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Soil and Plant Molybdenum Status in Coconut Palms of the Southern Coastal Plain (AEU 1), Kerala, India

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Aims: To assess plant molybdenum concentrations in coconut palms across the Southern Coastal Plain (Agro Ecological Unit 1 of Kerala) and evaluate nutritional status against established sufficiency standards for tree crops.
Study Design: Survey-based field study with spatial sampling.
Place and Duration of Study: Forty-seven panchayats across blocks of Agro-Ecological Unit 1 (Southern Coastal Plain), Kerala, India, during the year 2024-25.
Methodology: Soil samples at two depths (0-15 cm and 15-30 cm) and corresponding mature leaf samples were collected from 141 geo-referenced locations across 47 panchayats across blocks of Southern Coastal Plain. Available molybdenum in soil was determined using acid ammonium

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oxalate extraction followed by AAS analysis. Plant tissue samples were digested using di-acid mixture and analyzed for Mo concentration. Spatial variability was assessed through descriptive statistics, and plant nutritional status was evaluated by comparing observed concentrations with established sufficiency ranges for other crops.

Results: Soil available Mo showed considerable variation with mean concentration of 0.04 mg kg^{-1} in both surface (range 0.02-0.07 mg kg^{-1}) and subsurface (range 0.02-0.07 mg kg^{-1}) layers, with majority of soils below critical level. Plant Mo concentrations exhibited considerable spatial variability (CV = 38.34%) with mean of 0.22 mg kg^{-1} (range 0.15-0.44 mg kg^{-1}). Approximately 89% of sampled locations exhibited plant Mo concentrations below 0.25 mg kg^{-1}, substantially lower than sufficiency ranges for rice (0.4-1.0 mg kg^{-1}) and fruit trees (0.10-2.00 mg kg^{-1}), indicating widespread deficiency directly attributable to inadequate soil Mo availability in sandy soils.

Conclusion: Molybdenum deficiency is widespread in both soil and coconut palms across the Southern Coastal Plain, likely constraining Mo-dependent enzyme activities. Strategic interventions including adequate Mo application and soil pH management are essential to elevate Mo availability and plant uptake for improved productivity.

Keywords: Molybdenum deficiency; coconut nutrition; coastal plain; micronutrient; sandy soils.

1. INTRODUCTION

The soil ecosystem is the primary reservoir for biologically active micronutrients that sustain plant metabolism and human nutritional security (Mitchell & Burridge, 1979; Welch, 1995). Among these, Molybdenum (Mo) is a critical trace element, serving as a catalytic centre for various redox enzymes essential for the health of both plants and animals (Gustafsson & Tiberg, 2015; Williams & Silva, 2002) Plants absorb Mo primarily as the molybdate anion (MoO_4^{2-}), which is the predominant soluble form in neutral to alkaline soils (Zahedi et al., 2024; Tejada-Jiménez et al., 2013). Mo acts as a vital cofactor in the nitrogenase enzyme complex, driving biological nitrogen fixation and denitrification within the global nitrogen cycle (Burgess, 1990; Silva et al., 2023). Molybdenum is a component of the molybdenum cofactor (Moco), essential for the catalytic activity of several enzymes involved in nitrogen metabolism, sulfur assimilation, and hormone biosynthesis, the most prominent Mo-containing enzymes in plants include nitrate reductase (NR), sulfite oxidase (SO), xanthine dehydrogenase (XDH), and aldehyde oxidase (AO) (Mendel, 2011). Nitrate reductase catalyzes the reduction of nitrate to nitrite, representing a key step in nitrogen assimilation, while aldehyde oxidase catalyzes the biosynthesis of abscisic acid (ABA), a phytohormone crucial for stress responses While Mo deficiency limits crop yields and severely affects plant growth, leading to impaired nitrogen metabolism and altered leaf morphology (Silva et al., 2023; Mendel, 2011). Globally, Mo deficiency is widespread, especially in acidic (pH < 5.5) or phosphorus-poor soils (Murphy & Walsh, 1972; Hadole et al., 2019). Modern agricultural practices, characterized by intensive fertilizer use and reduced organic manure application, have further increased these micronutrient deficiencies (Velamala & Pant, 2024). Studies have demonstrated that Mo supplementation enhances nitrate reductase activity, improves nitrogen use efficiency, and increases crop productivity under various environmental conditions (Silva et al., 2023; Silva et al., 2009; Zahedi et al., 2024).

