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Geographic and breed-specific traceability of cashmere *via* mineral element profiling in Inner Mongolia (Ordos, Chifeng, and Alxa League)

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The study investigates a consistent technique for tracing the cashmere breeds and their geographical origins using mineral element fingerprinting from Inner Mongolia, China. 237 cashmere samples were collected from three different regions (Ordos, Chifeng and Alxa League) and four breeds (Albas, Mingan, Hanshan, Alxa white cashmere goats). Concentrations of 21 mineral elements were quantified by inductively coupled plasma mass spectrometry (ICP-MS) and assessed using multivariate statistical methods such as principal component analysis (PCA), partial least squares discriminant analysis (PLS-DA), and orthogonal partial least squares-discriminant analysis (OPLS-DA). Among them, six elements (Mg, Mn, As, Sr, Ce and U; with Ce in regions and Sr in breeds, while the other five are common) discriminated significant regional and breed-specific differences ($P < 0.05$). Their concentrations ranged from 189.25–639.49 μg g^{-1}, 7.48–16.24 μg g^{-1}, 19.03–66.73 μg/100 g, 311.26–888.30 μg/100 g, 56.03–113.92 μg/100 g and 1.64–9.87 μg/100 g respectively across the regions with highly enriched Alxa samples. These six mineral elements served as key identifiers for traceability with high variable importance in projection (VIP > 1.0). The OPLS-DA model achieved excellent classification accuracy for both origin ($R^2 = 0.97$) and breeds ($R^2 = 0.787$). This novel study presents an integrated ICP-MS and OPLS-DA approach for authenticating geographical origins and breeds, providing a robust analytical basis for preventing fraud, certifying products and ensuring supply chain transparency in the luxury textile sector.

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1. Introduction

Cashmere, one of the most valuable natural fibers, has dominated luxury textile markets contributing to global trade and regional economies due to its outstanding fineness, thermal insulation and elasticity.[1] China, particularly the Inner Mongolia Autonomous Region, is the world's largest producer, accounting for a significant share of global supply. The region's favorable climatic conditions, grazing systems and indigenous goat breeds furnish Inner Mongolian cashmere to produce superior fiber quality and yield.[2] However, this high market value also elevates the risk of adulteration and mislabeling frauds, where inferior fibers, such as sheep wool, are mixed with superior ones and their origins are misrepresented. The deceptive production damages the buyer's trust, product reputation and the sustainability of the industry.[3,4] Therefore, the cashmere's origin and breed can be authenticated consistently through traceability systems. Current morphological and physicochemical methods like observation, identification and molecular assays lack precision in detecting regional differences within same species or production regions.[5] These approaches have been failed to certify and verify cashmere quality and production origins. These significant gaps have explored new methods to provide sufficient discrimination. Nowadays, mineral element fingerprinting has emerged as a promising traceability tool due to its regional specificity.[6]

The elemental configuration of biomaterials indicates their dietary and environmental sources, serving as a chemical sign of geographical origin. Previous studies have demonstrated its accuracy across various agricultural and animal-derived products. In agriculture sector, the tea products have been authenticated by multi-element fingerprinting through ICP-MS[7,8] has also demonstrated the integration of chemometric techniques (OPLS-DA and ICP-MS) with multi-element fingerprinting for the identification geographical origins of Chinese Baijiu. Across animal-derived products,[9] differentiated goat and sheep samples from different Chinese regions using 11 mineral

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elements and achieved >90% accuracy by multivariate statistical analysis. While,[10] validated Inner Mongolian beef origins by marking 95% accuracy through integration of isotopes and elemental data.[11] authenticated the Italian cheese through elemental characterization. This technique also enabled precise regional discrimination of *Ephedra* spp. herbs across six Chinese provinces using multi-element data and pattern recognition.[12] These findings demonstrate the high regional sensitivity and analytical precision of mineral profiling. Despite these breakthroughs, cashmere traceability has not yet been approached systemically using mineral element analysis. These existing studies only concerned milk, meat or plantbased products leaving their fibers un-explored.[13] The research gap exists as the soil-forage-animal transfer pathway affects the microbial content deposited within hair fibers. Thus, mineral element fingerprinting in cashmeres will reflect both geographic and genetic differentiations.

To overcome these gaps, this study investigates the usage of multi-element fingerprinting in combination with chemometric modeling to justify cashmere origins and breeds. From three main production region (Ordos, Chifeng and Alxa League) of Inner Mongolia and four goat breeds, total of 237 cashmere samples was processed through inductively coupled plasma mass spectrometry (ICP-MS). Multivariate statistical approaches like principal component analysis (PCA), partial least square discriminant analysis (PLS-DA) and orthogonal partial least square discriminant analysis (OPLS-DA) were applied for the identification of mineral elements and evaluation of classification performance. Concentrations of 21 mineral elements, including trace and rare earth elements, have been quantified to establish regional and breed-specific profiles.

The study relates with multi-element fingerprinting of cashmere fibers, exhibiting that both regional origin and breed could be distinguished precisely (R^2 = 0.97 and R^2 = 0.787 respectively). Six discriminative elements, including Mg, Mn, As, Sr, Ce and U were identified for origin verification. This technique thus offers immense advantages compared to molecular or isotopic markers: stable elemental signatures are unaffected by short-term biological variation and allow rapid authentication in a high-throughput manner. This research also provides a scientific basis for traceability certification in the cashmere industry to help curb mislabeling of products, build trust among consumers and help drive sustainability with transparency in value chains for textiles globally. The novelty of the study exists in trending multi-element fingerprinting, previously experimented with on seaweeds and meats but now on animal fibers for the very first time. A dual-level authentication framework has been developed for discriminating both

