Original Article

Non-invasive monitoring of camel hair from a free-grazing herd as a biomarker in linking environmental exposure and nutritional status in desert ecosystems

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Abstract

Camels are vital livestock in arid regions, yet their elemental exposure remains underexplored, particularly through non-invasive biomarkers. This study is novel in applying camel hair as a non-invasive, long-term biomarker to assess nutritional adequacy and environmental exposure in a free-grazing desert herd, with age-stratified evaluation of essential and toxic element accumulation. For this purpose, a cross-sectional study was conducted on a herd of 18 apparently healthy camels (≤6 months: 28%; >6 months: 72%). Initially, hair samples were collected, washed, digested, and analyzed using inductively coupled plasma mass spectrometry (ICP-MS). The samples were then analyzed to determine the concentrations of 12 essential and 13 toxic elements. Results indicated that magnesium (617,611 ppb), calcium (487,461 ppb), phosphorus (478,471 ppb), and potassium (220,459 ppb) were the most abundant essential elements, followed by zinc (122,063 ppb) and iron (62,608 ppb). On the other hand, aluminum was the most toxic element (56,512 ppb), with barium (2,322 ppb) and lead (1,229 ppb) also notable. Age-related differences revealed that older camels had significantly higher phosphorus, potassium, and zinc levels, reflecting dietary transition to fibrous grazing plants. In contrast, cadmium was elevated in younger camels, suggesting maternal transfer via milk, while arsenic levels were higher in older animals, consistent with cumulative environmental exposure. Essential element profiles indicate the adequacy of traditional grazing systems, while alarming levels of some trace elements were found in calves. Camel hair analysis provides a practical and welfare-friendly tool for integrated monitoring of animal health and environmental quality in arid ecosystems, supporting its use in surveillance programs and future ecosystem-based risk assessments. Future studies incorporating soil and forage analyses and broader populations are warranted to establish regional reference values.

Keywords: arid environments, biomonitoring, heavy metals, non-invasive sampling, trace elements

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Introduction

Camels have long been regarded as one of the most resilient domestic animals, uniquely adapted to thrive in arid and semi-arid environments (Gebreyohanes and Assen, 2017). In the Arabian Peninsula, camels remain an integral part of the cultural heritage and play an essential role in food security, transport and the economy (Alwahaibi *et al.*, 2024; Bagiyal *et al.*, 2024). Unlike intensively managed livestock, many camel herds depend exclusively on natural desert pastures for their nutrition (Askar et *al.*, 2024). This feeding strategy, while sustainable, also exposes camels to environmental variations in mineral availability and to potential sources of toxic elements present in soil, plants, and water (Abdelrahman *et al.*, 2023). Monitoring the elemental composition of camels is therefore essential for understanding both their nutritional status and potential health risks posed by environmental contaminants.

Trace elements are vital to animal physiology. Essential elements such as magnesium, phosphorus, calcium, potassium, iron, zinc, and copper support growth, metabolism, and immunity, while deficiencies impair health and productivity (Abdelrahman *et al.*, 2022). Toxic elements, including lead, cadmium, mercury, and aluminum, by contrast, have no biological role and can accumulate in tissues, disrupting nutrient absorption and organ function even at low levels (Yang *et al.*, 2020; Ullah *et al.*, 2023; Hadrup *et al.*, 2024). For grazing camels, whose diet depends on desert plants and soils, measuring these elements provides insight into both health and environmental quality.

Elemental exposure can be monitored in blood, urine, milk, or tissues, but these reflect only short-term status and often require invasive sampling (Lum *et al.*, 2021). Hair offers a non-invasive alternative for long-term data collection in toxicological and environmental studies (Pozebon *et al.*, 2017). Its slow growth and ease of collection make it a practical biomarker that also supports animal welfare. While hair analysis is established in humans (Florou *et al.*, 2025) and other animals (Ahmed *et al.*, 2018), studies in camels remain limited.

Advances in inductively coupled plasma mass spectrometry (ICP-MS) now allow highly sensitive detection of multiple trace elements in hair, providing a comprehensive profile of long-term exposure (Feisal *et al.*, 2019). Despite this capability, few studies have assessed both essential and toxic elements in camel hair (Meligy *et al.*, 2024), with most research focusing instead on serum, milk, or hair from slaughtered camels at abattoirs. Since the samples come from slaughterhouses, there is a gap in understanding hair as a biomarker for camels grazing in desert environments.