In oxygen-rich soils, Molybdenum mainly exists as the molybdate ion (MoO_4^{2-}), which largely determines its behaviour (Gustafsson & Tiberg, 2015). Adsorption mechanisms primarily control Mo transport, especially in acidic soils where it binds to positively charged iron (Fe) and aluminium (Al) oxides (Reisenauer et al., 1962; Raj et al., 2021; Jones, 1957), as well as clay minerals and organic matter. This adsorption is pH-dependent; retention is highest in acidic conditions (pH 4–5) and decreases sharply above pH 7, increasing Mo availability (Bibak & Borggaard, 1994). Structurally, Mo (VI) forms inner-sphere complexes with minerals like ferrihydrite (Arai, 2010) and complexes with natural organic matter, which can enhance bioavailability at low pH (Wichard et al., 2009). However, Mo mobility is easily disrupted by competing anions, particularly phosphate (PO_4^{3-}), which suppresses sorption and promotes leaching (Xie & MacKenzie, 1991; Sun & Selim, 2017).

This study focuses on the specific context of Agro-Ecological Unit 1 (AEU 1), where the soils are marine-derived, sandy, acidic, and deep, often limited by a highwater table. These soils are fundamentally characterized by low organic matter, poor nutrient content, and extremely low water and nutrient retention capacity necessitating substantial external inputs of lime and fertilizers for viable agricultural production (KSHIS, 2025). Furthermore, they struggle with moderate to high salinity, a problem often made worse by seawater seeping inland. From a mineral standpoint, farming here is challenging because the soil is predominantly quartz (SiO_2), which is intrinsically resistant to decomposition and offers little in the way of plant nutrients (White, 2013). The inherent fragility of this ecosystem marked by poor soil aggregation and high leaching potential means that nutrients (Adamala et al., 2019), including Mo, wash away easily (Kaiser et al., 2005, Brady and Weil, 2016). Understanding micronutrient bioavailability and developing efficient screening methods for nutrient deficiencies are critical components of such site-specific management strategies. Advanced techniques, including radiocarbon labeling approaches, have demonstrated effectiveness in rapidly assessing nutrient stress tolerance in crops under challenging soil conditions (Raj et al., 2019; Raj et al., 2020), while adaptive strategies for managing multiple nutrient limitations under climate change scenarios remain essential for sustainable agriculture (Karthu et al., 2025).

