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Fiber quality at dehairing and characterization of skin follicle parameters in Peruvian Q'ara llamas

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Introduction: Although Q'ara llama fleece was previously believed to lack quality attributes, the down fiber obtained during first shearing is of high quality. However, little is known about skin follicle parameters in Peruvian Q'ara llamas. In this context, the objective of this research was to compare fiber quality after manual dehairing and to characterize skin follicle parameters by body site, age, and sex.

Methods: A total of 240 fiber samples were collected from the shoulders, mid-side, and rump of 80 Q'ara llamas, taking into account their age category and sex. Each unprocessed fiber sample was manually dehaired, yielding two subsamples of 240 each: down fibers and guard hairs. Only the unprocessed and down fibers were used for fiber measurements. According to IWTO-47 standards, an OFDA 2000 was used to measure mean fiber diameter, standard deviation, coefficient of variation, comfort factor, and fiber curvature. Skin biopsies were collected from 65 llamas under local anesthesia using an 8 mm punch to analyze follicle densities and the secondary-to-primary ratio. We performed Type I and the Tukey test (α = 0.05) on transformed data. Spearman's correlation was applied without data transformation.

Results and discussion: Manual dehairing improved textile fiber quality by reducing the diameter by 1.91 μm and the coefficient of variation by 3.05%. It also increased the comfort factor by 4.79% and fiber curvature by 3.49°/mm. Secondary follicle density (16.80 follicles per mm^2) and secondary-to-primary follicle ratio (6.28) were similar across sex and body site. However, skin follicle density decreased in older llamas. There was a strong negative correlation (-0.82) between mean fiber diameter and comfort factor. Mean fiber diameter was negatively correlated with fiber curvature, total follicle density, and secondary to primary follicle ratio. However, comfort factor was positively correlated with fiber curvature, total follicle density, and secondary-to-primary follicle ratio. Total follicle density was positively associated with secondary-to-primary follicle ratio (0.52).

Conclusion: Dehairing improves fiber quality. The main factor affecting fiber quality and skin follicles is age. Young Q'ara llamas have higher follicle density and produce down fiber with a diameter of 22.61 μm. However, body site and sex do not influence quality. The favorable relationship between fiber diameter and follicle density allows for the selection of high-quality fiber.

KEYWORDS

Q'ara llama, dehairing, down fiber, skin, follicle density

Introduction

The llama (*Lama glama*) is the largest of the four South American camelids. It is adapted to a wide range of harsh Andean environmental conditions. Breeding llamas is economically important in Andean ecosystems because of their meat and fiber, as well as their use as pack animals. Llamas are also culturally significant to the Andean people (Stemmer et al., 2005; Antonini, 2010; Paredes et al., 2020; Quispe et al., 2023). Zimmer et al. (2023) suggest that llamas, through their latrine behavior and role as seed dispersers, enhance primary succession of the vegetation and the formation of novel ecosystems in recently deglaciated Peruvian landscapes. In addition, Andean pastoralism in local communities is under stress due to climate change, land tenure regimes, pressures to become sedentary, difficulties in interacting with market-based economies, isolation, and youth emigration (Vilá et al., 2020, 2021).

The Q'ara llama's fiber production has traditionally been underestimated due to its low quality. The industry has disparaged it because of its coarse hair. However, we believe it is important to reevaluate its fiber production and quality for local producers. In Argentina, Bolivia, and Peru, two main ecotypes or varieties of llamas have been identified according to their conformation for meat production and fleece types: Q'ara (double coat) and Ch'aku or Thampulli (single coat). The Q'ara is specialized for meat production and, to some extent, for its transportation function (Cano et al., 2012; Paredes et al., 2020) due to having little fiber on its body, which gives it a sleeker and more elegant appearance. Nevertheless, the down fiber could be used as a by-product for local or regional handicrafts (Stemmer et al., 2005; Lusky et al., 2006; Frank et al., 2011; Quispe et al., 2015; Laime et al., 2016).

Fiber quality is primarily determined by diameter, homogeneity, comfort factor, and fiber curvature (Pinares et al., 2023a). Primary follicles produce guard hairs, while secondary follicles produce down fibers (Antonini et al., 2004). Total follicle density (TFD) is the number of follicles per square millimeter of skin, including both primary and secondary follicles. The secondary-to-primary (S/P) follicle ratio is calculated by dividing the number of secondary follicles by the number of primary follicles. Higher S/P ratios and greater TFD are associated with improved fiber quality (Ferguson et al., 2012; Crossley et al., 2014; Moore et al., 2015). However, very little work has been done on Q'ara fiber quality and follicle characteristics (Lusky et al., 2006; Poma and Ayala, 2022; Quispe et al., 2023). The influence of internal and external environmental factors—referring to body site, age, and sex variables (Antonini et al., 2004; Lusky et al., 2006)—and genetic factors on follicle variables has been little studied in South American camelids (Frank et al., 2006).