The Al-Ahsa region, in the eastern Arabian Peninsula, with its desert environment and herds that rely solely on native vegetation, offers a valuable setting for studying elemental accumulation (Heneidy *et al.*, 2017). Assessing essential nutrients and toxic elements in these camels can inform both animal health and environmental quality. Age is a crucial factor, as young and adult camels may differ in their exposure and accumulation due to metabolism and diet (Mousa *et al.*, 2006; Abdelrahman *et al.*, 2022).

Given the challenges of repeated blood or tissue sampling in free-grazing camels and the need for biomarkers that reflect long-term exposure rather than short-term fluctuations, there is growing interest in non-invasive matrices that integrate environmental and nutritional signals over extended periods. Hair represents a valuable biomonitor, as it accumulates trace and toxic elements during growth and can provide insight into chronic exposure under natural grazing conditions in arid ecosystems. Accordingly, the present study is novel in applying camel hair as a non-invasive, integrative biomarker to simultaneously assess the profiles of essential and toxic elements in a free-grazing desert herd. This study aimed to measure essential and harmful elements in the hair of a grazing camel herd in Al-Ahsa and to compare profiles between camel milk suckling calves (≤6 months) and older (>6 months) camels. By applying non-invasive sampling and advanced analytical methods, it seeks to establish camel hair as a reliable biomarker of nutritional and environmental status.

Materials and Methods

Study design and population: This cross-sectional study included 18 female camels of different ages and breeds. All animals were part of a completely grazing herd in the Al-Ahsa region, where feeding depends solely on natural desert pasture plants. Demographic characteristics, including age, breed, and coat color, were recorded. The study included only apparently healthy camels without clinical signs of disease. The daily food consisted of grass and browse species, including *Haloxylon salicornicum*, *Neurada procumbens*, *Haloxylon persicum*, *Zygophyllum simplex,* and *Cyperus conglomeratus*.

Location of the study: The study includes a free-ranging camel herd centered at 25°25'06.3"N 49°50'10.8"E. The camels feed solely on desert plants within a 10 km radius of this location.

Sample collection: Hair sampling was chosen as a non-invasive technique to obtain precise biological results without imposing stress on the animals, thereby ensuring better animal welfare and minimal interference with animal behavior (Henry *et al.*, 2011; Rodrigues *et al.*, 2025). Samples were collected from the dorsal region at the back of the neck of each camel using sterile stainless-steel scissors. To minimize external contamination, the superficial hair layer was removed, and samples were taken close to the skin. Approximately 2–3 grams of hair were collected from each camel and stored in sterile polyethylene bags. Each sample was labeled with a unique identifier and transported to the laboratory under contamination-free conditions. The ICP-MS technique was used for analysis for its specificity and precision (Pozebon *et al.*, 2017). The analytical procedures were as previously described (Udristioiu *et al.*, 2021; Wills and Kutscher, 2022).

Sample cleaning and preparation

Cleaning: The collected samples were rinsed three times each with Milli-Q water, Tween 20, and HPLC-grade acetone (≥99.9%), all under agitation for 10 min to remove surface contaminants. Then, all samples were air-dried in a hot air oven at 60 °C.

Microwave digestion: Approximately 500 mg of dried hair was digested in 9 mL of concentrated HNO_3 (69%, Merck, Germany) and 1 mL H_2O_2 (30%, Suprapur®, Merck) using a closed-vessel microwave digestion system (ETHOS UP, Milestone, Italy). The digestion program was as follows: ramp to 200°C over 15 min, hold at 200°C for 20 min, cool to 50°C before opening. Then, the digested samples were diluted up to 50 mL with Milli-Q water and filtered (0.45 µm PTFE syringe filter) before analysis.