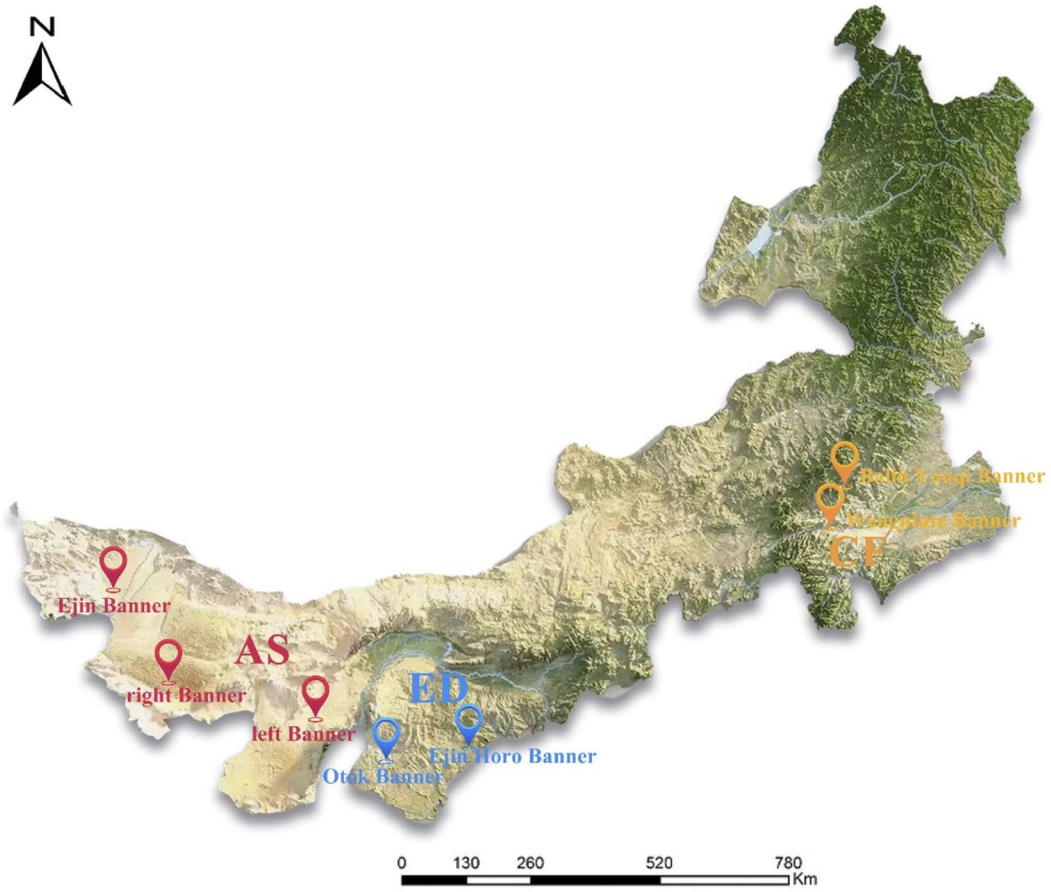

Fig. 1 Sampling locations in Inner Mongolia, China. AS (Alxa League): left Banner (approx. 38.83° N, 105.67° E), right Banner (approx. 40.27° N, 103.68° E), Ejin Banner (approx. 41.50° N, 100.00° E); ED (Ordos): Otok Banner (approx. 39.15° N, 107.80° E), Ejin Horo Banner (approx. 39.57° N, 109.76° E); CF (Chifeng): Wengniute Banner (approx. 42.85° N, 119.20° E), Balin Youqi Banner (approx. 43.56° N, 119.19° E).

the production regions and cashmere breeds with the integration of environmental geochemistry and breed-specific mineral assimilation. Such discrimination at this level has not been achieved so far using ICP-MS based chemometrics.

2. Materials and methods

2.1. Surveillance and sample collection

Total 237 cashmere samples were collected from 2 year-old female adults with body weight of 30 kg between april and may. These samples represented three Inner Mongolian autonomous regions, Ordos City, Chifeng City and Alxa League and four distinguished breeds: Albas, Mingan, Hanshan, Alxa white cashmere goats (Fig. 1). Otok Banner and Ejin Horo Banner from Ordos City, Balin Youqi Banner and Wengniute Banner from Chifeng City, and Alxa Right, Alxa Left and Ejin Banner from Alxa League City were selected sampling sites. Each site consisted of both grazing and feeding system to reveal production diversity as detailed in Table 1.

The actual number of cashmere samples collected in each region and breed varied from 15–60/site, considering the different goat population densities, accessibility and production scales in the banners. However, the total sample size, $n = 237$, was adequate to represent the three regions and four breeds. To reduce any possible impact of unbalanced sampling on the performance of a multivariate model, all the concentration data of elements were auto scaled and log-transformed before analysis. OPLS–DA models were developed by using 7-fold cross-validation and random resampling, which strongly decreased the impact of different sample sizes and proved model robustness: $R^2 = 0.97$, $Q^2 = 0.91$ for regional classification. Thus, variation in the volume of data from different sampling locations did not bias the discriminant accuracy of the models.

2.2. Sample preparation

About 5 g each raw cashmere sample was washed in 500 mL of 1% detergent solution and to eradicate dirt and grease, was ultra-sonicated at 40 Hz for 30 minutes. Samples were rinsed with tap and deionized water continuously to remove presence of any cleaning agent. Then samples were dried in an oven at 60 °C and cleaned manually. After, the fibers were cut into pieces and homogenized for uniformity. Using quartering method, homogenized sample was divided into subsamples. These subsamples were analyzed elementally.

2.3. Elemental analysis by ICP-MS

Mineral elements were quantified according to the Chinese National Standard GB 5009.268-2016: National Food Safety Standard: Determination of Multi-elements in Foods[14](National Health and Family Planning Commission 2016). Each 0.1 g sample was digested in 5 mL of 65% HNO_3 (Trace Metal Grade, Fisher Scientific) using PTFE microwave digestion system as outlined in Table 2. Then, the solutions were diluted in 50 mL volumetric flask with ultra-pure water after being cooled to room temperature and 5 mL of the solutions were filtered (0.22 μm) using a centrifuge tube for analysis.

The mineral elements were analyzed using ICP-MS (Agilent 7900, USA) at optimum conditions (1550 W RF power; 15 L min^{-1} plasma gas and 1 mL min^{-1} uptake).

