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Characterization of Low pH Soils of the coastal and eastern dry zones of Karnataka: Implications for soil acidity and nutrient management

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Abstract

Soil acidity is a major constraint to agricultural productivity in many parts of tropical and subtropical regions. The present study was undertaken to characterize the physico-chemical and fertility properties of low pH soils of the Coastal Zone and Eastern Dry Zone of Karnataka under contrasting agro-climatic conditions. Representative soil samples were collected from cultivated fields of selected districts at surface (0-15 cm) depth and analyzed for soil reaction, electrical conductivity, organic carbon, exchangeable acidity, base cations, available macro- and micronutrients using standard analytical procedures.

The results revealed pronounced zone-wise variation in soil properties. Soils of the Coastal Zone were moderately to strongly acidic (mean pH 5.12), with high exchangeable aluminium, low exchangeable calcium and magnesium, low available phosphorus, and excessive iron and manganese, indicating severe acidity-induced nutrient constraints under humid conditions. Despite higher organic carbon content, nutrient availability in coastal soils remained restricted due to leaching losses and metal-induced fixation. In contrast, soils of the Eastern Dry Zone were slightly acidic (mean pH 5.79) with comparatively higher base cation status and phosphorus availability but were constrained by low organic carbon and marginal availability of micronutrients such as zinc, copper, and boron.

Correlation analysis showed a strong negative relationship between soil pH and exchangeable aluminium and a positive association between soil pH and phosphorus availability, highlighting the dominant role of soil reaction in regulating nutrient dynamics. Overall, the study emphasizes that soil fertility constraints differ markedly between agro-climatic zones and require location-specific management strategies. Liming combined with phosphorus management is essential for Coastal Zone soils, whereas integrated nutrient management focusing on organic carbon enhancement and micronutrient supplementation is critical for sustaining productivity in the Eastern Dry Zone. The findings provide a scientific basis for developing zone-specific soil acidity and fertility management practices in Karnataka.

Keywords: Soil acidity, exchangeable aluminium, nutrient availability, coastal Karnataka, eastern dry zone, soil fertility characterization

1. Introduction

Soil reaction (pH) is a fundamental property governing soil chemical behaviour, nutrient availability, microbial activity, and overall crop productivity. Acidic soils, generally defined by a pH below 5.5, impose serious limitations on agricultural production due to aluminum and iron toxicity, low base saturation, fixation of phosphorus, and deficiencies of essential nutrients such as calcium, magnesium, and molybdenum (Brady and Weil, 2017; Fageria and Baligar, 2008; Rengel, 2011) [5, 8, 27]. These constraints are particularly pronounced in tropical and subtropical regions, where intense weathering and leaching processes dominate soil formation (Von Uexküll and Mutert, 1995; Kochian *et al.*, 2015) [15, 34].

Globally, acidic soils account for approximately 30-40% of the world's arable land, with major occurrences in humid tropics and subtropics (Von Uexküll and Mutert, 1995; Guo *et al.*, 2010) [10, 34]. In India, acid soils cover nearly 49 million hectares and are predominantly distributed in eastern, northeastern, southern coastal, and hilly regions characterized by high rainfall and highly weathered parent materials (Sarkar, 2002; Mandal *et al.*, 2019) [17, 28]. Continuous leaching

of base-forming cations, long-term application of acid-forming fertilizers, and organic matter mineralization have further accelerated soil acidification across these regions (Gupta *et al.*, 2017; Panda *et al.*, 2020) ^[11, 20].

In Karnataka, soil acidity is a major soil-related constraint affecting crop productivity and soil health, particularly in the Coastal Zone and parts of the Eastern Dry Zone. Karnataka exhibits diverse agro-ecological conditions ranging from humid coastal plains to semi-arid inland regions, resulting in wide spatial variability in soil properties (Sehgal *et al.*, 1995; ICAR-NBSS&LUP, 2020) ^[13, 29]. The Coastal Zone of Karnataka is characterized by a humid tropical climate, annual rainfall exceeding 3000 mm, and soils derived largely from lateritic parent material. These conditions promote intense leaching of calcium and magnesium and accumulation of exchangeable aluminum and iron, leading to strongly to extremely acidic soil reactions (Hegde and Bhat, 2014; Prakash *et al.*, 2016; Bhat *et al.*, 2015) ^[2, 12, 23].