Inductively coupled plasma mass spectrometry instrumentation and parameters: The iCAP RQ ICP-MS (Thermo Fisher Scientific, USA) has a single quadrupole mass analyzer, Ni sampler/skimmer cones and a Peltier-cooled spray chamber. The operating conditions were as follows: RF Power: 1550 W, plasma gas flow: 14 L/min Ar, auxiliary gas flow: 0.8 L/min Ar, nebulizer gas flow: 1.05 L/min Ar, sample uptake time: 40 sec (peristaltic pump), washing time: 40 sec (peristaltic pump), Dwell time: 10 ms per isotope, acquisition mode: Peak hopping (3 points per peak), main runs: 3 times.

The following 25 elements were quantified (with selected isotopes on KED mode to avoid interferences): 7Li, 11B, 24Mg, 27Al, 31P, 39K, 44Ca, 51V, 52Cr, 55Mn, 57Fe, 59Co, 60Ni, 63Cu, 66Zn, 75As, 77Se, 90Zr, 107Ag, 111Cd, 118Sn, 121Sb, 137Ba, 202Hg and 208Pb. A calibration curve was readied from a multi-element calibration standard (0–100 ppb) prepared from certified stock solutions obtained from LGC, Germany. The quality control was set at 50 ppb. Relative standard deviation (RSD) was kept <5% across replicate analyses.

Statistical analysis: Data were expressed as means with standard deviations (SD). Comparisons between camels ≤6 months, which depend solely on milk and those >6 months who started grazing were performed using the Kruskal–Wallis test, Wilcoxon rank-sum test, or Pearson's chi-square test, as appropriate. A *p-value* <0.05 was considered statistically significant. All statistical analyses were conducted using Jamovi version 2.4.8 (The jamovi, 2023).

Results

Characteristics of the study population: A herd comprising eighteen female camels was included in the study, with a mean age of 3.5 years (SD = 2.6; range 0.1–7.0 years). Slightly more than two-thirds (72%) were older than 6 months, while 28% were ≤6 months. The majority were of Sudanese origin (83.3%), with a smaller proportion belonging to the Omani breed (16.7%). Coat color distribution favored white (66.7%) over brown (33.3%) (Table 1).

Table 1 Characteristics of the included camels.

Variables	Overall (N=18)
Age years	
Mean (SD)	3.5 (2.6)
Range	0.1 - 7.0
Age group	
> 6 months	13 (72%)
≤ 6 months	5 (28%)
Gender	
Female	18 (100.0%)
Breed	
Omani	3 (16.7%)
Sudanese	15 (83.3%)
Coat color	
Brown	6 (33.3%)
White	12 (66.7%)

Essential elements in camel hair: Magnesium, phosphorus, potassium, and calcium were the most abundant essential elements, with mean values exceeding 200,000 ppb. More details on other elements are shown in Table 2.

Toxic elements in camel hair: Aluminum was the most abundant toxic element, followed by Barium and lead. No antimony was detected in any sample. More details on other toxic elements are shown in Table 3.

Age-Based Differences in Essential and Toxic Elements: For the essential elements, older camels (>6 months) had higher concentrations of phosphorus (535,084.3 ± 209,038.7 vs. 331,277.2 ± 69,760.9 ppb; P = 0.004), potassium (284,531.1 ± 242,876.2 vs. 53,871.3 ± 43,665.5 ppb; P = 0.046) and zinc (134,317.0 ± 86,146.4 vs. 90,201.5 ± 7,864.4 ppb; P = 0.035) compared with younger camels (≤6 months). Magnesium, calcium, iron, copper, manganese, cobalt, selenium, boron, and nickel did not show any significant age-related differences (Table 4).

For the toxic elements, cadmium levels were higher in younger camels (627.2 ± 1,147.1 vs. 46.6 ± 26.5 ppb; P = 0.046). Arsenic levels also differed between groups, with older camels showing higher values (72.4 ± 33.3 vs. 31.8 ± 20.7 ppb; P = 0.019). Aluminum, vanadium, chromium, zirconium, Barium, mercury, lead, tin, silver, or lithium showed any significant age-related differences. Antimony was not detected in either group (Table 4).

Table 2 Essential elements found in the camel's hair.