2. MATERIALS AND METHODS

The investigation focuses on Agro-Ecological Unit 1 (AEU 1), the Southern Coastal Plain, located on the southwestern edge of India in Kerala. The state features a 590 km coastline along the Arabian Sea, covering about 1.52% of the total geographical area. Based on climatic variability, landforms, and soil types, the National Bureau of Soil Survey & Land Use Planning (NBSS&LUP, 1999) has delineated the state into 23 distinct AEUs. AEU 1 represents a narrow strip of sandy lands spanning eight specific blocks: Chirayinkeezh, Pothencode, and Varkala in Thiruvananthapuram District; Chittumala, Ithikkara, and Mukathala in Kollam District; and Kanjikuzhy and Pattanakkad in Alappuzha District. Collectively, this unit covers 56,782 hectares, constituting approximately 1.46% of the state's geographical area (KSHIS, 2025). The region experiences a tropical humid monsoon climate with a mean annual temperature of 27.6°C and rainfall of 2360 mm. To ensure a representative evaluation of nutrient status across AEU 1, a systematic sampling strategy was employed involving 141 geo-referenced locations distributed across 47 representative panchayats of blocks in AEU 1. Three distinct sites were sampled within each panchayat at two specific depths: 0–15 cm (surface) and 15–30 cm (sub-surface) to assess vertical nutrient distribution. In the laboratory, available molybdenum in soil was determined using the Acid Ammonium Oxalate (Tamm's Reagent) extraction method (0.275 M ammonium oxalate and 0.1 M oxalic acid, pH 3.3) (Grigg, 1953). The extracted molybdenum was then concentrated via solvent extraction into Methyl Isobutyl Ketone (MIBK) and analyzed using Atomic Absorption Spectrophotometry (AAS) following the protocol adapted from Kim et al. (1974). For plant tissue analysis from the 141 corresponding sampling locations, dried samples (60°C) were ground, passed through 1.0 mm sieve, and subjected to di-acid digestion using HNO_3-$HClO_4$ mixture. Molybdenum in the digests was determined by AAS at 313 nm wavelength with aluminum chloride as ionization suppressor, using calibration standards of 0-10 mg L^{-1} prepared in matching acid matrix (Silva, 2009). The molybdenum concentrations in both soil (surface and subsurface layers) and plant tissues were analyzed using one-way ANOVA in RAISINS software (Hisham et al., 2025).

3. RESULTS AND DISCUSSION

Available molybdenum in surface and subsurface soils across 47 panchayats (Fig. 1) of blocks in AEU 1 Southern Coastal Plain showed considerable variation. In surface soil, Mo ranged from 0.02 mg kg^{-1} (Chirakkara) to 0.07 mg kg^{-1} (Manampoor and Thuravoor) with a mean of 0.04 mg kg^{-1}. Highest concentrations were in Manampoor (0.07 mg kg^{-1}), Thuravoor (0.07 mg kg^{-1}), Anjuthengu (0.06 mg kg^{-1}), Edava (0.06 mg kg^{-1}), and Ezhupunna (0.06 mg kg^{-1}). Lowest values were in Chirakkara (0.02 mg kg^{-1}), Aroor (0.03 mg kg^{-1}), Chemmaruthy (0.03 mg kg^{-1}), Kalluvathukkal (0.03 mg kg^{-1}), and Kanjikuzhy (0.03 mg kg^{-1}). In subsurface soil, Mo ranged from 0.02 mg kg^{-1} (Mangalapuram and Mayyanad) to 0.07 mg kg^{-1} (Perinad) with a mean of 0.04 mg kg^{-1}. Highest values were in Perinad (0.07 mg kg^{-1}), Azhoor (0.06 mg kg^{-1}), Ezhupunna (0.06 mg kg^{-1}), Kundra (0.06 mg kg^{-1}), and Nedumbana (0.06 mg kg^{-1}). Lowest values were in Mangalapuram (0.02 mg kg^{-1}), Mayyanad (0.02 mg kg^{-1}), Adichanalloor (0.03 mg kg^{-1}), Cherunniyoor (0.03 mg kg^{-1}), and East Kallada (0.03 mg kg^{-1}).