One of the most sought-after quality characteristics of llama fibers is skin comfort, or the effect of the garment fibers on the wearer's skin. The fibers of mixed fleeces (fine and coarse fibers), such as Q'ara fleece, require a special textile process for the garments made from them to be comfortable. Dehairing machines are not limited to llama fiber, so manual dehairing is usually necessary. Dehairing changes the structure of the raw material by removing the coarser, longer and straighter (objectionable) fibers, which affects the rest of the textile process (Frank et al., 2011; Quispe et al., 2015; Laime et al., 2016). In addition, it is important to study the main skin follicle parameters in llamas. Based on these considerations, the objective of this research was to compare fiber quality after manual dehairing and to characterize skin follicle parameters by body site, age, and sex in Q'ara llamas from Apurimac, Peru. The hypothesis was that dehairing improves fiber quality and that age, body site, and sex affect skin follicles in Q'ara llamas. Fiber quality is directly related to skin follicle characteristics.

Materials and methods

Location and vegetation

This research was conducted on different herds from the peasant community of Pilluni in the district of Cotaruse, province of Aymaraes, Apurímac region of Peru, located at coordinates 14° 18′04″S and 73°13′52″W, with elevations between 3,900 and 5,400 m above sea level. As described by Pinares et al. (2023b), the geography is characterized by dry puna. The plateau of the area shows a slight topographic slope, with scarce water availability during the dry season, limited to springs, a few wetlands, and small lagoons. According to SENAMHI (2020), the climate is generally cold and dry, with temperatures ranging from −5°C to 10°C at night and from 11°C to 24°C during the day. During the rainy season, from November to March, rainfall increases, and occasional snowfall may occur. The annual rainfall is approximately 720 mm. Llamas are raised through extensive grazing alongside plant species such as *Alchemilla pinnata, Trifolium amabile, Stipa braciphylla, Calamagrostis curvula, Calamagrostis* sp., *Calamagrostis vicunarum, Poa gilgiana, Paspalum pigmaeum, Bromus* sp., *Carex* sp, *Festuca huamachusensis, Poa* sp., *Stipa mucronata, Disticha muscoides, Muhlenbergia fastigiata y Hipochaeris taraxacoides* (Pinares et al., 2023b).

Animals and sampling

We applied non-probabilistic sampling by convenience. Eighty clinically healthy Q'ara llamas with no observable physical defects were sampled from the Pilluni farming community, based on the availability and consent of 11 different owners, each with herds of approximately 25 animals. Age categories were assigned by examining the type and stage of dentition: milk teeth, two teeth, four teeth, and full mouth, as described by Pinares et al. (2023a). Fiber and skin samples were collected from the shoulder, mid-side, and rump, respectively, according to the recommendations of Aylan-Parker and McGregor (2002) and Sasahara et al. (2022). A total of 240 fiber samples were collected from 80 llamas, including 40 males and 40 females of various ages and body sites (Figures 1A, B).

Manual dehairing

The removal process consisted of manual dehairing of the coarse fibers from 240 samples using the tactile–visual method. This was performed on a flat surface by placing a glass plate with a black contrast background to identify white bristles and a white background for colored bristles, according to the technique described by Frank et al. (2011) and Quispe et al. (2015). Once all coarse fibers were removed from the fleece (Figure 1C), and using a magnifying glass (Ove brand, model 99437, China), the resulting tuft consisted only of fibers from the inner coat ("*down*").

Fiber quality measurement

Measurements were conducted on 240 dehaired fiber (down) samples and 240 non-dehaired fiber samples. The textile properties assessed included mean fiber diameter (MFD, µm), standard deviation of MFD (SD MFD, µm), coefficient of variation of MFD (CV MFD, %), comfort factor (CF, %), and fiber curvature (CU, °/mm). These measurements were performed using an optical fiber diameter analyzer (BSC Electronics, model OFDA 2000, Australia) according to IWTO-47 procedures (IWTO-47, 2007) at the South American Camelid Research Center (CICAS La Raya), Fiber Laboratory of the National University of San Antonio Abad del Cusco. The fiber samples were transported and stored under ambient environmental conditions and measured under standard laboratory conditions of 20 ± 2°C and 65 ± 5% relative humidity.