Essential Element	Isotope (KED) [ppb]	Mean (SD)	Range
Magnesium	Mg (^{24}Mg)	617,610.7 (332,176.1)	1,899.9 – 1,527,357.0
Phosphorus	P (^{31}P)	478,471.2 (202,023.3)	0.0 – 836,223.1
Potassium	K (^{39}K)	220,458.9 (231,061.2)	0.0 – 757,815.7
Calcium	Ca (^{44}Ca)	487,461.3 (300,940.4)	923.0 – 1,327,459.9
Iron	Fe (^{57}Fe)	62,608.3 (56,022.4)	0.0 – 251,086.0
Zinc	Zn (^{66}Zn)	122,062.7 (75,275.8)	0.0 – 331,504.4
Copper	Cu (^{63}Cu)	2,425.7 (830.2)	0.0 – 4,289.9
Manganese	Mn (^{55}Mn)	10,381.0 (7,000.0)	25.0 – 29,075.0
Cobalt	Co (^{59}Co)	64.4 (56.8)	0.0 – 226.9
Nickel	Ni (^{60}Ni)	513.5 (1,138.3)	4.0 – 4,990.0
Selenium	Se (^{77}Se)	749.9 (311.9)	0.0 – 1,560.0
Boron	B (^{11}B)	3,820.0 (2,947.5)	0.0 – 13,159.8

Table 3 Toxic elements found in the camel's hair.

Elements	Symbol (Isotope)	Mean (SD) [ppb]	Range [ppb]
Arsenic	As (^{75}As)	61.1 (35.1)	0.0 – 131.4
Cadmium	Cd (^{111}Cd)	207.9 (617.8)	3.1 – 2,672.8
Mercury	Hg (^{202}Hg)	177.9 (232.5)	0.0 – 946.9
Lead	Pb (^{208}Pb)	1,228.7 (715.4)	0.0 – 2,630.9
Antimony	Sb (^{121}Sb)	0.0 (0.0)	0.0 – 0.0
Tin	Sn (^{118}Sn)	256.2 (101.8)	0.0 – 482.2
Silver	Ag (^{107}Ag)	8.2 (9.2)	0.0 – 36.5
Lithium	Li (^{7}Li)	130.8 (109.1)	0.0 - 485.2
Aluminum	Al (^{27}Al)	56,512.2 (71,349.3)	0.0 – 277,156.2
Vanadium	V (^{51}V)	667.2 (513.0)	2.0 – 2,212.5
Chromium	Cr (^{52}Cr)	239.6 (276.7)	3.0 – 1,240.1
Zirconium	Zr (^{90}Zr)	54.1 (81.7)	0.0 - 286.7
Barium	Ba (^{137}Ba)	2,322.0 (1,918.2)	0.0 – 7,469.5

Table 4 Essential and toxic elements found in the camels' hair based on their age.

Elements (KED) [ppb]	Symbol	> 6 months N = 13 (72%) Mean (SD)	≤ 6 months N = 5 (28%) Mean (SD)	p-value
Essential elements				
Magnesium	Mg (^{24}Mg)	646,880.30 (380,773.78)	541,509.65 (154,788.56)	0.77
Phosphorus	P (^{31}P)	535,084.32 (209,038.67)	331,277.15 (69,760.87)	**0.004**
Potassium	K (^{39}K)	284,531.06 (242,876.19)	53,871.33 (43,665.52)	**0.046**
Calcium	Ca (^{44}Ca)	524,633.71 (340,477.54)	390,813.03 (144,775.96)	0.44
Iron	Fe (^{57}Fe)	67,178.00 (64,417.02)	50,727.00 (25,410.78)	0.92
Copper	Cu (^{63}Cu)	2,232.76 (797.37)	2,927.31 (765.64)	0.17
Zinc	Zn (^{66}Zn)	134,316.99 (86,146.39)	90,201.54 (7,864.37)	**0.035**
Manganese	Mn (^{55}Mn)	10,930.61 (8,202.43)	8,951.87 (1,695.94)	>0.99
Cobalt	Co (^{59}Co)	66.47 (63.82)	58.87 (38.13)	>0.99
Selenium	Se (^{77}Se)	677.13 (276.38)	939.13 (349.65)	0.095
Nickel	Ni (^{60}Ni)	273.91 (253.16)	1,135.67 (2,155.29)	0.63
Boron	B (^{11}B)	4,122.23 (3,386.64)	3,034.08 (1,202.78)	0.63
Toxic elements				
Lithium	Li (^{7}Li)	153.90 (119.44)	70.61 (39.64)	0.075
Aluminum	Al (^{27}Al)	55,773.15 (74,606.78)	58,433.78 (70,218.50)	0.77
Vanadium	V (^{51}V)	674.83 (582.51)	646.99 (316.79)	0.70
Chromium	Cr (^{52}Cr)	262.08 (316.41)	180.66 (139.78)	0.92
Arsenic	As (^{75}As)	72.40 (33.28)	31.79 (20.68)	**0.019**
Zirconium	Zr (^{90}Zr)	63.59 (93.28)	29.50 (34.89)	>0.99
Silver	Ag (^{107}Ag)	8.49 (10.57)	7.33 (4.52)	0.76
Cadmium	Cd (^{111}Cd)	46.59 (26.49)	627.15 (1,147.13)	**0.046**
Tin	Sn (^{118}Sn)	235.87 (88.17)	309.05 (125.92)	0.21
Antimony	Sb (^{121}Sb)	0	0	
Barium	Ba (^{137}Ba)	2,149.85 (1,980.27)	2,769.75 (1,877.77)	0.44
Mercury	Hg (^{202}Hg)	146.17 (147.26)	260.28 (391.10)	>0.99
Lead	Pb (^{208}Pb)	1,100.27 (669.17)	1,562.71 (799.09)	0.34