Several studies conducted in coastal districts such as Dakshina Kannada, Udupi, and Uttara Kannada have reported low soil pH, low base saturation, high phosphorus fixation, and excess availability of iron and manganese, all of which adversely affect nutrient uptake and crop growth (Nayak *et al.*, 2017; Shivakumar *et al.*, 2018; Prasad *et al.*, 2019) ^[19, 24, 31]. Although these soils often contain moderate to high organic carbon due to dense vegetation and high biomass turnover, nutrient availability remains constrained because of acidity-induced fixation and metal toxicity (Rao *et al.*, 2016) ^[25].

The study was conducted in two contrasting agro-climatic zones of Karnataka, namely the Coastal Zone and the Eastern Dry Zone, which differ markedly in climate, parent material, and soil-forming processes. The Coastal Zone, located along the western coast of the state, is characterized by humid tropical climate and high rainfall, while the Eastern Dry Zone represents a semi-arid region with comparatively lower rainfall. The selection of these two zones enabled assessment of the influence of contrasting pedo-climatic conditions on soil acidity and nutrient dynamics.

The Eastern Dry Zone of Karnataka, despite receiving comparatively lower rainfall (600-900 mm), also exhibits occurrences of acidic soils. Prolonged cultivation, continuous nutrient removal by crops, depletion of exchangeable bases, limited organic matter inputs, and imbalanced fertilizer use have contributed to gradual soil acidification in this region (Patil *et al.*, 2016; Ramesh *et al.*, 2018; Anil Kumar *et al.*, 2020) ^[1, 21, 26]. Soils derived from granitic gneiss parent material typically possess low buffering capacity, making them particularly susceptible to pH decline under intensive cropping systems (Srinivas *et al.*, 2021; Shankar *et al.*, 2017) ^[30, 32].

Although several studies have documented soil acidity in different parts of Karnataka, most investigations have focused

on isolated locations or individual soil properties. Comprehensive characterization of low pH soils across contrasting agro-climatic zones, with emphasis on soil reaction, exchangeable acidity, base saturation, and macro- and micronutrient status, remains limited (ICAR-NBSS&LUP, 2020; Panda *et al.*, 2020) ^[13, 20]. Such characterization is essential for understanding zone-specific soil constraints and for formulating effective soil acidity amelioration strategies, including liming and integrated nutrient management.

Therefore, the present study was undertaken to characterize the low pH soils of the Coastal and Eastern Dry Zones of Karnataka with respect to their physico-chemical properties and fertility status, with the objective of supporting sustainable soil and crop management in these regions.

2. Materials and Methods

2.1 Study Area

The present investigation was carried out in two contrasting agro-climatic zones of Karnataka, namely the Coastal Zone and the Eastern Dry Zone, representing humid and semi-arid soil environments, respectively. The Coastal Zone is characterized by a humid tropical climate with mean annual rainfall exceeding 3000 mm and soils predominantly derived from lateritic parent material. In contrast, the Eastern Dry Zone experiences semi-arid climatic conditions with annual rainfall ranging from 600 to 900 mm and soils developed mainly from granitic gneiss parent material. These zones were selected due to the widespread occurrence of low pH soils and their contrasting pedo-climatic conditions (Sehgal *et al.*, 1995; ICAR-NBSS&LUP, 2020) ^[13, 29].

2.2 Soil Sampling

Representative soil sampling sites were selected from cultivated agricultural fields in both zones following a stratified random sampling approach. At each location, composite soil samples were collected from the surface (0-15 cm). The samples were air-dried under shade, gently crushed, and passed through a 2-mm sieve before laboratory analysis (Jackson, 1973) ^[14]. Analytical methods used for characterization of soil samples are tabulated in Table 1

2.3 Chemical Analysis

Soil pH was measured in a 1:2.5 soil-water suspension using a calibrated digital pH meter (Jackson, 1973) ^[14]. Electrical conductivity (EC) was determined in the same extract using a conductivity bridge and expressed as dS m⁻¹ at 25°C.

Soil organic carbon content was estimated by the Walkley and Black wet oxidation method (Walkley and Black, 1934) ^[35]. Cation exchange capacity (CEC) was determined by the neutral normal ammonium acetate (1 N NH₄OAc, pH 7.0) method, followed by steam distillation of adsorbed ammonium (Chapman, 1965) ^[7].