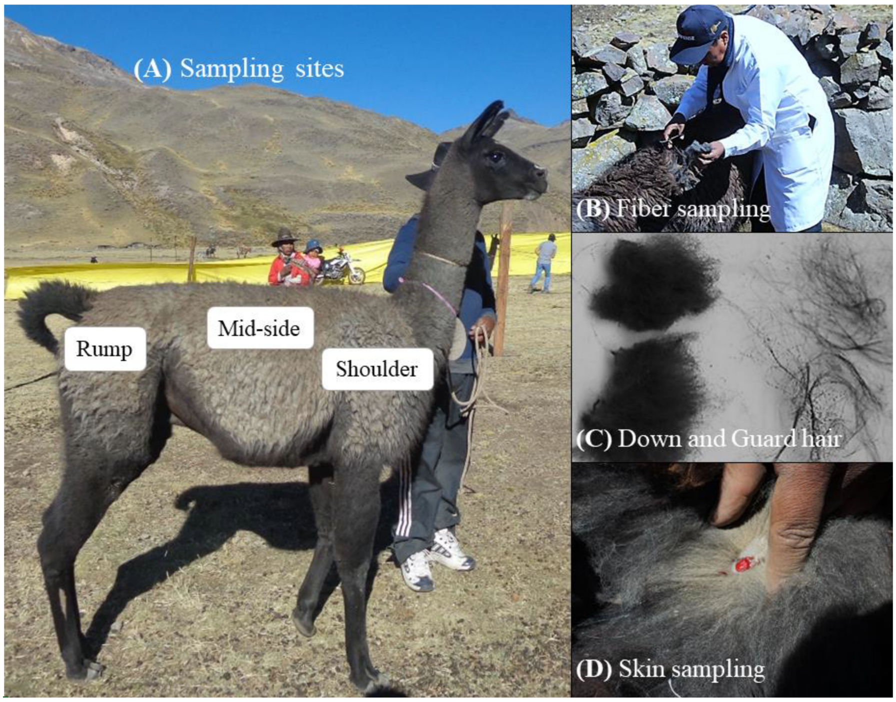

FIGURE 1
The photographs show the sampling sites **(A)**, fiber sampling **(B)**, manual dehairing **(C)**, and skin sampling **(D)**.

Skin biopsies

The limited number of skin histology samples was due to the owners' acceptance of the invasive skin biopsy method. Therefore, only 195 samples were obtained, with three subsamples per animal from the shoulder, mid-side, and rump body sites, as well as from various age groups: milk teeth, two teeth, four teeth, and full mouth. These samples were collected from 65 llamas (32 males and 33 females) out of the 80.

To characterize the primary follicle density, secondary follicle density, total follicle density, and the secondary-to-primary follicle ratio, skin was shaved using disposable stainless steel blades (Figure 1D), followed by local anesthesia (2% lidocaine injected subcutaneously at the margins of the sampling sites). After allowing approximately 5 min for the lidocaine to take effect, the skin was stretched using the thumb and forefinger.

A specially designed 8 mm diameter biopsy punch (KaiMedical, Japan) was used to obtain skin biopsies, according to the procedures recommended by Frank et al. (1989, 2006), Sasahara et al. (2022), and Jones (2023). The biopsies were wrapped in sterile gauze together with Canson tracing paper labeled with each animal's identification. The three subsamples from each animal were carefully placed together in a single jar containing 10% formaldehyde solution (Sasahara et al., 2022). The samples were subsequently transported in rigid technopor boxes at refrigeration temperature to avoid direct exposure to light for at least 72 h after sampling. Finally, the samples were stored and processed under standard conditions in the Histology Laboratory at the National University of Altiplano in the Puno region of Peru.

Histology and image analysis

For the identification of primary and secondary follicles per mm², the skin samples were processed using the standard technique of embedding in solid paraffin, and 5–7 µm sections were collected on slides and stained with Masson trichrome (Lusky et al., 2006; Sasahara et al., 2022). The image sections were captured using a digital camera connected to a light microscope with LAS EZ 3.4 DVD 272 software (Leica Microsystems brand, DM750 model, Germany). Follicle characteristics were observed at 10X magnification with a resolution of 1920 × 1080 pixels. The most appropriate area for follicle density counting was selected, and the primary and secondary follicles were identified and carefully recorded. These images were stored on a computer and then multiplied by 0.84 (Antonini et al., 2004), the correction coefficient calculated after contraction of the skin sample due to fixation and dehydration procedures (Lusky et al., 2006).

Statistical analysis

The normality of the data was verified using the Shapiro–Wilk normality test. Since some response variables of fiber quality and follicle parameters did not conform to normality, arcsine transformations were applied. Analysis of variance (Type I ANOVA, without assuming equal variances) was performed separately for each fixed factor and its levels: age (milk teeth, two teeth, four teeth, and full mouth) and body site (shoulder, mid-side, and rump). A Tukey test ($\alpha = 0.05$) was used for multiple comparisons of means. In addition, fiber quality between dehaired and non-dehaired samples, as well as the effect of sex (female or male), was compared using paired and independent Student's t-tests ($\alpha = 0.05$), respectively. The nonparametric Spearman rank correlation coefficient was calculated for all fiber quality variables and follicle parameters without transformation ($\alpha = 0.05$). Statistical analyses were performed using R software, version 4.2.3 (R Core Team, 2023).