These 21 elements (Mg, Al, V, Mn, Fe, Zn, As, Rb, Sr, Cs, La, Ce, Pr, Nd, Sm, Eu, Gd, Dy, Yb, Tl, U) were calibrated against certified reference materials (IV-ICPMS-71A standard solution, Inorganic Ventures) and results were quantified using external standard calibration. Internal standards, including Sc, Ge, Y, In, Rh, and Re were used to ensure instrument stability (<5% RSD). All measurements were reported in triplicate and mean values were analyzed.

2.4. Statistical and chemo-metric analysis

The elemental data were statistically analyzed using SPSS 20.0 for *t*-test and ANOVA ($P < 0.05$) and were auto scaled and log-transformed before multivariate analysis. These preprocessed data were subjected to principal component analysis (PCA), partial least squares discriminant analysis (PLS-DA), and orthogonal partial least squares-discriminant analysis (OPLS-DA) using SIMCA 14.1 for samples classification by regions and breed. R^2 (goodness of fit) and Q^2 (predictive accuracy) evaluated the model performances. Statistical parameter R^2 represents the goodness of fit of OPLS-DA. The variables with a Variable Influence on Projection (VIP) value > 1 were considered significant.[15]

3. Results

3.1. Analysis of mineral content differences in different regions

Twenty-one elements among cashmere samples from Ordos, Chifeng and Alxa League perceived the significant regional differences as shown in Table 3. The highest concentrations were detected for Mg, Al, V, Fe, Zn, As, Rb, Sr, La, Ce, and Nd

Table 1 The region information of goats and cashmere samples

Region	Banner county	Goat breed	No. of samples	Feeding pattern
Ordos	Otok	Albas white cashmere	60	Grazing
	Ejin horo	Mingai white cashmere	45	Barn feeding
Chifeng	Wengniute	Hanshan white	19	Grazing
	Balin youqi	cashmere	35	Grazing
Alxa league	Alxa left	Alxa white cashmere	18	Grazing
	Alxa right		15	Grazing
	Ejin		45	Grazing

Table 2 The procedure of microwave digestion for samples pretreatment

Procedure	Target temperature/°C	Heating up time/min	Hold time/min
1	160	18	3
2	180	3	7
3	100	10	7
4	100	1	1

Table 3 Mean elemental concentrations and standard deviations for twenty-one elements from three regions (Ordos, Chifeng, and Alxa league) in cashmere goat samples. Numbers with different superscripts are significantly ($P < 0.05$) different across rows for the different regions[a]

Element	Ordos ($N = 105$)	Chifeng ($N = 54$)	Alxa league ($N = 78$)	Mean value ($N = 237$)	P-value
Mg (μg g^{-1})	189.25 ± 61.17^{c}	288.95 ± 74.97^{b}	639.49 ± 441.83^{a}	360.14 ± 326.41	<0.05
Al (μg g^{-1})	216.47 ± 90.02^{c}	330.33 ± 171.86^{b}	590.78 ± 373.54^{a}	365.60 ± 287.52	<0.05
V (μg per 100 g)	41.09 ± 16.69^{c}	64.39 ± 32.99^{b}	117.45 ± 76.70^{a}	71.53 ± 58.37	<0.05
Mn (μg g^{-1})	7.48 ± 2.80^{b}	6.38 ± 4.92^{b}	16.24 ± 10.03^{a}	10.11 ± 7.77	<0.05
Fe (μg g^{-1})	240.51 ± 95.61^{bc}	310.59 ± 176.98^{b}	632.87 ± 421.15^{a}	385.61 ± 315.90	<0.05
Zn (μg g^{-1})	88.35 ± 18.67^{c}	99.49 ± 16.93^{b}	140.48 ± 90.13^{a}	108.04 ± 58.36	<0.05
As (μg per 100 g)	19.03 ± 8.17^{c}	39.64 ± 16.59^{b}	66.73 ± 39.65^{a}	39.42 ± 32.18	<0.05
Rb (μg 100 g)	126.98 ± 48.78^{b}	153.78 ± 61.23^{a}	175.12 ± 109.72^{a}	148.93 ± 79.15	<0.05
Sr (μg per 100 g)	311.26 ± 117.55^{c}	403.72 ± 181.05^{b}	888.30 ± 629.64^{a}	522.24 ± 458.37	<0.05
Cs (μg per 100 g)	4.28 ± 1.96^{c}	6.30 ± 3.97^{b}	14.18 ± 9.76^{a}	8.00 ± 7.47	<0.05
La (μg per 100 g)	22.36 ± 8.70^{c}	27.80 ± 14.70^{b}	55.35 ± 36.78^{a}	34.46 ± 27.25	<0.05
Ce (μg per 100 g)	56.03 ± 23.96^{b}	57.27 ± 30.87^{b}	113.92 ± 75.47^{a}	75.36 ± 55.30	<0.05
Pr (μg per 100 g)	5.27 ± 2.05^{c}	6.74 ± 3.55^{b}	12.96 ± 8.71^{a}	8.14 ± 6.42	<0.05
Nd (μg per 100 g)	31.79 ± 11.77^{b}	36.05 ± 19.94^{b}	68.59 ± 45.54^{a}	33.27 ± 2.16	<0.05
Sm (μg per 100 g)	3.74 ± 1.51^{c}	5.09 ± 2.84^{b}	9.52 ± 6.46^{a}	5.95 ± 4.79	<0.05
Eu (μg per 100 g)	0.71 ± 0.33^{c}	1.05 ± 0.53^{b}	1.93 ± 1.30^{a}	1.19 ± 0.97	<0.05
Gd (μg per 100 g)	3.29 ± 1.32^{c}	4.79 ± 2.58^{b}	8.80 ± 6.06^{a}	5.45 ± 4.49	<0.05
Dy (μg per 100 g)	2.29 ± 0.93^{c}	3.38 ± 1.84^{b}	6.07 ± 4.21^{a}	3.78 ± 3.11	<0.05
Yb (μg per 100 g)	0.89 ± 0.37^{c}	1.42 ± 0.81^{b}	2.37 ± 1.61^{a}	1.50 ± 1.21	<0.05
Tl (μg per 100 g)	0.61 ± 0.28^{b}	0.70 ± 0.33^{b}	1.44 ± 0.98^{a}	0.91 ± 0.72	<0.05
U (μg per 100 g	1.64 ± 0.57^{b}	1.82 ± 0.92^{b}	9.87 ± 9.27^{a}	4.39 ± 6.57	<0.05