Table 1: Analytical methods used for characterization of soil samples

Sl. No.	Soil property	Method / Extractant	Reference
1	Soil pH	1:2.5 soil-water suspension, digital pH meter	Jackson (1973) ^[14]
2	Electrical conductivity (EC)	Conductivity meter (1:2.5 soil-water extract)	Jackson (1973) ^[14]
3	Organic carbon	Walkley and Black wet oxidation method	Walkley and Black (1934) ^[35]
4	Soil texture	International pipette method	Piper (1966) ^[22]
5	Cation exchange capacity (CEC)	Neutral normal ammonium acetate (1 N NH ₄ OAc, pH 7.0)	Chapman (1965) ^[7]
6	Exchangeable acidity (H ⁺ + Al ³⁺)	1 N KCl extraction followed by titration	McLean (1982) ^[18]
7	Available nitrogen (N)	Alkaline potassium permanganate method	Subbiah and Asija (1956) ^[33]
8	Available phosphorus (P)	Bray-I extraction method	Bray and Kurtz (1945) ^[6]
9	Available potassium (K)	Neutral normal ammonium acetate extraction; flame photometry	Jackson (1973) ^[14]
10	Available micronutrients (Fe, Mn, Zn, Cu)	DTPA extraction (0.005 M DTPA + TEA + CaCl ₂)	
11	Hot water soluble boron (B)	Hot water extraction; azomethine-H method	Berger and Truog (1939) ^[3]

2.4 Exchangeable Acidity

Exchangeable acidity ($H^+ + Al^{3+}$) was extracted using 1 N KCl and determined by titration with standard NaOH solution (McLean, 1982) ^[18]. Exchangeable aluminum was estimated separately by back titration after fluoride complexation. (Jackson, 1973) ^[14].

2.5 Available Macronutrients

Available nitrogen was estimated by the alkaline potassium permanganate method as described by Subbiah and Asija (1956) ^[33]. Available phosphorus was extracted using the Bray-I method, suitable for acidic soils, and quantified colorimetrically using a spectrophotometer (Bray and Kurtz, 1945) ^[6]. Available potassium was extracted with neutral normal ammonium acetate and determined using a flame photometer (Jackson, 1973) ^[14].

2.6 Available Micronutrients

DTPA-extractable micronutrients (Fe, Mn, Zn, and Cu) were extracted using a solution containing 0.005 M DTPA, 0.1 M triethanolamine, and 0.01 M $CaCl_2$ (pH 7.3) and analyzed using an atomic absorption spectrophotometer (Lindsay and Norvell, 1978) ^[16].

The sampling and analytical procedures adopted in the present study are based on standard and widely accepted protocols in soil science research. The use of composite sampling, coupled with established laboratory methods for physical, chemical, and fertility analyses, ensures the reliability and reproducibility of the generated data. Selection of appropriate extractants and analytical techniques for acidic soils enabled accurate assessment of soil reaction, exchangeable acidity, base saturation, and macro- and micronutrient availability. The methodological framework employed in this study provides a robust basis for comparative characterization of low pH soils across contrasting agro-climatic zones and supports meaningful interpretation of results for developing site-specific soil acidity management strategies.

3. Results and Discussion

The physico-chemical and chemical properties of soils from the Coastal and Eastern Dry Zones of Karnataka are presented in Tables 2 and 3, and their comparative trends are illustrated in Figures 1 and 2. The results reveal pronounced zone-wise differences in soil reaction, nutrient availability, and exchangeable cation composition, reflecting the influence of agro-climatic conditions, parent material, and land-use history.

3.1 Soil Reaction and Exchangeable Aluminium

Soil pH varied significantly between the two agro-climatic zones (Figure 1). Coastal Zone soils exhibited moderately to strongly acidic reaction with a mean pH of 5.12, whereas Eastern Dry Zone soils recorded comparatively higher pH values with a mean of 5.79, indicating slightly acidic conditions. The lower pH of coastal soils is attributed to intense leaching of base-forming cations under high rainfall and advanced weathering of

lateritic parent materials (Von Uexküll and Mutert, 1995; Hegde and Bhat, 2014) ^[2, 12, 34].

Exchangeable aluminium content showed an inverse relationship with soil pH (Figure 1). Coastal Zone soils recorded substantially higher exchangeable Al (mean $1.46 \text{ cmol}(p^+) \text{ kg}^{-1}$) compared to Eastern Dry Zone soils (mean $0.81 \text{ cmol}(p^+) \text{ kg}^{-1}$). Elevated aluminium levels under acidic conditions increase the risk of aluminium toxicity, which restricts root growth and impairs nutrient uptake (Fageria and Baligar, 2008; Kochian *et al.*, 2015) ^[8, 15].