Results

Quality characteristics of non-dehaired and dehaired fibers

This section provides a brief description of the main textile characteristics of raw Q'ara llama fiber and the quality of the dehaired fiber after the manual dehairing process. Age category was found to influence the quality of both non-dehaired and dehaired fiber, while sampling site had a greater influence on the homogeneity of fiber diameter (Table 1).

Effect of dehairing in Q'ara fiber quality variation

Dehairing contributed to absolute differences in each fiber characteristic of Q'ara llama fiber. MFD, along with its SD and CV, decreased by –1.91 µm, 1.04 µm, and 3.05%, respectively, while CF and CU increased by 4.79% and 3.49°/mm, respectively ($p \leq 0.01$). Manual dehairing improved the fiber quality of Q'ara llamas raised in the Apurímac region by reducing fiber fineness and homogeneity and increasing both comfort factor and fiber curvature (Table 2). Therefore, it is recommended that this type of fiber be marketed only after dehairing to ensure quality-based payment.

Characterization of skin follicle parameters in Q'ara llamas

Table 3 shows the mean values of primary follicle density (2.33 ± 0.04), secondary follicle density (14.49 ± 0.32), total follicle density (16.80 ± 0.36), and the secondary-to-primary follicle ratio (6.28 ± 0.08). Primary follicle density varies by age category, body site, and sex. However, secondary follicle density is affected only by age ($p < 0.05$). All follicle parameters were significantly affected by age category ($p < 0.001$).

This illustration shows hair follicles forming either as a compound follicle group (CFG) or a simple follicle group (SFG). The SFG consists of secondary follicles, as seen in young llamas (Figure 2A). The CFG consists of primary follicles surrounded by

TABLE 1 Mean and standard error of dehaired and non-dehaired fiber quality in Peruvian Q'ara llamas by sex, age, and body site.

Non-dehaired fiber quality						
	n	MFD (μm)	SD MFD (μm)	CV MFD (%)	CF (%)	CU (°/mm)
Sex		ns	ns	ns	n.s	ns
Female	120	25.90 ± 0.26^{a}	6.28 ± 0.83^{a}	21.90 ± 0.22^{a}	82.30 ± 1.01^{a}	40.0 ± 0.43^{a}
Male	120	26.60 ± 0.37^{a}	6.27 ± 1.03^{a}	21.90 ± 0.24^{a}	80.70 ± 1.41^{a}	38.7 ± 0.54^{a}
Age category		***	***	***	***	ns
Milk teeth	60	23.70 ± 0.18^{c}	5.51 ± 0.05^{c}	23.33 ± 0.15^{c}	89.68 ± 0.53^{a}	36.21 ± 0.59^{a}
Two teeth	60	25.00 ± 0.41^{b}	6.28 ± 0.14^{b}	25.25 ± 0.25^{a}	84.67 ± 1.38^{b}	37.52 ± 0.95^{a}
Four teeth	60	26.93 ± 0.33^{a}	6.59 ± 0.12^{ab}	24.38 ± 0.18^{b}	77.28 ± 1.62^{c}	37.09 ± 0.68^{a}
Full mouth	60	27.81 ± 0.29^{a}	6.74 ± 0.10^{a}	24.19 ± 0.17^{b}	74.66 ± 1.34^{c}	36.71 ± 0.55^{a}
Body site		ns	ns	*	ns	ns
Shoulder	80	25.75 ± 0.29^{a}	6.25 ± 0.10^{a}	24.34 ± 0.17^{ab}	82.94 ± 0.99^{a}	37.26 ± 0.59^{a}
Mid-side	80	25.65 ± 0.23^{a}	6.15 ± 0.10^{a}	23.96 ± 0.19^{b}	82.18 ± 1.22^{a}	37.64 ± 0.60^{a}
Rump	80	26.23 ± 0.37^{a}	6.45 ± 0.12^{a}	24.57 ± 0.19^{a}	79.35 ± 1.60^{a}	37.74 ± 0.64^{a}
Dehaired fiber quality						
Sex		ns	ns	ns	ns	ns
Female	120	24.5 ± 0.21^{a}	5.22 ± 0.89^{a}	21.30 ± 0.2 0^{a}	85.90 ± 0.91^{a}	41.50 ± 0.51^{a}
Male	120	24.7 ± 0.32^{a}	5.25 ± 1.04^{a}	21.40 ± 0.20^{a}	84.50 ± 1.32^{a}	40.30 ± 0.62^{a}
Age category		***	***	*	***	*
Milk teeth	60	22.61 ± 0.16^{b}	4.49 ± 0.05^{c}	19.84 ± 0.20^{b}	93.67 ± 0.37^{a}	39.80 ± 0.56^{ab}
Two teeth	60	23.76 ± 0.41^{b}	5.21± 0.13^{b}	21.97 ± 0.31^{a}	87.38 ± 1.37^{b}	40.04 ± 1.06^{ab}
Four teeth	60	25.50 ± 0.34^{a}	5.49 ± 0.12^{ab}	21.34 ± 0.22^{a}	82.97 ± 1.53^{c}	42.41 ± 0.68^{a}
Full mouth	60	26.02 ± 0.30^{a}	5.76± 0.11^{a}	21.84 ± 0.23^{a}	81.20 ± 1.13^{c}	39.25 ± 0.55^{b}
Body site		n.s	**	***	*	ns
Shoulder	80	24.51 ± 0.28^{a}	5.24 ± 0.10^{ab}	21.13 ± 0.22^{b}	86.88 ± 0.94^{ab}	40.27 ± 0.61^{a}
Mid-side	80	24.06 ± 0.28^{a}	5.01 ± 0.10^{b}	20.69 ± 0.25^{b}	88.03 ± 1.01^{a}	41.16 ± 0.65^{a}
Rump	80	24.85 ± 0.37^{a}	5.46 ± 0.12^{a}	21.92 ± 0.20^{a}	83.91 ± 1.44^{b}	39.68 ± 0.69^{a}