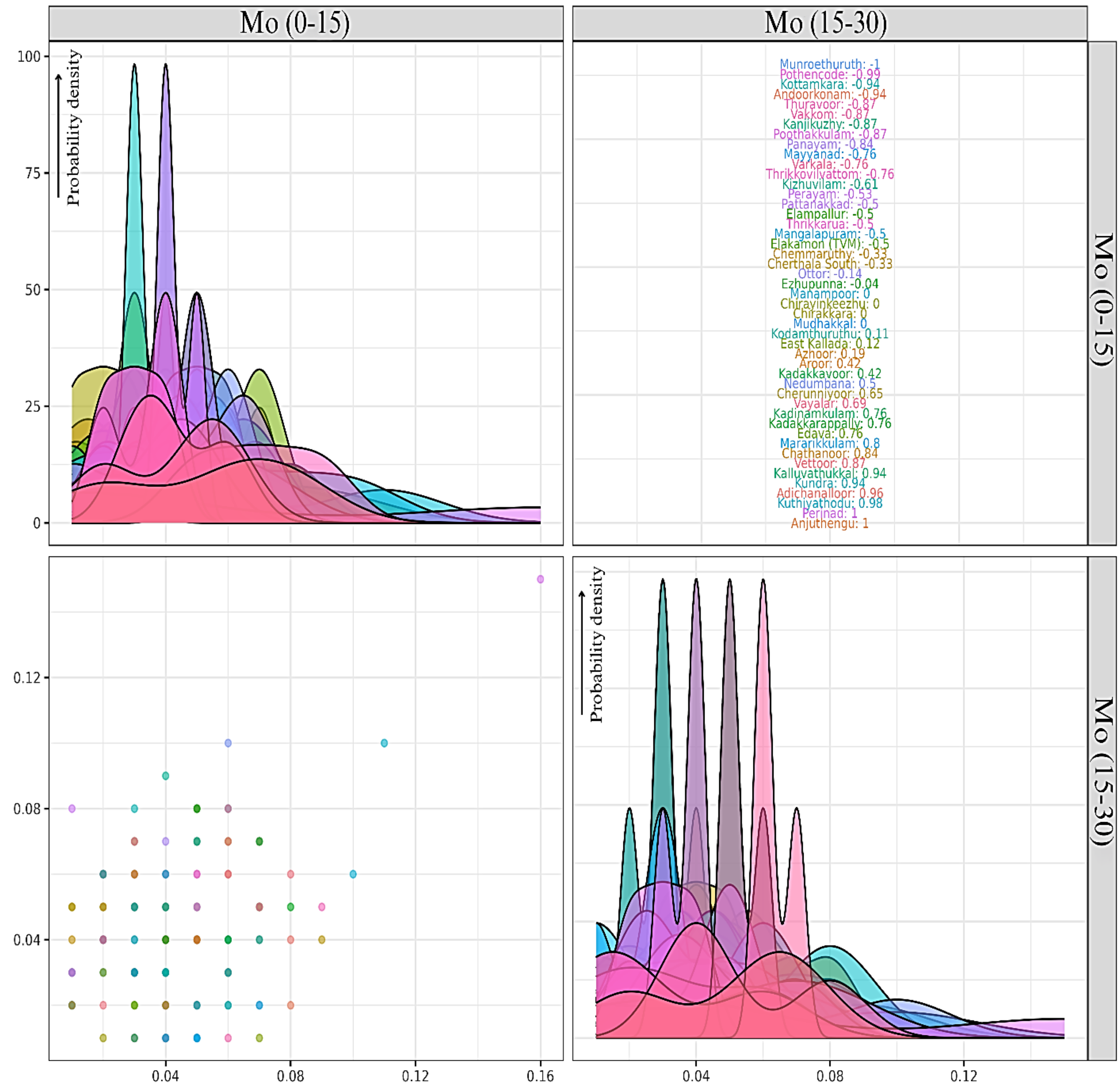

Fig. 1. Available molybdenum in surface (0–15 cm) and subsurface (15–30 cm) soils across 47 panchayats of AEU 1 (Hisham et al., 2025)

These findings indicate that the soils of this agro-ecosystem fall at the lowest end of the Mo availability spectrum when compared with other Indian regions, soils from Madurai and Sivagangai districts in Tamil Nadu recorded extractable Mo ranging from 0.028–0.661 and 0.035–0.961 mg kg^{-1}, respectively the same authors established a critical limit of 0.043 mg kg^{-1} for available Mo in green gram, below which Mo fertilization significantly improved plant response (Velmurugan et al. 2013). Soils from Agra district of Uttar pradesh contained 0.04–0.65 mg kg^{-1} of available Mo (Thakur and Kumar 2012), while those from ratnagiri and palghar districts in Maharashtra were reported to have 0.01–0.64 mg kg^{-1} (Ghatole et al. 2020; Hadole et al. 2019).Indian soils is generally low due to strong adsorption under acidic conditions and restricted solubility of MoO_4^{2-}, at low pH (Deb et al. 2002). This aligns with the present findings, as the coastal soils of AEU 1 are acidic and therefore inherently less capable of supplying available Mo.