[a] The higher concentrations of Mg, As and U in Alxa samples indicate uranium-bearing soils and arid-steppe vegetation,[19] sanctioning that local geochemistry dictates mineral uptake into cashmere fibers.

while Mn, Cs, Pr, Sm, Eu, Gd, Dy, Yb, Tl, and U showed lower concentrations. ANOVA analysis indicated significant differences in fourteen elements: Mg, Al, V, Zn, As, Sr, Cs, La, Pr, Sm, Eu, Gd, Dy, and Yb, across the three regions ($P < 0.05$). Mg (639.5 μg g^{-1}), As (66.7 μg/100 g) and U (9.87 μg/100 g) of Alxa cashmere exhibited 5–6 times high elevations as compared to Chifeng and Ordos due to different soil and climate conditions. The distinguished elemental clustering by region was revealed by multivariate modeling. PCA and PLS-DA were outperformed by OPLS-DA with quality separation ($R^2 = 0.97$). For geographic perception, the elements like Mn, As, U, Mg and Ce were discovered by VIP analysis as the most influential markers (VIP > 1.0). Three well defined clusters overlapping the regions; Alxa and the other two, confirmed by hierarchical cluster analysis (HCA) as shown in Fig. 2.

3.2. Breed specific differences in mineral composition

Mineral elements also varied significantly among the four breeds ($P < 0.05$) as presented in Table 4. The highest elemental concentrations were consistently observed in Alxa white cashmere goats while the lowest concentrations in Mingai cashmere goat. The significance of elements; Mn, Mg, Ce, As and U, in regional classification was also described by distinct breed level differentiation. The OPLS-DA model ($R^2 = 0.97$) successfully distinguished the cashmere samples from the three regions based on their mineral element content, comparing PCA and PLS-DA as shown in Fig. 2a–c.

Identifying the regional difference among five elemental markers (Mn, As, U, Mg, Ce; VIP >1.0), Alxa samples showed relative high concentrations of As, Mg, Mn and Ce ($P < 0.05$), followed by Chifeng and then Ordos samples while U concentration remained much higher in Alxa (Table 3). These results were supported by Hierarchical Cluster Analysis by describing the breed-specific clustering. Alxa breed cluster was superiorly discrete using a longitudinal clustering distance of 0.5 as the threshold from Albas, Mingai and Hanshan described the combined effect of genetic and environments (Fig. 3).

3.3. Multivariate classification and discrimination of goat breeds

Integrated chemo-metric models further validated the breed discrimination. PCA provided the initial visualization of sample

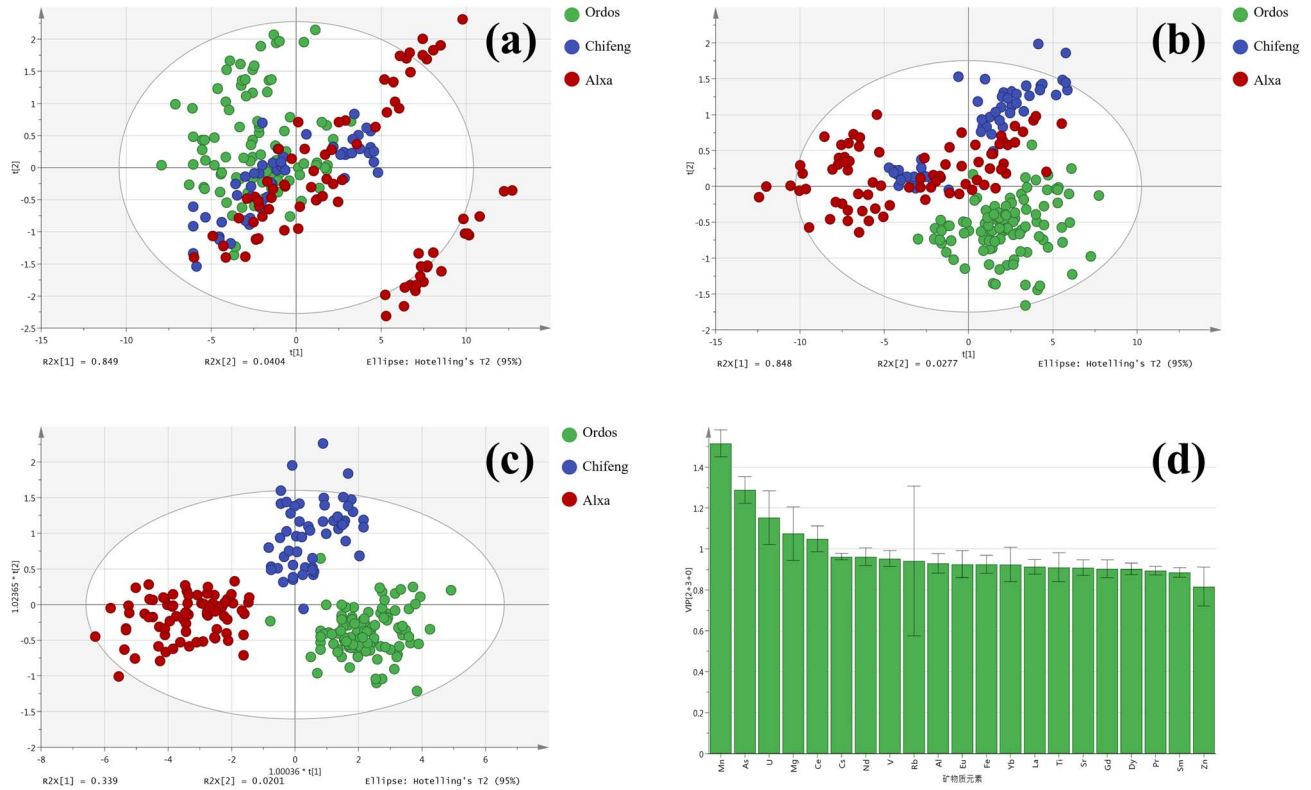

Fig. 2 The principal component analysis (PCA), partial least squares discriminant analysis (PLS-DA) and orthogonal partial least squares discriminant analysis (OPLS-DA) of cashmere samples in three regions cashmere with the data of elements and variable importance values of 21 elements (Mg, Al, V, Mn, Fe, Zn, As, Rb, Sr, Cs, La, Ce, Pr, Nd, Sm, Eu, Gd, Dy, Yb, Tl and U). (a) PCA of Ordos city, Chifeng city, and Alxa league. (b) PLS-DA of Ordos city, Chifeng city, and Alxa league. (c) OPLS-DA of Ordos city, Chifeng city, and Alxa league. Green represents Ordos city, blue represents Chifeng city, and red represents Alxa league. (d) Distribution of important factors of the OPLS-DA model in the three regions of cashmere.