3.2 Organic Carbon and Nitrogen Status

Organic carbon content differed markedly between zones (Table 2; Figure 1). Coastal Zone soils recorded higher organic carbon (mean 1.30%) owing to dense vegetation cover, higher biomass addition, and slower decomposition under humid acidic conditions. In contrast, Eastern Dry Zone soils exhibited low organic carbon content (mean 0.50%), reflecting limited organic inputs, rapid oxidation of organic matter under a semi-arid climate, and continuous cultivation (Shivakumar *et al.*, 2018; Ramesh *et al.*, 2018) ^[26, 31].

Available nitrogen followed trends similar to organic carbon, with Coastal Zone soils showing slightly higher mean values (303 kg ha^{-1}) than Eastern Dry Zone soils (293 kg ha^{-1}) (Table 2). This indicates that organic matter serves as a key reservoir of mineralizable nitrogen in both zones.

3.3 Phosphorus and Potassium Availability

Available phosphorus content was consistently low in Coastal Zone soils (mean 15.8 kg ha^{-1}) compared to Eastern Dry Zone soils (mean 33.4 kg ha^{-1}) (Table 2; Figure 2). Low phosphorus availability in coastal soils is primarily due to strong fixation by iron and aluminium oxides under acidic conditions (Bray and Kurtz, 1945; Prakash *et al.*, 2016) ^[6, 23]. The relatively higher pH of Eastern Dry Zone soils reduces fixation intensity, resulting in improved phosphorus availability.

Available potassium levels were comparable between zones, with mean values of 101 kg ha^{-1} in the Coastal Zone and 102 kg ha^{-1} in the Eastern Dry Zone (Table 2). However, leaching losses in coastal soils and continuous crop removal in Eastern Dry Zone soils influence district-wise variability.

3.4 Exchangeable Bases and Secondary Nutrients

Exchangeable calcium and magnesium were significantly lower in Coastal Zone soils (mean Ca 1.36 and Mg $0.37 \text{ cmol}(p^+) \text{ kg}^{-1}$) compared to Eastern Dry Zone soils (mean Ca 2.28 and Mg $0.44 \text{ cmol}(p^+) \text{ kg}^{-1}$) (Table 3; Figure 2). Depletion of base cations in coastal soils reflects prolonged leaching and their replacement by acidic cations, whereas higher base status in Eastern Dry Zone soils indicates better buffering capacity against soil acidity. Available sulphur content was also lower in Coastal Zone soils (mean 10.88 mg kg^{-1}) than in Eastern Dry Zone soils (mean 18.10 mg kg^{-1}) (Table 3), likely due to leaching losses under humid conditions.

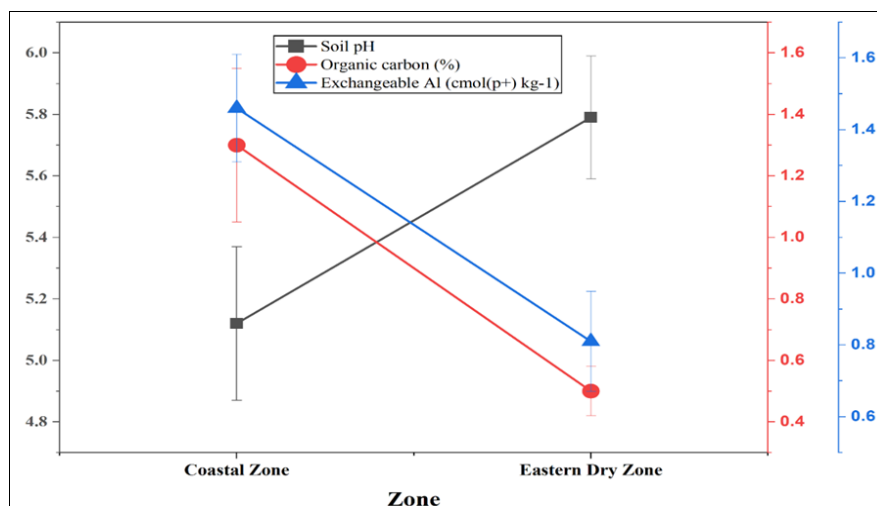


Fig 1: Comparison of a) Soil pH, b) Organic carbon content and c) Exchangeable aluminium in soils of the Coastal and Eastern Dry Zones of Karnataka