A comprehensive assessment of plant molybdenum (Mo) concentrations across the 47 panchayat blocks constituting Agro-ecological Unit 1 (Southern Coastal Plain) revealed

Table 1. Plant molybdenum concentration in coconut across 47 panchayats of Agro-Ecological Unit 1 Southern Coastal Plain

Sl No.	Location	Mo (mg kg^{-1})	Sl No.	Location	Mo (mg kg^{-1})
1	Adichanalloor	0.16 ± 0.11	27	Manampoor	0.24 ± 0.04
2	Andoorkonam	0.20 ± 0.03	28	Mangalapuram	0.20 ± 0.02
3	Anjuthengu	0.26 ± 0.01	29	Mararikkulam	0.23 ± 0.08
4	Aroor	0.18 ± 0.01	30	Mayyanad	0.21 ± 0.03
5	Azhoor	0.29 ± 0.10	31	Mudhakkal	0.20 ± 0.04
6	Chathanoor	0.24 ± 0.03	32	Munroethuruth	0.21 ± 0.04
7	Chemmaruthy	0.21 ± 0.04	33	Nedumbana	0.25 ± 0.09
8	Cherthala South	0.21 ± 0.05	34	Ottor	0.18 ± 0.09
9	Cherunniyoor	0.19 ± 0.02	35	Panayam	0.22 ± 0.02
10	Chirakkara	0.16 ± 0.07	36	Pattanakkad	0.22 ± 0.04
11	Chirayinkeezhu	0.22 ± 0.02	37	Perayam	0.20 ± 0.02
12	East Kallada	0.19 ± 0.02	38	Perinad	0.44 ± 0.35
13	Edava	0.20 ± 0.12	39	Poothakkulam	0.18 ± 0.01
14	Elakamon	0.19 ± 0.01	40	Pothencode	0.22 ± 0.03
15	Elampallur	0.22 ± 0.04	41	Thrikkarua	0.17 ± 0.14
16	Ezhupunna	0.27 ± 0.03	42	Thrikkovilvattom	0.19 ± 0.02
17	Kadakkarappally	0.15 ± 0.10	43	Thuravoor	0.25 ± 0.10
18	Kadakkavoor	0.23 ± 0.06	44	Vakkom	0.20 ± 0.04
19	Kadinamkulam	0.20 ± 0.04	45	Varkala	0.18 ± 0.01
20	Kalluvathukkal	0.19 ± 0.00	46	Vayalar	0.21 ± 0.03
21	Kanjikuzhy	0.21 ± 0.01	47	Vettoor	0.24 ± 0.02
22	Kizhuvilam	0.32 ± 0.24	Mean		0.22
23	Kodamthuruthu	0.22 ± 0.09	CV (%)		38.34
24	Kottamkara	0.21 ± 0.02	SE(m)		0.05
25	Kundra	0.19 ± 0.02			
26	Kuthiyathodu	0.23 ± 0.08			