clustering to reveal broad separation trends with incomplete grouping as shown in Fig. 4a. While Fig. 4b defined PLS-DA with improved breed discrimination having moderate overlap. The best separation results among the four breeds ($R^2 = 0.787$) were revealed by OPLS-DA with cross-validation of above 95% as shown in Fig. 4c. Five discriminatory elements; Mn, Mg, Sr, As and U identified by VIP analysis (VIP > 1.0) were considered as primary contributor in breed classification. The concentrations of all five elements in Alxa white cashmere were seen the highest. Mg, Sr and U were 2.8–7.0 times higher than all other breeds ($P < 0.05$) while Mn and As were 2.2 and 5.2 folds higher than Mingai and Albas as detailed in Table 4. Hanshen samples described intermediate Mg and Sr levels whereas Mingai showed the lowest As and U concentration while Mn content in Albas was high with low As and Rb ($P < 0.05$).

The cluster overlap of four breeds was confirmed by HCA analysis using clustering distance of 0.5 was used as the threshold as shown in Fig. 5. The analysis revealed distinct clustering patterns based on the mineral composition of the samples. Minor overlaps were observed, clustering Albas samples with Alxa and Hanshan samples with Albas, indicating regional environments similarities. Breed effects, particularly the enrichment in Alxa white goats, purpose genotype-linked variances in mineral metabolism, validating the interaction of environment and heredity exposed by OPLS-DA loadings.

3.4. Novelty and implications

Distinct regional and breed-associated mineral signatures were discerned in 21 elements. The OPLS-DA model systematically performed better than PCA and PLS-DA, with R^2 values of 0.97 (region) and 0.787 (breed). Six elements (Mn, As, U, Mg, Ce, Sr) proved to be the most discriminative markers for traceability. Alxa cashmere showed the most evident elemental enrichment, owing to distinct soil–climate–breed interactions. These results, for the first time, show that ICP–MS-based multi-element fingerprinting coupled with chemometric modeling is capable of authenticating, in a simultaneous manner, origin of the cashmere as well as the breed, and provides a rigorously scientific platform for tracing as well as quality certification in the cashmere trade.

4. Discussion

The multiple fingerprinting integrated with chemometrics has been successfully applied for the identification of seaweeds as discussed by[16] and[17] identified and distinguished the quality of cashmere and wool fibers through PLS-DA spectroscopy. The study verifies a multi-element fingerprinting method integrated with chemometric modeling as a reliable and measurable approach to determine the geographic origins and cashmere breeds. The high discrimination accuracy achieved with OPLS-

Table 4 Mean elemental concentrations and standard deviations for twenty-one elements from four breeds (Albas white cashmere goat, Mingai white cashmere goat, Hanshan white cashmere goat, and Alxa white cashmere goat) in cashmere goat samples. Numbers with different superscripts are significantly ($P < 0.05$) different for rows for the different cashmere goat breeds

Element	Albas white cashmere goat ($N = 60$)	Mingai white cashmere goat ($N = 45$)	Hanshan white cashmere goat ($N = 54$)	Alxa white cashmere goat ($N = 78$)	Mean value ($N = 237$)
Mg (μg g^{-1})	162.19 ± 42.48^{d}	225.33 ± 63.97^{c}	288.95 ± 74.97^{b}	639.49 ± 441.83^{a}	360.14 ± 326.41
Al (μg g^{-1})	258.37 ± 86.09^{c}	160.60 ± 60.24^{d}	330.33 ± 171.86^{b}	590.78 ± 373.54^{a}	365.60 ± 287.52
V (μg per 100 g)	48.56 ± 15.98^{c}	31.13 ± 11.77^{d}	64.39 ± 32.99^{b}	117.45 ± 76.70^{a}	71.53 ± 58.37
Mn (μg g^{-1})	8.75 ± 2.64^{b}	5.78 ± 2.02^{c}	6.38 ± 4.92^{c}	16.24 ± 10.03^{a}	10.11 ± 7.77
Fe (μg g^{-1})	277.85 ± 90.08^{b}	190.72 ± 79.29^{c}	310.59 ± 176.98^{b}	632.87 ± 421.15^{a}	385.61 ± 315.90
Zn (μg g^{-1})	102.36 ± 9.06^{b}	69.68 ± 9.46^{c}	99.49 ± 16.93^{b}	140.48 ± 90.13^{a}	108.04 ± 58.36
As (μg per 100 g)	23.74 ± 7.58^{c}	12.74 ± 3.16^{d}	39.64 ± 16.59^{b}	66.73 ± 39.65^{a}	39.42 ± 32.18
Rb (μg per 100 g)	114.97 ± 36.45^{b}	143.00 ± 58.16^{a}	153.78 ± 61.23^{a}	175.12 ± 109.72^{a}	148.93 ± 79.15
Sr (μg per 100 g)	254.30 ± 67.17^{c}	387.21 ± 127.61^{bc}	403.72 ± 181.05^{b}	888.30 ± 629.64^{a}	522.24 ± 458.37
Cs (μg per 100 g)	5.35 ± 1.85^{b}	2.85 ± 0.94^{c}	6.30 ± 3.97^{b}	14.18 ± 9.76^{a}	8.00 ± 7.47
La (μg per 100 g)	25.80 ± 8.61^{b}	17.78 ± 6.48^{c}	27.80 ± 14.70^{b}	55.35 ± 36.78^{a}	34.46 ± 27.25
Ce (μg per 100 g)	55.04 ± 17.27^{b}	57.34 ± 30.90^{b}	57.27 ± 30.87^{b}	113.92 ± 75.47^{a}	75.36 ± 55.30
Pr (μg per 100 g)	6.08 ± 2.03^{b}	4.18 ± 1.50^{c}	6.74 ± 3.55^{b}	12.96 ± 8.71^{a}	8.14 ± 6.42
Nd (μg per 100 g)	33.52 ± 10.82^{b}	29.48 ± 12.69^{b}	36.05 ± 19.94^{b}	68.59 ± 45.54^{a}	44.87 ± 33.27
Sm (μg per 100 g)	4.36 ± 1.50^{b}	2.91 ± 1.08^{c}	5.09 ± 2.84^{b}	9.52 ± 6.46^{a}	5.95 ± 4.79
Eu (μg per 100 g)	0.87 ± 0.32^{b}	0.50 ± 0.20^{c}	1.04 ± 0.53^{b}	1.93 ± 1.30^{a}	1.19 ± 0.97
Gd (μg per 100 g)	3.86 ± 1.30^{b}	2.52 ± 0.91^{c}	4.79 ± 2.58^{b}	8.80 ± 6.06^{a}	5.45 ± 4.49
Dy (μg per 100 g)	2.67 ± 0.93^{b}	1.77 ± 0.64^{c}	3.38 ± 1.84^{b}	6.07 ± 4.21^{a}	3.78 ± 3.11
Yb(μg per 100 g)	1.05 ± 0.36^{c}	0.67 ± 0.25^{d}	1.42 ± 0.80^{b}	2.37 ± 1.61^{a}	1.50 ± 1.21
Tl (μg per 100 g)	0.77 ± 0.26^{b}	0.40 ± 0.14^{c}	0.70 ± 0.33^{b}	1.44 ± 0.98^{a}	0.91 ± 0.72
U (μg per 100 g)	1.89 ± 0.55^{b}	1.29 ± 0.38^{c}	1.82 ± 0.92^{b}	9.87 ± 9.27^{a}	4.39 ± 6.57