Discussion

The investigation into the elemental composition of camel hair from the Al-Ahsa region reveals a complex relationship between environmental exposure and physiological aspects. The dominance of essential macroelements—magnesium, phosphorus, potassium, and calcium—in hair samples reflects the fundamental nutritional priorities of these desert-adapted animals (Birnie-Gauvin *et al.*, 2017). These elements, averaging above 200,000 ppb, demonstrate that despite relying entirely on natural desert vegetation, the camels maintain strong mineral profiles essential for their metabolic functions.

The exceptionally high magnesium concentrations (617,610.7 ppb) likely arise from the mineral-rich

halophytic plants that dominate desert ecosystems (Toderich *et al.*, 2009). These salt-tolerant species concentrate minerals as an adaptive mechanism, passing this nutritional wealth to their grazers. Similarly, the substantial iron (62,608 ppb) and zinc (122,062.7 ppb) levels suggest that the sparse but specialized desert flora provides adequate nutrition for trace elements, contradicting assumptions about nutritional scarcity in arid environments (Pérez-Reverón *et al.*, 2024).

The observed pattern of essential elements indicates a likely significant mineral change among the studied camel group. There is an increased risk of deficiencies in copper, cobalt, and selenium because their levels were below normal values in the camel hair. This increased risk may be attributed to elevated calcium and phosphorus levels, which could antagonize their absorption.

Age emerged as a critical factor in elemental accumulation patterns. Older camels showed significantly higher phosphorus, potassium, and zinc concentrations, which aligns with their transition from milk-based nutrition to exclusive grazing (Damarany, 2016). This dietary shift exposes them to a broader spectrum of plant species and, consequently, a more diverse mineral intake. The maturation of digestive systems in older animals also enhances their capacity to extract and absorb minerals from fibrous desert vegetation (Bikker and Jansman, 2023).

Among toxic elements, aluminum's prominence (56,512.2 ppb) reflects the geological reality of desert soils, where aluminum-rich minerals weather and become bioavailable through plant uptake (Abedi *et al.*, 2013). The higher cadmium levels in younger camels (627.2 vs. 46.6 ppb in older animals) present an interesting paradox. The pattern suggests maternal transfer via milk, in which cadmium accumulated in the mother's body is mobilized during lactation. Conversely, the elevated arsenic levels in older camels (72.4 vs. 31.8 ppb) indicate cumulative environmental exposure through years of grazing on plants growing in naturally arsenic-enriched soils.