**Mo Concentration In mg kg^{-1}; Values = Mean ± Sd; Cv = Coefficient Of Variation; Se(M) = Standard Error*

pronounced spatial variability, with values ranging from a minimum of 0.15 mg kg^{-1} in Kadakkarappally to a maximum of 0.44 mg kg^{-1} in Perinad against an overall mean of 0.22 mg kg^{-1} (Table 1). The data indicated significant heterogeneity in Mo uptake patterns, evidenced by a coefficient of variation of 38.34%, which points to the strong influence of localized soil properties and site-specific environmental factors on nutrient availability, even as the relatively low standard error (0.05 mg kg^{-1}) confirmed the precision of the analytical means. In terms of specific distribution patterns, the highest Mo accumulation was recorded in Perinad (0.44 mg kg^{-1}), followed by descending concentrations in Kizhuvilam (0.32 mg kg^{-1}), Azhoor (0.29 mg kg^{-1}), Ezhupunna (0.27 mg kg^{-1}), and Anjuthengu (0.26 mg kg^{-1}); conversely, the most acute limitations were identified in Kadakkarappally (0.15 mg kg^{-1}), Adichanalloor (0.16 mg kg^{-1}), Chirakkara (0.16 mg kg^{-1}), and Thrikkarua (0.17 mg kg^{-1}), where tissue levels fell well below the regional average. To contextualize these findings within established plant nutrition standards, the Mo concentrations observed in these coconut samples were found to be substantially lower than the sufficiency ranges documented for a wide array of other cultivated species, including rice (0.4–1.0 mg kg^{-1}; Bergmann, 1992), sugar beet (0.2–20.0 mg kg^{-1}; Ulrich & Hills, 1973), and various horticultural crops such as apple, pear, peach, citrus, strawberry, and sunflower (Mills & Jones, 1996).

Marschner (1995) postulates a general physiological requirement of 0.2 to 2.0 mg kg^{-1} for adequate nutrition in most plant species, the widespread Mo deficiency observed in coconut tissues in this region appears to be directly attributable to the inherent pedological constraints specifically the inadequate soil Mo availability associated with the sandy soil textures that dominate the Southern Coastal Plain. The leaf molybdenum status observed in the present study warrants particular attention. Mean leaf molybdenum concentrations were below levels generally considered adequate for optimal physiological functioning. Previous investigations on coconut root (wilt) disease have consistently reported lower nutrient concentrations in affected palms compared to healthy palms, with values falling below the normal range (Mathew *et al.,* 2021; Krishnakumar *et al.,* 2015). Given the essential role of molybdenum as a cofactor of the nitrate reductase enzyme system, its deficiency can impair nitrate reduction and nitrogen assimilation even when leaf nitrogen concentrations appear sufficient (Kaiser *et al*., 2005). Consequently, the marginal molybdenum status observed in the present study may contribute to physiological nitrogen limitation and increased stress sensitivity, particularly under nutrient-imbalanced or disease-prone environments. Overall, it adds to the view that coconut productivity is governed not merely by the sufficiency of individual nutrients but by the balance and interaction among nutrients under specific agro-ecological conditions. As emphasized by Fairhurst (2003), optimum nutrient requirements vary with palm age, soil moisture regime, nutrient interactions, and environmental conditions, highlighting the importance of location-specific nutrient diagnostics and balanced nutrition strategies for sustaining coconut productivity of Kerala.

4. CONCLUSION

The study revealed widespread molybdenum deficiency in coconut palms across the southern coastal plain Agro-ecological Unit, with plant Mo concentrations falling substantially below established sufficiency standards for crops. This deficiency is directly attributable to inadequate Mo availability in the sandy soils characteristic of the region, which limits molybdenum uptake and constrains the activity of Mo-dependent enzymes including nitrate reductase, aldehyde oxidase, and xanthine dehydrogenase. Impaired enzyme activity consequently reduces nitrogen use efficiency and overall coconut productivity. Considerable spatial variability across panchayats suggests heterogeneous soil chemical properties influencing Mo bioavailability. Strategic interventions including foliar Mo application and soil pH management through liming are essential to elevate coconut Mo concentrations into adequate ranges that support optimal enzyme function. Addressing Mo deficiency through targeted supplementation represents a critical pathway for enhancing coconut production sustainability and improving farmer livelihoods in this important coastal agricultural region.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that they have no known competing financial interests or non-financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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