than that reported by Wuliji et al. (2000) for a group of black alpacas in New Zealand (31.60 µm), and values observed in Peruvian populations, such as 27.10 µm reported in Huancavelica (Oria et al. 2009) and similar values (24.40 µm) reported for a group of black Huacaya females from the Rural Alianza herd (Lencinas and Guevara 2021). However, when compared with white Huacayas from the same Pacomarca herd (23.26 µm), the value is slightly higher (Cruz et al. 2025). Reducing fiber diameter in alpacas has already been demonstrated (Cruz et al. 2023; Mancisidor et al. 2021), suggesting that a staged breeding program could later address this challenge. Measuring fiber diameter in black alpacas is possible under a reasonable cost using devices such as the Fiber-EC (Quispe et al. 2018), although the primary goal is currently to expand the black alpaca population to produce a much higher amount of intense black fiber, regardless of fineness.

Fleece weight of black alpacas (2.49 kg/animal) is lower compared to white alpacas (3.09 kg/animal) from Pacomarca (Cruz et al. 2025), mainly due to the greater selection intensity applied to white animals (Cruz et al. 2020). The difference in fleece weight performance between white and black alpacas is due to the fact that this selection objective has not been established for black alpacas. However, the strategy of culling during weaning using a subjective fleece density methodology has shown that it can reduce fleece diameter and increase fleece weight in Huacayas alpacas (Cruz et al. 2025). The black alpaca program is using a similar strategy to cull less dense animals during weaning. The current fleece weight performance of black alpacas is similar to the fleece weight when the white alpaca improvement program began some 20 years ago in Pacomarca, where an average of 2.14 kg/animal was reported (Gutiérrez et al. 2009). Similarly, when the white alpaca improvement program began in New Zealand, average weights of 2.29 kg/animal were reported by the 2000s (Wuliji et al. 2000). This demonstrates that there is an opportunity to improve fleece weight in alpacas in the black alpaca program.

Heritability and genetic correlation estimates

In particular, the extremely low heritability estimates for colorimetric traits (0.01–0.04) and the near-perfect negative correlations reported between fiber diameter and a* (−0.99) and b* (−0.94) are biologically unusual and statistically questionable, and may indicate issues related to model specification, data structure, scaling, or multicollinearity. However, previous studies have shown that the direction of the correlation (negative sign) is as expected (Cruz et al. 2021). Regarding the model, it has been shown that when it is not adjusted for the fixed effect of coat color, heritability can be higher (Bartolomé et al. 2009). However, it is better to adjust the model by including the color group (Cruz et al. 2021), since a significant portion of genetic variability is attributed to this fixed effect. These values were even lower than those reported by Cruz et al. (2021), who evaluated the entire population including nine basic coat colors, and substantially lower than those described in a Spanish population grouped into four color categories (Bartolomé et al. 2009).

Fiber diameter showed very high and unfavorable genetic correlations with all CIELAB values (–0.55 to −0.99) in black alpacas, indicating that selecting animals for a more intense black coat would strongly increase fiber diameter, since darker animals tend to have thicker fibers (Cruz et al. 2021), the difference can even be up to 3.09 microns when compared to white-coated animals (Cruz et al. 2017). Given the magnitude of these correlations, improving both traits simultaneously may be challenging. Similarly, an unfavorable correlation was observed between fleece weight and luminosity, suggesting that animals with deeper black coloration tend to produce lighter fleeces. To address these challenges, a combined selection index, such as the approach proposed by Gutierrez et al. (2014), may be necessary. Another option may be to prioritize the production of intense black color in this program, without considering fiber quality.

Another challenge is implementing genomic selection to enhance the production of intense black fibers in alpacas. The "Colour Coat DNA Test," which includes the black phenotype (https://alpaca.asn.au/colour-coat-dna-tests/), could be a useful tool. However, the CIELAB values on which the test is based show similarities with those reported here for the a* (0 to 1.2) and b* (-0.5 to 1) axes, but they differ markedly for the L* (36 to 38) axis (Gray et al. 2023). The same study reported luminosity values ranging from 36 to 38 whilst the present study found considerably lower values, between 17 and 18 for black alpaca (Table 1). In that sense, ideally the desired black for the textile should be easily identifiable by the human eye, but the genetic mechanisms controlling coat color are also not yet fully understood. For instance, two animals sharing the same color phenotype may have different genotypes, whereas identical genotypes may produce distinct color phenotypes (Anello et al. 2022a, b; Pinares et al. 2021). Despite these challenges, integrating genetic and genomic information into breeding programs has proven effective in improving genetic progress and accuracy, as shown for traits such as fiber diameter and medullation percentage in alpacas (Cruz et al. 2023; Mancisidor et al. 2021). Therefore, incorporating genomic data could be a valuable tool for advancing the black alpaca program.

Black alpacas offer a commercial opportunity that can support their conservation. However, selection could be based on colorimetric values as a selection criterion, especially L* and b* values. Years of selecting by coat color have produced very effective results in establishing an intense black color. Once this initial objective has been achieved, it could be set aside in order to focus on improving the fineness and weight of the fleece.

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Declarations

Ethical approval This is an observational study. The Research has confirmed that no ethical approval is required.

Consent to participate Not applicable.

Consent for publication Not applicable.

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