Compared with previous studies, our findings expand the understanding of camel mineral profiles by focusing on hair analysis in young and adult females. Faraz *et al.* (2020) highlighted dietary and environmental influences, reporting lower levels of Ca, Mg, Cu, Zn, Fe, and Mn in camels reared under extensive systems. In contrast, our study consistently found high levels of Ca, Mg, Fe, Zn, and Mn in hair, regardless of age, with only P, K, Zn, Cd, and As showing significant age-related variation (Faraz *et al.*, 2021). Faye *et al.* (2008) identified iron as the dominant serum element, followed by copper and zinc, with sex and physiological status influencing concentrations (Faye *et al.*, 2008); our results similarly revealed high Fe and Zn but emphasized toxic elements such as Al, Pb, and Cd, largely unaddressed in serum-based studies. Agamy *et al.* (2024) also reported camel hair minerals, but with lower absolute concentrations than ours; notably, we observed much higher toxic elements (Al, Pb, Cd, Hg), suggesting possible environmental contamination in our population.

These findings have important implications for camel health and environmental monitoring in arid regions. The powerful essential element profiles suggest that traditional grazing systems adequately meet camels' nutritional needs, challenging assumptions about the necessity of mineral supplementation and supporting the value of indigenous husbandry practices.

Age-related patterns point to critical intervention windows. Higher cadmium levels in young camels underscore the need to monitor maternal body burdens, especially in areas with environmental contamination. Strategic zinc and selenium supplementation during lactation may help limit cadmium transfer by competing for similar transport pathways (Hudson *et al.*, 2025).

From an environmental perspective, camel hair emerges as a valuable sentinel for ecosystem health. The relatively low levels of industrial pollutants (lead, mercury) compared with those of higher agricultural contaminants (cadmium, arsenic) suggest that natural geological sources are the main drivers of exposure. These baseline data provide a valuable reference as the region experiences economic development and potential industrialization.

The data indicate a notable age-related variation in elemental accumulation. Camels older than six months revealed elevated concentrations of phosphorus, potassium, and zinc, suggesting dietary accumulation, alongside increased arsenic levels, which may indicate chronic environmental exposure. The primary finding indicates significantly elevated cadmium levels in young calves (≤6 months), suggesting substantial lactational transfer from dam to calf, which poses a serious toxicological risk to neonates. The consistent low levels of copper, cobalt, and selenium across all age groups indicate an extensive nutritional deficiency within the population. The findings highlight two critical health issues: 1) chronic environmental exposure to arsenic and cadmium, and 2) a severe dietary deficiency in some trace minerals.

Our study's main strength is the non-invasive hair sampling, which enabled assessment of elemental status without compromising animal welfare. Advanced ICP-MS provided highly sensitive, multi-element profiling while focusing on a free-grazing herd, capturing authentic environmental exposure patterns.

Limitations include the small sample size (n=18), which reduces generalizability, and the cross-sectional design, which provides only a snapshot and does not account for seasonal variation or long-term accumulation. The lack of soil and plant samples prevented clear identification of exposure sources, and excluding male camels and other management systems limited broader comparisons.

In conclusion, this study demonstrates that free-grazing camels in Al-Ahsa maintain adequate macro-mineral status, supporting the sustainability of traditional extensive grazing systems. However, consistent deficiencies in essential trace elements, particularly copper and cobalt, indicate an underlying nutritional imbalance that may affect health and productivity. Age-related differences revealed cumulative arsenic exposure in adult camels and markedly elevated cadmium levels in calves, suggesting significant lactational transfer of toxic

metals. Overall, camel hair proved to be a reliable, non-invasive biomarker for monitoring nutritional adequacy and environmental contamination, with clear value for regional herd surveillance and management strategies.

Recommendations: Moving forward, we recommend expanding this research through longitudinal studies that track seasonal variations in elemental accumulation. Establishing region-specific reference ranges for both essential and toxic elements would enhance veterinary diagnostic capabilities. Integration of environmental sampling—analyzing soil, water and predominant forage plants—would elucidate exposure pathways and inform targeted interventions. Finally, developing standardized protocols for hair sampling and analysis would facilitate inter-regional comparisons and contribute to global understanding of camel health in changing environments.

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Animal rights statement: Not applicable

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Data Availability Statement: Data can be requested from the corresponding author upon reasonable request.

Authors' contribution: Conceptualization, I.A.; methodology, I.A.; software, I.A.; formal analysis, I.A.; resources, I.A.; data curation, I.A.; writing—original draft preparation, I.A.; writing—review and editing, I.A.

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