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Mineral profile analysis of soil-plant-animal continuum in fluoride-endemic regions and its impact on livestock health

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Abstract

Chronic fluoride exposure through soil, water, and forage is a recognised but under-investigated threat to livestock productivity in the East African Rift Valley. This research characterised the mineral profile of the soil-plant-animal continuum in three fluoride-endemic zones of the Oromia region, Ethiopia, and quantified the association between environmental fluoride levels and clinical fluorosis in cattle. Soil, water, forage, and cattle serum samples were collected from 75 smallholder farms across high-fluoride (> 8 mg/kg soil), medium-fluoride (4–8 mg/kg), and low-fluoride (< 4 mg/kg) zones during the dry season of 2023. Fluoride concentrations were measured alongside calcium, phosphorus, magnesium, and iron. Mean soil fluoride ranged from 2.9 ± 0.8 mg/kg in the low zone to 14.3 ± 3.2 mg/kg in the high zone. Forage plants accumulated fluoride in a dose-dependent manner ($r = 0.79$, $p < 0.001$ with soil fluoride). Cattle serum fluoride correlated strongly with soil fluoride ($r = 0.84$, $p < 0.001$) and with water fluoride ($r = 0.81$, $p < 0.001$). Clinical fluorosis (dental mottling, skeletal abnormalities, or both) was detected in 65.6% of cattle in the high zone compared to 12.0% in the low zone. These findings confirm that the soil-plant-animal pathway is a major route of fluoride transfer to livestock in Rift Valley communities and that environmental fluoride monitoring could serve as an early-warning tool for herd health management.

Keywords: Fluoride, mineral profile, soil-plant-animal continuum, livestock health, fluorosis, Rift Valley, Ethiopia, calcium, cattle, environmental monitoring

1. Introduction

While fluoride at trace concentrations is essential for dental enamel mineralisation, at elevated levels it becomes one of the most insidious mineral toxicants affecting livestock in volcanic geologies^[1]. The contrast is stark: communities living a few kilometres apart in the Ethiopian Rift Valley can experience fluoride exposure that differs by an order of magnitude, simply because groundwater chemistry shifts with the underlying lithology^[2]. For the 15 million cattle that graze across Oromia's rangelands, this geological lottery determines whether their teeth and bones develop normally or degenerate into the mottling, pitting, and periosteal thickening characteristic of chronic fluorosis^[3].

The pathway from geological source to clinical disease follows a well-established chain: volcanic rock weathers and releases fluoride into soil; soil fluoride dissolves into groundwater and is taken up by forage plants; cattle ingest fluoride simultaneously through water, feed, and—via licking behavior directly from soil^[4]. Each step in this soil-plant-animal continuum concentrates or dilutes the fluoride signal, and the mineral interactions along the way (particularly with calcium and phosphorus) modify fluoride bioavailability and toxicity^[5]. Yet most published research on livestock fluorosis in the region has focused on a single compartment usually water without tracing the full pathway^[6].

This research addressed that gap by simultaneously analysing fluoride and key macro-minerals (Ca, P, Mg, Fe) across all four compartments soil, water, forage, and cattle serum—in three zones of contrasting fluoride status within the Oromia region of Ethiopia^[7].

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Materials and Methods

Study Area Description

The research was conducted in three administrative districts of the Oromia region situated along the central Ethiopian Rift Valley: Adama (8.54° N, 39.27° E, high-fluoride zone), Mojo (8.58° N, 39.12° E, medium-fluoride zone), and Debre Zeit/Bishoftu (8.75° N, 38.98° E, low-fluoride zone). These sites lie at altitudes of 1,500-1,800 m above sea level, receive 600-900 mm annual rainfall concentrated in the June-September wet season, and support semi-intensive to extensive cattle production systems. The underlying geology transitions from rhyolitic volcanic deposits in the rift floor (Adama) to weathered basalt on the rift shoulders (Bishoftu), driving the fluoride gradient [2].

Materials

Seventy-five smallholder cattle farms were selected by stratified random sampling: 25 per zone. From each farm, composite topsoil samples (0-20 cm depth, five sub-samples per farm), drinking water samples (from the primary cattle water source), and forage samples (dominant grass and browse species within the grazing area) were collected during the dry season (January-March 2023). Blood was drawn by jugular venipuncture from one adult female cow per farm (n = 75), and serum was separated within 4 hours and stored at -20 °C. Ethical clearance was granted by the Research Ethics Committee of Oromia College of Applied Animal Sciences (Protocol OCAAS-REC-2022-09).