n, number of fiber samples. MFD, Mean fiber diameter; SD MFD, standard deviation of mean fiber diameter; CV MFD, coefficient of variation of mean fiber diameter; CF, comfort factor; CU, mean fiber curvature. Significant differences are indicated by different superscript letters in the columns within each factor, and ns means non-significant.
***p < 0.001; **p < 0.01; *p < 0.05.

secondary follicles, as seen in adult llamas, especially older ones (Figures 2B–D). A decreasing trend in follicle density is observed, which becomes more pronounced with age.

Relationship between fiber quality and skin follicle parameters in Q'ara

All fiber quality characteristics were correlated with follicle parameters in Q'ara llama ($p < 0.05$), except for fiber curvature and the secondary-to-primary follicle ratio (Table 4). There was a moderate correlation (0.52) between total follicle density and the secondary-to-primary follicle ratio. Mean fiber diameter was negatively correlated with fiber curvature, total follicle density, and the secondary-to-primary follicle ratio. However, comfort factor was moderately correlated with fiber curvature (0.49), and slightly correlated with both total follicle density and the secondary-to-primary follicle ratio.

Discussion

Fiber quality in the raw and dehaired states

The MFD in non-dehaired fiber was 25.95 μm, influenced only by age, while sex and sampling site were not significant, similar to the reports of Pinares et al. (2014); Quispe-Ccasa et al. (2020), and Apaza et al. (2022). Our result of 24.04 μm for non-dehaired fiber is

TABLE 2 Effect of dehairing on Q'ara fiber quality.

Fiber quality	Non-dehaired (Mean ± EE)	Dehaired (Mean ± EE)	Absolute difference	P-value	Significance
MFD (μm)	25.95 ± 0.19[a]	24.04 ± 0.18[b]	1.91	0.004	**
SD (μm)	6.28 ± 0.06[a]	5.24 ± 0.06[b]	1.04	0.008	**
CV (%)	24.29 ± 0.10[a]	21.24 ± 0.13[b]	3.05	0.001	***
CF (%)	81.51 ± 0.75[a]	86.30 ± 0.67[b]	4.79	0.006	**
CU (°/mm)	36.88 ± 0.35[a]	40.37 ± 0.38[b]	3.49	0.009	**

MFD, Mean fiber diameter; SD, standard deviation of mean fiber diameter; CV, coefficient of variation of mean fiber diameter; CF, comfort factor; CU, mean fiber curvature. Different superscript letters in the same row indicate significant differences.
***p < 0.001; **p < 0.01; *p < 0.05.

physiologically and nutritionally consistent with the 25.83 μm reported by Celis and Panez (2025) for Q'ara llamas from Cerro de Pasco and the 25.47 μm reported by Quispe-Ccasa et al. (2020) for Ch'aku llamas from CICAS La Raya of Cusco. It is also consistent with the 24.72 μm reported by Poma and Ayala (2022) in Bolivian Q'ara llamas. However, Paucar (2021) reported a value of 27.93 μm in Q'ara llamas from Quimsachata in Puno, Peru. This variation could be explained by population and nutritional management, especially selection criteria for fiber or meat.

The comfort factor in non-dehaired fiber was 81.51% (Table 2), similar to the 84.88% reported by Poma and Ayala (2022) and higher than the 70.62% reported by Paucar (2021), with no significant difference by sex. However, comfort decreased by 15.02% from the milk teeth stage (89.68%) to the full mouth stage (74.66%). Our result is similar to the decreasing trend of 79.76% in llamas >5 years old found by Quispe (2016) and Quispe-Ccasa et al. (2020). The standard deviation and coefficient of variation of MFD in raw fiber did not show significant differences by sex, but age had an important effect, as these characteristics decreased with increasing age.