Table 2: Physico-chemical and chemical properties of the soils of coastal and eastern dry zones of Karnataka

Districts	pH	EC (dS m ⁻¹)	OC (%)	Available nitrogen (kg ha ⁻¹)	Available phosphorus (P ₂ O ₅) (kg ha ⁻¹)	Available potassium (K ₂ O) (kg ha ⁻¹)	Exchangeable Al (cmol (p+) kg ⁻¹)
Coastal zone							
Uttar Kannada	5.33 (5.02-5.45)	0.021 (0.010-0.032)	1.42 (0.75-2.42)	328 (257-429)	17.7 (10.4-23.9)	97.1 (70.2-116)	1.51 (1.31-1.63)
Udupi	4.60 (4.53-4.72)	0.030 (0.012-0.061)	1.26 (0.65-2.21)	273 (213-341)	15.0 (9.81-19.4)	129 (87.1-199)	1.60 (1.49-1.68)
Dakshina Kannada	5.44 (4.94-5.86)	0.033 (0.022-0.064)	1.21 (0.52-2.34)	308 (267-308)	14.8 (10.5-18.7)	82.8 (40.3-221)	1.28 (1.12-1.36)
Mean	5.12	0.028	1.30	303	15.8	101	1.46
Eastern dry zone							
Tumkur	5.64 (5.44-5.83)	0.152 (0.102-0.192)	0.46 (0.33-0.56)	259 (207-291)	24.2 (17.4-37.0)	94.8 (50.4-217)	0.84 (0.67-0.98)
Ramanagara	5.74 (5.66-5.84)	0.137 (0.100-0.184)	0.62 (0.57-0.69)	301 (216-398)	48.2 (32.3-64.6)	105 (61.2-214)	0.86 (0.73-1.05)
Chickaballapur	5.58 (5.23-5.84)	0.113 (0.101-0.128)	0.42 (0.34-0.46)	322 (219-453)	27.9 (21.3-36.2)	107 (98.2-127)	0.72 (0.63-0.88)
Mean	5.79	0.134	0.50	293	33.4	102	0.81

Table 3: Physico-chemical and chemical properties of the soils of coastal and eastern dry zones of Karnataka

Districts	Exchangeable Ca [cmol (p+) kg ⁻¹]	Exchangeable Mg [cmol (p+) kg ⁻¹]	Available sulphur (mg kg ⁻¹)	DTPA- Fe (mg kg ⁻¹)	DTPA- Zn (mg kg ⁻¹)	DTPA-Cu (mg kg ⁻¹)	DTPA- Mn (mg kg ⁻¹)	Hot water B (mg kg ⁻¹)
Coastal zone								
Uttar Kannada	1.50 (1.10-1.80)	0.40 (0.26-0.51)	11.00 (9.21-13.8)	14.6 (12.2-19.9)	0.48 (0.40-0.68)	1.71 (1.32-2.10)	2.48 (1.96-2.90)	0.41 (0.31-0.48)
Udupi	1.24 (0.898-1.56)	0.33 (0.24-0.48)	13.10 (9.25-18.3)	14.9 (8.40-24.1)	0.55 (0.32-0.60)	1.35 (0.640-1.98)	3.97 (3.03-6.20)	0.45 (0.18-0.68)
Dakshina Kannada	1.34 (0.891-2.36)	0.40 (0.25-0.59)	8.55 (5.79-11.8)	11.7 (8.46-16.2)	0.50 (0.36-0.68)	1.09 (0.555-1.65)	3.78 (1.46-7.64)	0.38 (0.21-0.65)
Mean	1.36	0.37	10.88	13.8	0.51	1.38	3.41	0.41
Eastern dry zone								
Tumkur	2.31 (2.05-3.02)	0.44 (0.22-0.62)	19.9 (13.7-23.7)	4.46 (3.71-5.20)	0.42 (0.31-0.59)	0.313 (0.108-0.582)	1.53 (1.11-1.94)	0.19 (0.12-0.23)
Ramanagara	2.41 (1.82-2.77)	0.43 (0.32-0.50)	19.6 (14.3-25.3)	5.16 (4.34-6.95)	0.49 (0.42-0.59)	0.901 (0.396-1.26)	2.78 (2.10-3.92)	0.15 (0.12-0.22)
Chickaballapur	2.53 (2.0-3.1)	0.45 (0.40-1.20)	14.4 (11.8-16.1)	5.07 (4.55-5.44)	0.37 (0.32-0.44)	0.634 (0.552-0.701)	1.67 (1.21-2.64)	0.38 (0.32-0.48)
Mean	2.28	0.44	18.10	4.90	0.42	0.616	1.98	0.24