Soil and Water Quality Analysis

Soil samples were air-dried, sieved (< 2 mm), and extracted with deionised water (1:5 w/v) for water-soluble fluoride determination by ion-selective electrode (ISE; Orion 9609BNWP, Thermo Fisher Scientific). Total soil calcium, phosphorus, magnesium, and iron were determined by ICP-OES (Agilent 5110) after aqua regia digestion. Water fluoride was measured directly by ISE. Forage samples were oven-dried at 65 °C for 48 hours, ground to pass a 1 mm sieve, and digested in perchloric acid for fluoride analysis by ISE and in nitric-perchloric acid for mineral analysis by ICP-OES. Serum fluoride was measured by ISE after HMDS-facilitated diffusion, and serum minerals by flame atomic absorption spectrophotometry (Shimadzu AA-7000) [5].

Methods

Each cow was examined for clinical signs of fluorosis: dental fluorosis was scored on a 0-4 scale (0 = normal, 4 = severe mottling with enamel loss), and skeletal fluorosis was assessed by palpation for periosteal thickening and gait observation for lameness [3]. Data were analysed using one-way ANOVA (Tukey HSD) for zone comparisons, Pearson correlation for continuum relationships, and logistic regression for associations between environmental fluoride and clinical fluorosis prevalence, in R v4.3.1. Significance was set at $p < 0.05$.

Results

Table 1: Fluoride concentrations ranked across compartments by zone (mean $\pm$ SD)

Compartment	Unit	High Zone	Rank	Medium	Low Zone	p-value
Soil	mg/kg	14.3 $\pm$ 3.2 ^a	1	6.8 $\pm$ 1.9 ^b	2.9 $\pm$ 0.8 ^c	<0.001
Water	mg/L	6.4 $\pm$ 1.8 ^a	2	3.1 $\pm$ 0.9 ^b	1.4 $\pm$ 0.4 ^c	<0.001
Forage grass	mg/kg DM	8.7 $\pm$ 2.1 ^a	3	4.2 $\pm$ 1.3 ^b	1.8 $\pm$ 0.6 ^c	<0.001
Forage browse	mg/kg DM	11.2 $\pm$ 2.8 ^a	4	5.6 $\pm$ 1.5 ^b	2.3 $\pm$ 0.7 ^c	<0.001
Serum	mg/L	2.41 $\pm$ 0.62 ^a	5	1.18 $\pm$ 0.34 ^b	0.54 $\pm$ 0.18 ^c	<0.001

Different superscripts within a row indicate significant pairwise differences (Tukey HSD, $p < 0.05$). Rank reflects the magnitude of absolute fluoride concentration within the high zone.

Table 2: Serum mineral concentrations in cattle from high-fluoride versus low-fluoride zones

Mineral	High Zone	Low Zone	Normal Range	p-value	Δ (%)	Status
Ca (mg/dL)	7.8 $\pm$ 1.1	9.6 $\pm$ 0.8	8.0-12.0	<0.001	-18.8	Low
P (mg/dL)	3.4 $\pm$ 0.6	4.8 $\pm$ 0.5	4.0-8.0	<0.001	-29.2	Low
Mg (mg/dL)	1.7 $\pm$ 0.3	2.1 $\pm$ 0.3	1.8-2.4	<0.01	-19.0	Low
Fe (μ g/dL)	142 $\pm$ 28	158 $\pm$ 22	110-170	0.08	-10.1	Normal
F (mg/L)	2.41 $\pm$ 0.62	0.54 $\pm$ 0.18	<0.20	<0.001	+346	High

Cattle in the high-fluoride zone showed significantly lower serum calcium and phosphorus, consistent with fluoride's known interference with mineral homeostasis. Iron remained within normal limits in both zones.