Dehairing leads to structural changes in the textile raw material, as the longer and straighter (objectionable) fibers are eliminated. This directly affects spinning and dyeing processes. Greater fiber diameter variation has been observed in double-coated fleeces (Coates and Ayerza, 2004; Frank et al., 2012; Apaza et al., 2022; Quispe et al., 2023; Hick et al., 2024). Similarly, MFD decreases between 2.50 and 4.21 μm (Pinares et al., 2014; Paucar, 2021; Poma and Ayala, 2022), and CV MFD decreases between 2.51% and 9.97% (Pinares et al., 2014; Paucar, 2021; Quispe et al., 2023). However, in dehaired fiber, CF increases between 6.64% and 16.13%, and CU increases between 4.75 and 5.48°/mm (Pinares et al., 2014; Paucar, 2021; Poma and Ayala, 2022). This may be due to a guard hair yield of only 16 ± 7.4% in Q'ara llamas (Quispe et al., 2023), although all reported values are slightly higher than those observed in our study. Selecting for improved fiber quality would likely be a more effective approach than relying solely on dehairing.

TABLE 3 Mean and standard error of skin follicle parameters in Peruvian Q'ara llamas by sex, age, and body site.

	n	PFD (mm^2)	n	SFD (mm^2)	n	TFD (mm^2)	n	S/P
Sex		*		ns		ns		ns
Female	99	2.24 ± 0.06[b]	99	14.22 ± 0.45[a]	98	16.32 ± 0.48[a]	98	6.32 ± 0.12[a]
Male	96	2.42 ± 0.06[a]	93	14.63 ± 0.45[a]	94	17.01 ± 0.49[a]	94	6.14 ± 0.11[a]
Age category		***		***		***		***
Milk teeth	51	2.73 ± 0.08[a]	48	18.53 ± 0.58[a]	47	21.01 ± 0.62[a]	51	7.05 ± 0.15[a]
Two teeth	42	2.24 ± 0.08[b]	42	14.11 ± 0.62[b]	43	16.35 ± 0.68[b]	39	6.09 ± 0.13[ab]
Four teeth	45	2.26 ± 0.08[b]	45	13.66 ± 0.53[b]	45	15.93 ± 0.59[b]	45	6.16 ± 0.19[b]
Full mouth	57	2.09 ± 0.06[b]	57	11.78 ± 0.38[c]	57	13.87 ± 0.44[c]	57	5.66 ± 0.10[c]
Body site		**		ns		ns		ns
Shoulder	65	2.35 ± 0.08[ab]	64	14.47 ± 0.59[a]	64	16.79 ± 0.65[a]	65	6.22 ± 0.13[a]
Mid-side	65	2.46 ± 0.07[a]	63	14.97 ± 0.53[a]	63	17.19 ± 0.55[a]	64	6.18 ± 0.14[a]
Rump	65	2.18 ± 0.07[b]	65	13.84 ± 0.52[a]	65	16.02 ± 0.58[a]	63	6.30 ± 0.15[a]
General	195	2.33 ± 0.04[a]	192	14.49 ± 0.32[a]	192	16.80 ± 0.36[a]	192	6.28 ± 0.08[a]

n, number of fiber samples. PFD, primary follicle density; SFD: secondary follicle density; TFD, total follicle density; S/P, secondary to primary follicle ratio. Significant differences are indicated by different superscript letters in the columns within each factor, and ns means non-significant.
***p < 0.001; **p < 0.01; *p < 0.05.