DA modeling ($R^2 = 0.97$ for region, $R^2 = 0.787$ for breed) demonstrates the potential of mineral profiles for traceability. Six elements (Mg, Mn, As, Sr, Ce, and U) were recognized as significant indicators for distinguishing samples derived from diverse ecological and genetic origins. These results relate with prior studies on the traceability of food and animal-derived products, including the authenticity of mutton or beef *via* elemental signatures.[9,10] Nonetheless, this represents the inaugural comprehensive application of this methodology to animal fibers, establishing a scientific basis for traceability within the international cashmere sector. Variations in elemental composition across regions reflect inherent geochemical and environmental differences as discussed by.[18] Cashmere sourced from Alxa League exhibited markedly elevated concentrations of Mg, As, and U, by *a* factor of five or six, when contrasted with samples from Ordos and Chifeng, an observation attributed to the arid desert-steppe climate and uranium-rich soils prevalent in the area as mentioned by.[19] This supports the presence of a "soil-forage-animal" mineral transfer pathway, wherein regional soil characteristics and vegetation impact element absorption.[20] Comparable processes are noted in other animal production systems:[21] indicated that Se and Rb concentrations in pork correspond to regional soil geochemistry, while[22] identified Se/Rb/Ti signatures in yak muscle tissue from the Qinghai–Tibet Plateau. Aligned with these observations, the pronounced elemental signature observed in Alxa cashmere suggests that local geological factors primarily dictate mineral

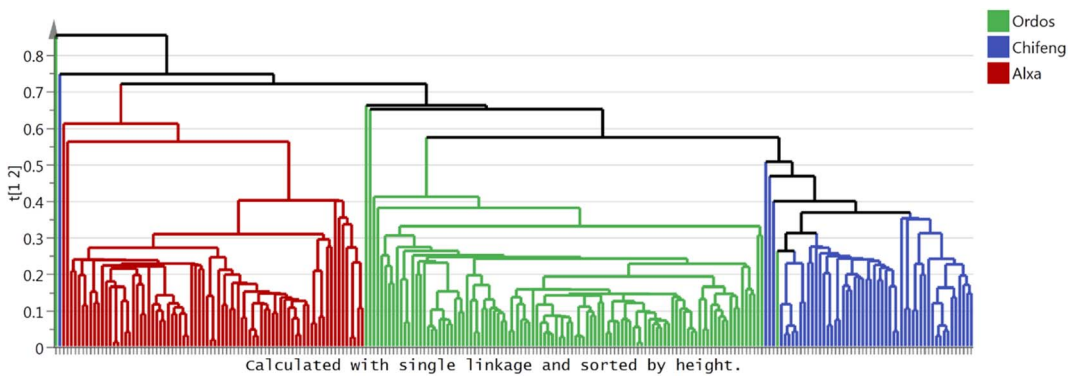

Fig. 3 The Hierarchical Cluster Analysis (HCA) diagram of cashmere samples in three regions with the data of elements and variable importance values of 21 elements (Mg, Al, V, Mn, Fe, Zn, As, Rb, Sr, Cs, La, Ce, Pr, Nd, Sm, Eu, Gd, Dy, Yb, Tl and U). Green represents Ordos city, blue represents Chifeng city, red represents Alxa league.