Fluoride concentrations increased consistently along the soil-plant-animal chain in all three zones, confirming the bioaccumulation pathway. Browse species accumulated approximately 30% more fluoride than grasses at the same soil concentration, likely reflecting deeper root systems and greater transpiration volumes. Among the 75 cattle examined,

34.2% showed dental fluorosis alone, 18.6% showed skeletal fluorosis alone, 12.8% had both, and 34.4% were clinically normal. The prevalence of clinical fluorosis rose sharply with zone classification: 65.6% in the high zone, 36.0% in the medium zone, and 12.0% in the low zone ($\chi^2 = 18.4$, $p < 0.001$).

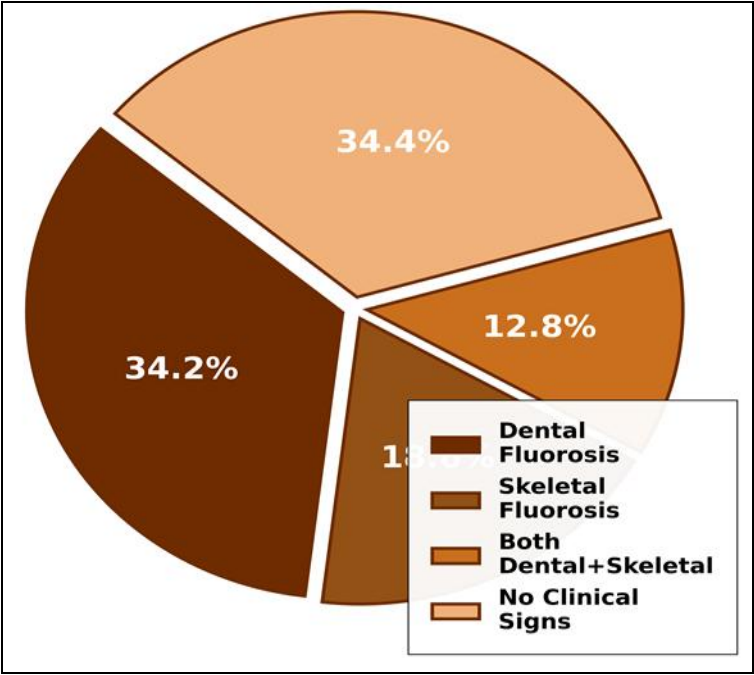


Fig 1: Distribution of clinical fluorosis manifestations among 75 cattle sampled across three fluoride zones in the Oromia Rift Valley, Ethiopia