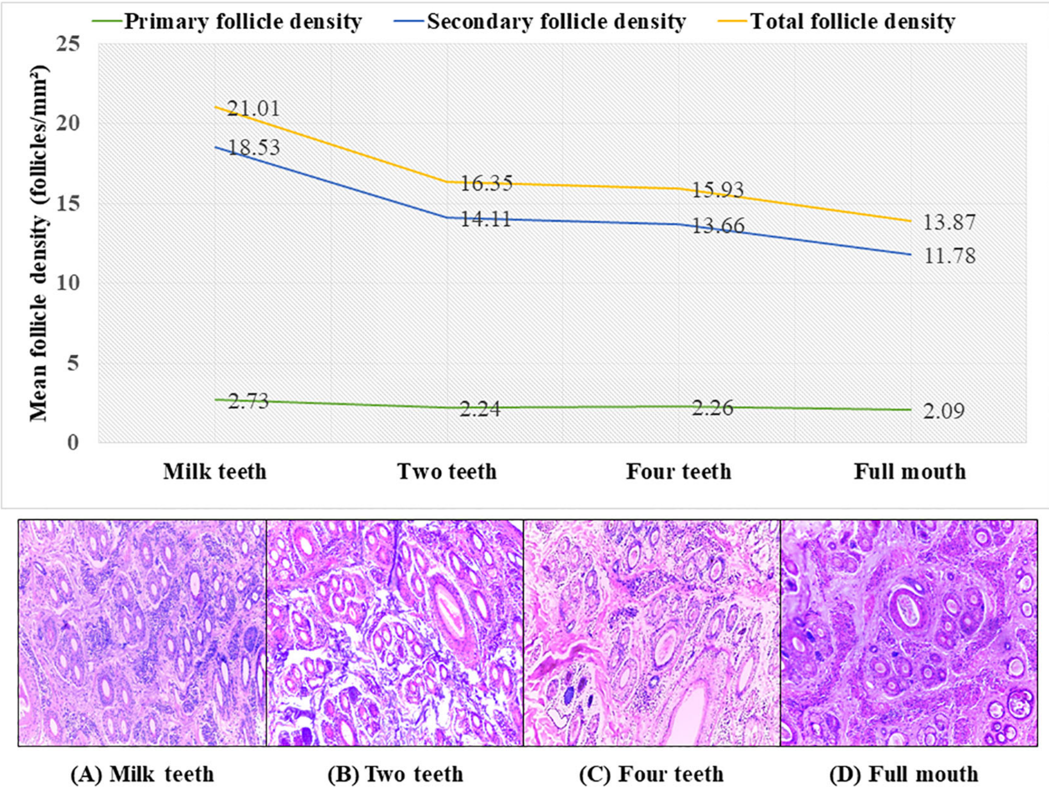

FIGURE 2
Primary and secondary skin follicle characteristics in Q'ara llama, showing decreasing follicle densities by age category: **(A)** milk teeth, **(B)** two teeth, **(C)** four teeth, and **(D)** full mouth

Fine fiber is economically important due to its value in the textile industry; however, the total economic value also depends on follicle population density. Higher density results in greater individual fleece weight, allowing breeders to earn more income from fiber sales (Pallotti et al., 2020). In this regard, developing sustainable fiber production systems using llamas is a viable option in the puna. The greater ability of llamas to adapt to very poor soils and their larger body size provide them a significant advantage over alpacas. Their fine mean fiber diameter (less than 23 µm, if guard hairs are excluded) allows their fleeces to be sold at a premium price (Coates and Ayerza, 2004; Stemmer et al., 2005). Switching to llama production would increase farmers' incomes and enhance the sustainability of agriculture in the Apurímac region of Peru. Baby and young llamas produce valuable dehaired fiber at first shearing, which sells at high prices, making llama production more profitable. Producers could raise llamas for both meat and fiber to boost their income (Coates and Ayerza, 2004; Antonini, 2010).

TABLE 4 Correlation between fiber quality and follicle parameters in Q'ara llama.

	CF	CU	TFD	S/P
MFD	-0.82 ***	-0.38 ***	-0.17 **	-0.18 **
CF		0.49 ***	0.19 **	0.17 **
CU			-0.25 **	-0.05 ns
TFD				0.52 ***

MFD, mean fiber diameter; CF, comfort factor; CU, mean fiber curvature; TFD, total follicle density and S/P, secondary to primary follicle ratio. The correlation coefficient value is shown in each box. The correlation coefficient value is shown in each box. Below are the significant statistics, indicated by asterisks, and ns means non-significant.
***p < 0.001; **p < 0.01.

Skin follicle parameters

The mean TFD was 16.80 follicles per mm^2. However, Frank et al. (2001) reported a value of 24.36 in double-coated Argentinean llamas. The primary follicle density (PFD) found in this study was 2.33 follicles per mm^2, comparable to the values of 4.25, 3.77, and 2.11 reported by Frank et al. (2001, 2006) and Curasma and Rodriguez (2016) in Q'ara llamas. Secondary follicle density was 14.49 follicles per mm^2, consistent with the values of 14.24 and 16.92 reported by Curasma and Rodriguez (2016) and Frank et al. (2006), respectively.

Skin follicle parameters were not influenced by sex or sampling site, except for primary follicle density (Table 3). The effect of sex was not taken into account in the statistical analysis by Antonini et al. (2004) and Pallotti et al. (2020). However, all skin follicle parameters decreased in older llamas. TFD was influenced by age, with the highest value of 21.01 in the milk teeth category and the lowest value of 13.87 in the full mouth category (Figure 2, $p < 0.001$). In addition, fiber density decreased with increasing age, with a strong negative linear correlation of –0.57 between age and fiber density (Flores et al., 2023). This mode of development is also present in secondary follicle density. While primary follicle density showed slight variation, it decreased at the rump site (Table 3). On the other hand, total follicle density has been found to decrease with age, although it is not affected by type of shearing, locality, or fleece type (Frank et al., 2006). This may be due to skin stretching caused by animal growth (Curasma and Rodriguez, 2016). The genetic correlation between hair duct density and fiber density per mm^2 in alpacas was 0.87 ± 0.06 (Flores et al., 2023).