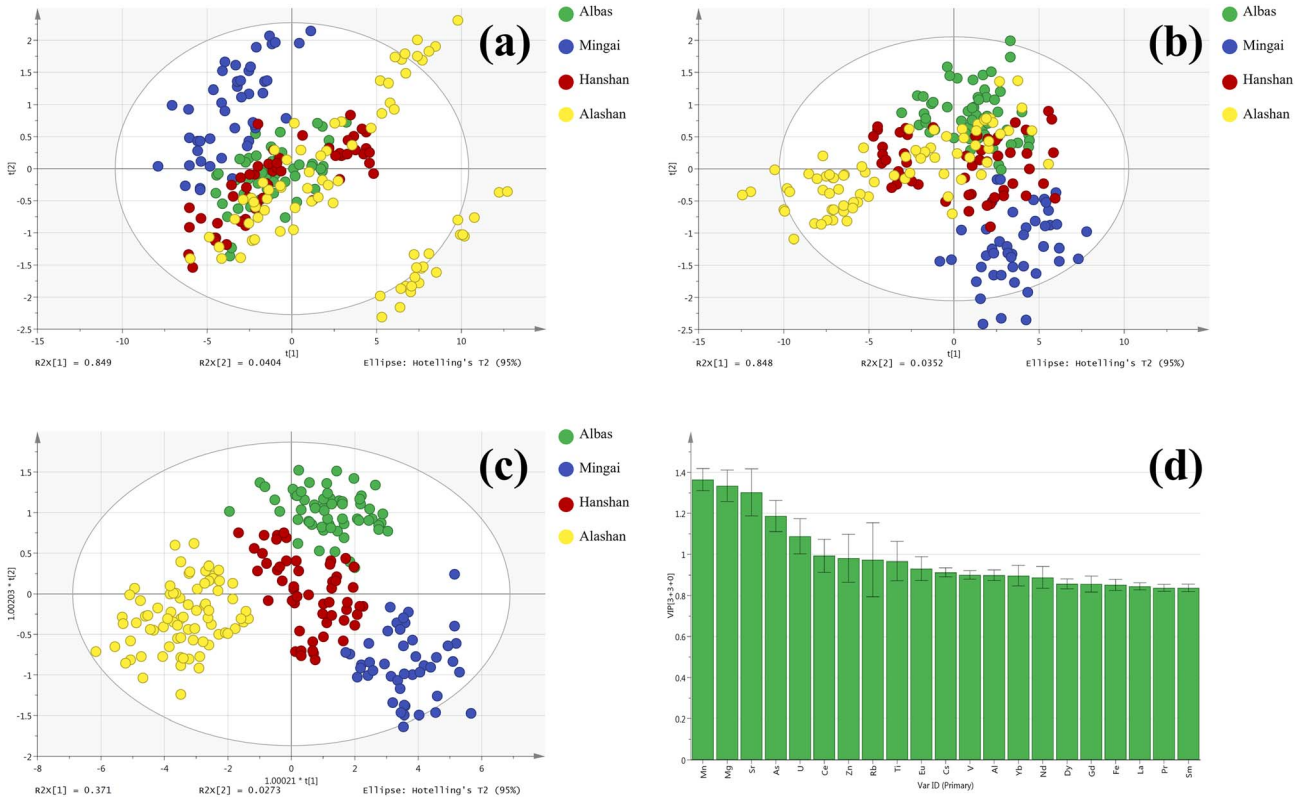

Fig. 4 The principal component analysis (PCA), partial least squares discriminant analysis (PLS-DA) and orthogonal partial least squares discriminant analysis (OPLS-DA) of cashmere samples in four goat breeds with the data of elements and variable importance values of 21 elements (Mg, Al, V, Mn, Fe, Zn, As, Rb, Sr, Cs, La, Ce, Pr, Nd, Sm, Eu, Gd, Dy, Yb, Tl and U). (a) PCA of Albas white cashmere goat; Mingai white cashmere goat, Hanshan white cashmere goat, and Alxa white cashmere goat. (b) PLS-DA of Albas white cashmere goat; Mingai white cashmere goat, Hanshan white cashmere goat, and Alxa white cashmere goat. (c) OPLS-DA of Albas white cashmere goat; Mingai white cashmere goat, Hanshan white cashmere goat, and Alxa white cashmere goat. Green represents the Albas cashmere goat, blue represents the Mingai white cashmere goat, red represents the Hanshan white cashmere goat, and yellow represents the Alxa white cashmere goat. (d) Distribution of important factors of OPLS-DA model in four goat breeds.

incorporation into fibers through stable geographic chemical signatures.[23]

Actually, the previous research regarding cashmere authentication has mainly been conducted from a genetic and isotopic perspective, with a focus on fiber morphology or DNA-based differentiation rather than elemental composition[24].[18] detected protein markers corresponding to cashmere fiber diameter variation in Albas and Alxa goats, evidencing breed-specific biochemical fingerprints without geographic validation. Moreover,[25] investigated microbial diversity in Alxa cashmere dairy

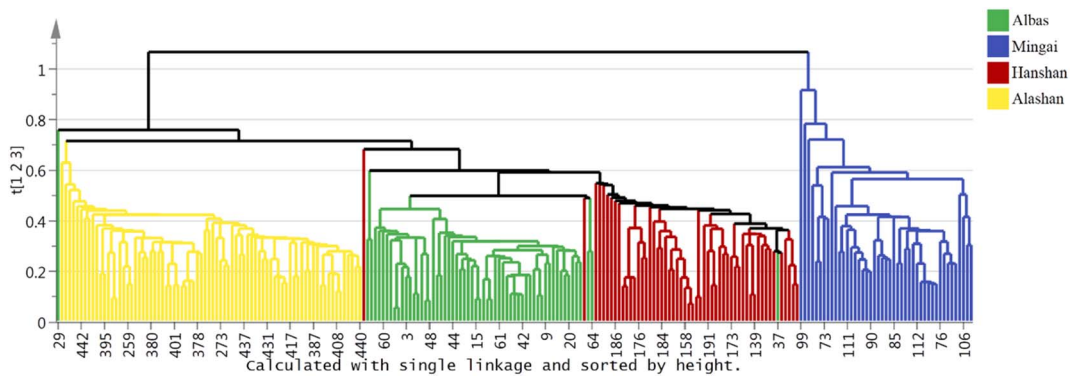

Fig. 5 The Hierarchical Cluster Analysis (HCA) diagram of four breeds (Albas white cashmere goat, Mingai white cashmere goat, Hanshan white cashmere goat, and Alxa white cashmere goat) of cashmere based on mineral elements. Green represents the Albas cashmere goat, blue represents the Mingai white cashmere goat, red represents the Hanshan white cashmere goat, and yellow represents the Alxa white cashmere goat.

products and noted region-linked biochemical variation, indirectly supporting the contribution of environmental factors to product differentiation.[26] utilized RF, GBDT and XG Boost algorithms under genomic selection to forecast fiber traits; however, the lack of environmental traceability existed therein. Such elemental profiling, as illustrated in this work, therefore extends these genomic and proteomic endeavors by incorporating environmental geochemistry within authentication models. This builds upon the traceability paradigm from simply genetics toward an integration of soil-forage-fiber mineral transfer for a more holistic approach to authenticity in the cashmere supply chain. The direct quantification of 21 mineral and rare-earth elements in the present study provides the first comprehensive physicochemical baseline for cashmere traceability that can be linked with molecular or isotopic markers in future multi-omics frameworks.