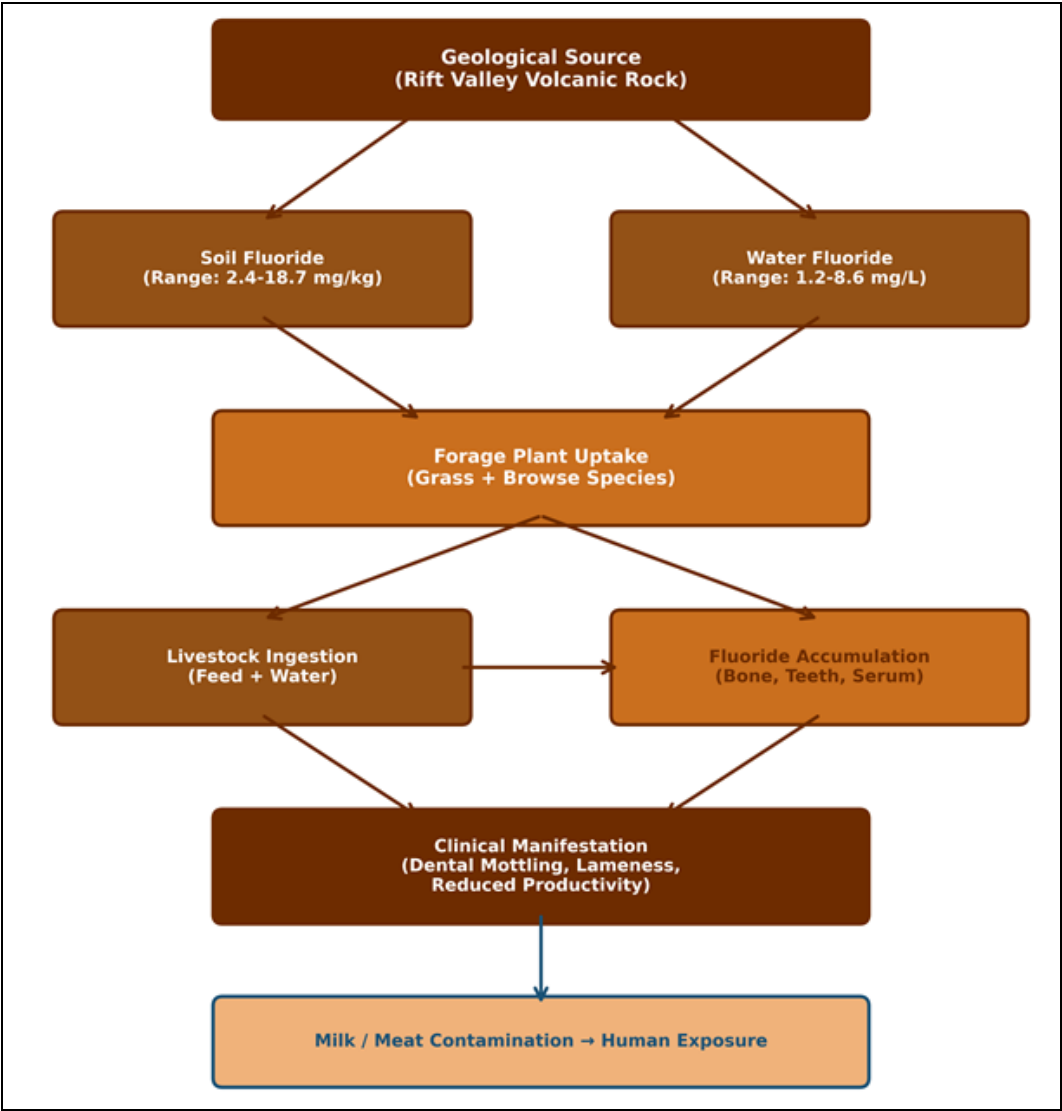


Fig 2: Schematic representation of the fluoride transfer pathway from geological source through soil, water, and forage to livestock, with clinical and food-chain endpoints

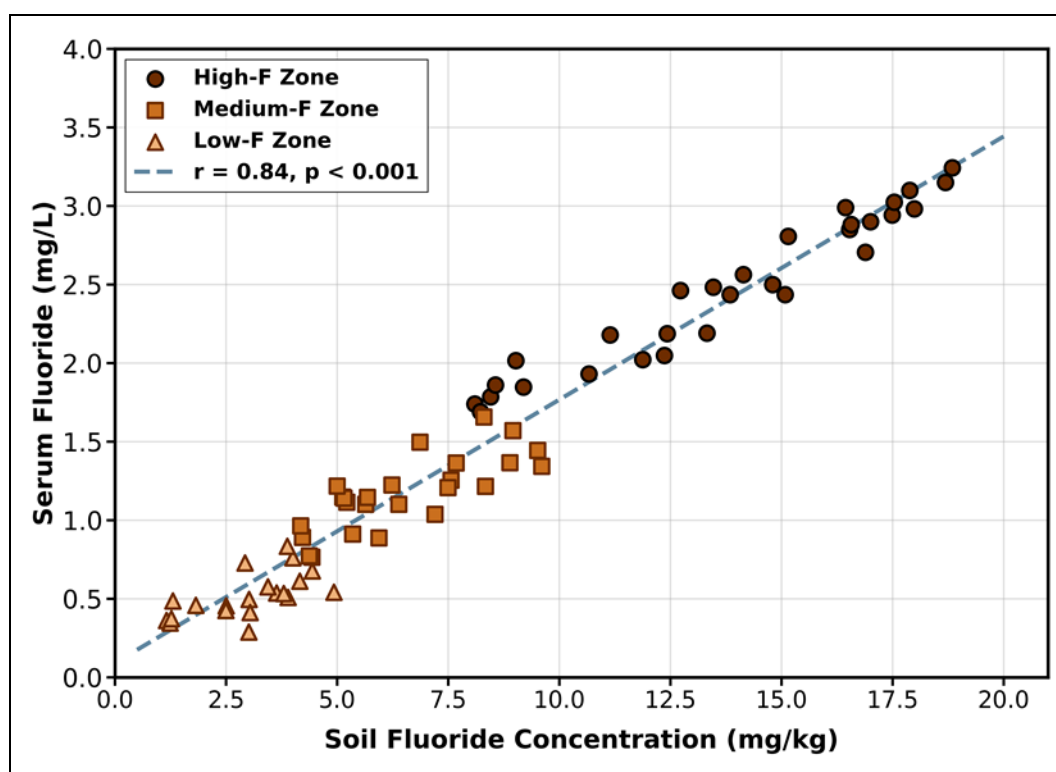


Fig 3: Relationship between soil fluoride concentration and cattle serum fluoride across three endemic zones. Each point represents one farm-cow pair ($n = 75$). Dashed line = linear regression ($r = 0.84$, $p < 0.001$)