The secondary-to-primary follicle ratio of 6.28 was slightly higher than the 4.89 reported in Ch'aku llamas by Antonini et al. (2004) and the 5.35 ± 1.44 in Q'ara llamas reported by Lusky et al. (2006), who also reported 5.45 in Th'ampulli llamas, with no significant differences. However, these values are lower than those reported in Huacaya alpacas, with S/P ratios of 8.62 and 8.51 in shorn and unshorn animals, respectively, at 16 months of age (Pallotti et al., 2020). In a detailed study, Atlee et al. (1997) reported an S/P ratio of 9 in llamas. The S/P ratio decreased as the age category increased, consistent with the patterns described by Curasma and Rodriguez (2016), although Lusky et al. (2006) found no changes with age in young animals.

Our findings indicate that the density of primary follicles was higher on the mid-side than on the rump. Fiber quality and production depend on skin properties (Antonini et al., 2004). Consistent with our results, total skin volume was higher in the femoral area and lower in the shoulder area. The total follicle group volume was also higher in the femoral area, resulting in increased fiber production (Sasahara et al., 2022). Follicle density is related to skin thickness. The epidermis is thick on the heads and necks of guanacos, llamas, and crosses. Llamas have a very thick dermis, with marked differences between the superficial and deep layers (Atlee et al., 1997; Carpio, 1991; Lacolla et al., 2010). This may be unfavorably related to follicle density and fiber diameter.

Relationship among fiber quality and follicle parameters

The relationship between MFD and TFD showed a negative correlation (–0.17), lower than the values of –0.35 to –0.47 found in Chilean colored alpacas by Crossley et al. (2014), and –0.8 reported by Carpio (1991). This indicates that as follicle density increases, mean fiber diameter decreases. This result was expected, as the negative correlation between MFD and TFD has already been established in Argentinean llamas with different fleece types (Frank et al., 1989). This could be partly explained by the decrease in TFD that occurs as the animal grows, while the inflection points of MFD increase (Frank et al., 2006). In this study, TFD and the S/P ratio showed a positive correlation (0.52), similar to the 0.38 reported in alpacas by Ferguson et al. (2012).

Between MFD and the S/P ratio, we found a negative correlation (–0.18), which is lower than –0.3 reported by Oruna (2016) and –0.44 reported by Ferguson et al. (2012). Badajoz (2007) reported stronger negative correlations of –0.73 and –0.75 for Suri and Huacaya alpacas, respectively. This is favorable, as it indicates that a higher secondary-to-primary follicle ratio is associated with a smaller fiber diameter. The main histological characteristic of fine fibers is the greater number of secondary follicles, as it has been widely demonstrated that animals with smaller fiber diameters have more secondary follicles (Atlee et al., 1997; Moore et al., 2015).

Although the S/P ratio is the main parameter used to define skin follicle structure in both types of llamas, it may be a subjective classification due to variation in traits within the same genetic population (Lusky et al., 2006; Antonini, 2010). Due to the limited sample size and the study's focus on a single breed, future research should examine environmental effects on fiber properties and the influence of age from birth to adulthood. These studies could help inform breeding programs, genetic correlations, and marker-based selection strategies.

Conclusions

The Q'ara llama produces high-quality fiber for the textile industry. Dehairing improves the uniformity, fineness, comfort, and curvature of the down fibers. The main factor affecting fiber quality and skin follicle characteristics is age, which leads to a decline in these parameters in older llamas. Body site and sex do not influence fiber or follicle characteristics.

There are important relationships between skin follicles and fiber quality in Q'ara llamas. In practice, favorable opportunities exist for improving fiber quality through genetic selection. Key correlations identified include a negative correlation between mean fiber diameter and the secondary-to-primary follicle ratio, as well as a positive correlation between the secondary-to-primary ratio and total follicle density.

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Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The animal studies were approved by Research Ethics Committee (R-093-2018-CU-UNAMBA) of the National

University of Micaela Bastidas de Apurimac, in accordance with Peruvian National Law No. 30407 (Animal Protection and Welfare Law). The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent was obtained from the owners for the participation of their animals in this study.

Author contributions

VM: Methodology, Conceptualization, Funding acquisition, Project administration, Investigation, Writing – original draft. RP: Conceptualization, Writing – review & editing, Writing – original draft, Visualization, Formal analysis. FL: Visualization, Writing – original draft. AQ: Visualization, Writing – original draft. AM: Visualization, Writing – original draft. AB: Writing – original draft, Visualization, Conceptualization.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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