Breed genetics and management systems also contribute to an appreciable influence in the determination of elemental composition. Out of the four breeds investigated, the Alxa white cashmere goat showed, in all cases, the highest concentrations of the majority of the minerals, indicating animal-based differences in mineral metabolism and fiber deposition efficiency. Comparatively, the Mingai breed, generally reared under barn-feeding systems, showed lower concentrations of trace elements, As and U. Comparable feeding impacts in other species are documented; pasture-grazed species tend to accumulate higher environmental minerals, while confinement-fed species show feed-based enrichments in some of the trace metals.[9,27] Even so, the good separation obtained through OPLS-DA attests that regional geochemical forces remain the main indicators of classification accuracy. In addition, the consistency in the appearance of Mn, As, and U as the discriminative variables in both the regional and the breed-based analyses indicates an interplay among the genetic forces and the environment in the determination of the mineral assimilation, which is a new understanding into the mechanisms of fiber traceability.[26]

The classification accuracy in the present study surpassed that in most prior studies of elemental authentication. For example, 85–96% accuracy has been claimed for pork, mutton and milk products,[9,21,25] while in the current study, the accuracy reached 97% at the regional and 95% at the breed levels of discrimination. The improved accuracy can likely be attributed to the broad panel of 21 elements that were investigated by ICP–MS and OPLS-DA modeling, because these minimize irrelevant variations and sharpen predictive accuracy. The rare-earth elements La, Ce, Nd, Sm, and Yb have been enhancing sensitivity to geologically driven differences, as explored by[15] in relation to regional differentiation in plant-based systems. Noteworthy, the sample numbers among sites were not equal, but statistical standardization and cross-validation sufficiently addressed the potential bias. Multivariate modeling, such as OPLS–DA, is well-known for accommodating moderately unbalanced data sets using auto-scaling and random validation.10,15 The similar predictive accuracies across regions (97%) and breed (95%) indicate that elemental differences are driving the classification and not the number of samples. Hence the unequal volume of data had negligible effects on model validity or discriminatory power. Collectively, the findings confirm the methodological innovation and analytical rigor in the application of multi-element chemometrics to the cashmere authentication.

5. Limitations and future directions

Despite achieving very high accuracy, a number of limitations need to be acknowledged. Sampling was confined to a single spring season; seasonal fluctuations in soil and forage minerals could influence the elemental uptake.[28] The multi-season samplings may enhance temporal stability of models.[29] Thus, variations in the feeding systems and water sources may further contribute to elemental variations, suggesting that controlled feeding studies are recommended to counteract the environmental influences as also mentioned by.[30] Additionally, biological factors such as age, lactation and health status may also influence the absorption of minerals and fiber deposition.[31] Although ICP–MS provides quantitative results of high precision but requires laboratory facilities field deployment.[32] The future research could explore portable techniques such as pXRF or LIBS for rapid, on-site authentication. Mineral profiling combined with stable isotope ratios ($\delta^{13}C$, $\delta^{15}N$, $\delta^{2}H$) and genomic or proteomic markers may improve predictive reliability and multi-omics authentication systems. Creating a national database with comprehensive mineral fingerprints of cashmere and connecting it with blockchain certification would support origin labeling in a transparent and verifiable manner throughout the supply chain.

The implications of these findings extend beyond academic investigations and scrutiny. Development of a mineral fingerprinting library for different cashmere production regions could enable protected designation of origin (PDO) and geographical indication (GI) systems, providing an effective barrier against adulteration and misbranding. The elemental authentication in integration with digital and blockchain-based certification could improve transparency and consumer trust. Mineral-based verification ties environmental geochemistry with animal physiology, combining them as an interdisciplinary analytical tool for ecological monitoring, sustainable livestock management and fiber quality assurance. These findings are mounting evidence upon the foundation of establishing common, evidence-based traceability pathways to enhance product integrity and product sustainability in a global cashmere marketing.

6. Conclusions

This research demonstrates that mineral element fingerprinting using OPLS-DA chemometrics successfully verifies the geographic origin (Ordos, Chifeng, Alxa League) and breed (Albas, Mingai, Hanshan, Alxa) of Inner Mongolian cashmere. The main discriminative elements are Mn, As, U, Mg, Ce for regions, and Mn, Mg, Sr, As, U for breeds. These findings offer a proven technique to strengthen cashmere quality assurance. The method validates origin and breed statements, fights fraud,

facilitates trustworthy certification schemes, and enhances supply chain traceability, potentially through blockchain. Implementation of this method will guarantee product integrity, gain consumer confidence, and foster a sustainable cashmere value chain.

Ethical statement

All animal procedures were performed in accordance with the Guidelines for Care and Use of Laboratory Animals of Inner Mongolia Academy of Agricultural and Animal Husbandry Sciences and approved by the Animal Ethics Committee of Resolution on the Scientific Ethics Review of the Research Ethics Committee of the Inner Mongolia Academy of Agricultural and Animal Husbandry Sciences.

Author contributions

Study design, Zhang Chunhua, and Sun Haizhou; formal analysis, Zhang Chunhua, and Sun Haizhou; methodology, Zhang Chunhua, Li Shengli, Bao Hua, Chen Panliang, Li Wenting, Fu Le, Han Aricha, Wu Yahan, Wang Longwei and Wang Li; project administration, Sun Haizhou; validation, Zhang Chunhua; writing – original draft, Zhang Chunhua; writing – review & editing, Sun Haizhou.

Conflicts of interest

The authors declare no conflict of interest.

Data availability

The data supporting this article have been included as part of the supplementary information (SI). Supplementary information: raw baseline obtained from running all samples Inductively Coupled Plasma Mass Spectrometer (ICP-MS). See DOI: https://doi.org/10.1039/d5ra08122j.

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