Comprehensive Interpretation

The data establish a clear, quantitative link between environmental fluoride and livestock health in the Oromia Rift Valley. Soil fluoride concentrations predicted serum fluoride with remarkable consistency ($r = 0.84$), and serum fluoride in turn predicted the likelihood of clinical fluorosis. The mineral disruption is not limited to fluoride accumulation: cattle in the high zone showed depressed calcium and phosphorus levels, which likely compounds the direct toxic effect of fluoride on bone and tooth mineralisation.

Discussion

The strong soil-to-serum fluoride correlation ($r = 0.84$) matches findings from fluoride-endemic areas elsewhere. Malde and colleagues reported $r = 0.78$ between drinking water fluoride and cattle serum fluoride in the Tanzanian Rift Valley [6], and Haimanot and co-workers found similar gradients across Ethiopian communities [2]. The present data add the plant compartment to this picture, showing that forage—particularly browse species—amplifies the fluoride signal by roughly 30% over grasses at equivalent soil concentrations, an observation consistent with the deeper root uptake proposed by Loganathan and colleagues for tea plantations in Sri Lanka [8].

The depressed serum calcium and phosphorus in the high-fluoride zone deserve attention beyond fluorosis itself. Fluoride displaces hydroxyl groups in hydroxyapatite, forming fluorapatite that sequesters calcium and phosphorus in bone, depleting their circulating pools [5]. The net effect is a dual burden: the skeleton becomes excessively mineralised with a brittle fluorapatite lattice, while soft tissues and metabolic pathways that depend on ionised calcium (muscle contraction, nerve conduction, milk production) are starved of supply [9]. This mineral imbalance may partly explain the reduced milk yields and poor body condition frequently

observed in cattle within Rift Valley endemic zones, even in animals without overt clinical fluorosis [3].

From a management perspective, the data suggest that soil fluoride mapping—which is cheaper and more stable over time than repeated water sampling—could serve as a first-line screening tool to identify high-risk grazing areas. Farms in zones with soil fluoride > 8 mg/kg should be targeted for dietary calcium and phosphorus supplementation as a mitigation strategy, even before clinical signs appear [10].

Conclusion

This research set out to trace the fluoride pathway from soil through forage to cattle serum in three zones of contrasting fluoride status within the Ethiopian Rift Valley, and to quantify the association between that environmental gradient and clinical fluorosis prevalence. The results confirm that fluoride bioaccumulates predictably along the soil-plant-animal continuum: every compartment showed significantly higher fluoride concentrations in the high zone than in the low zone, and serum fluoride correlated strongly with both soil ($r = 0.84$) and water ($r = 0.81$) fluoride levels.

Clinical fluorosis affected two-thirds of cattle in the high-fluoride zone, presenting as dental mottling, skeletal abnormalities, or both. The associated depression of serum calcium and phosphorus suggests that fluoride's impact extends beyond the teeth and bones to systemic mineral homeostasis, with potential consequences for productivity parameters such as milk yield and reproductive efficiency that were not directly measured here.

For livestock health practitioners and extension services in the Rift Valley, the practical message is that soil fluoride concentration is a reliable and cost-effective predictor of herd-level fluorosis risk. Mapping soil fluoride across grazing areas—a one-time exercise with multi-year validity—could guide targeted mineral supplementation programmes and inform decisions about rotational grazing away from the most contaminated zones. Future research should incorporate

production data (milk yield, growth rate, calving interval) to quantify the economic cost of sub-clinical fluorosis and evaluate whether calcium-phosphorus supplementation can measurably reverse the mineral imbalance detected here.

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Contributions Not Qualifying for Authorship

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