3.5 Micronutrient Distribution

DTPA-extractable iron and manganese were markedly higher in Coastal Zone soils (mean Fe 13.8 mg kg⁻¹ and Mn 3.41 mg kg⁻¹) compared to Eastern Dry Zone soils (mean Fe 4.9 mg kg⁻¹ and Mn 1.98 mg kg⁻¹) (Table 3). Elevated availability of Fe and Mn under acidic conditions may induce micronutrient toxicity and antagonistic interactions with phosphorus and zinc (Lindsay and Norvell, 1978; Prasad *et al.*, 2019) [16, 24].

In contrast, Eastern Dry Zone soils exhibited marginal availability of zinc, copper, and boron. Hot water soluble boron content was notably lower in Eastern Dry Zone soils (mean 0.24 mg kg⁻¹) compared to Coastal Zone soils (mean 0.41 mg kg⁻¹)

(Table 3), indicating potential boron deficiency under intensive cropping systems.

3.6 Integrated Assessment of Soil Fertility Constraints

A combined evaluation of Tables 2 and 3 and Figures 1 and 2 indicates that Coastal Zone soils are constrained primarily by strong acidity, high exchangeable aluminium, low base cation status, phosphorus fixation, and excess iron and manganese. In contrast, soils of the Eastern Dry Zone exhibit moderate acidity with improved base status and phosphorus availability but are limited by low organic carbon and marginal micronutrient availability.

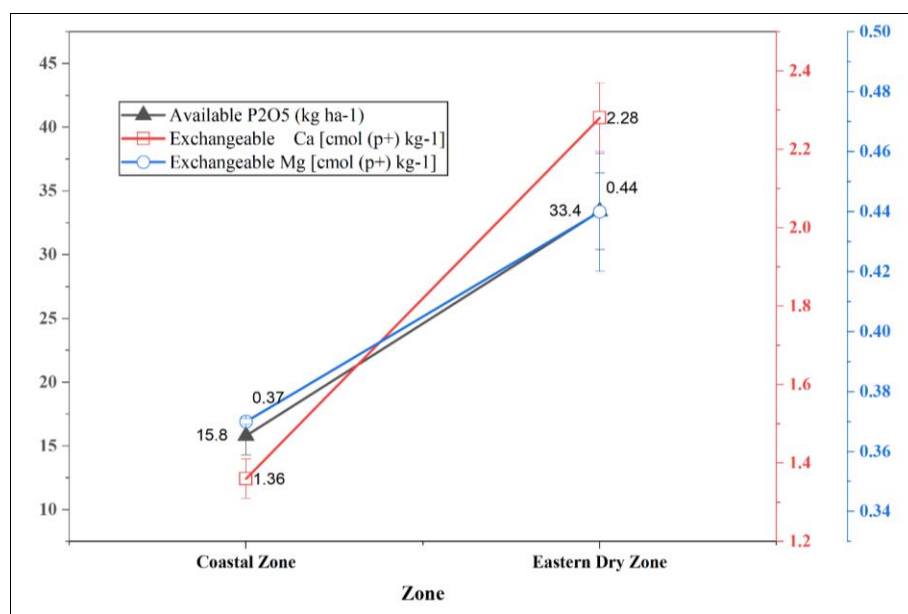


Fig 2: Comparison of a) Available phosphorus (P₂O₅), b) Exchangeable Ca and c) Exchangeable Mg in soils of the Coastal and Eastern Dry Zones of Karnataka

The results clearly demonstrate that agro-climatic conditions exert a dominant control on soil acidity and nutrient dynamics in Karnataka. Coastal Zone soils are affected mainly by acidity-induced toxicity and nutrient fixation, whereas Eastern Dry Zone soils face nutrient depletion and imbalance. These contrasting constraints underscore the necessity for zone-specific soil management strategies rather than uniform recommendations.

4. Conclusion

The study characterized low pH soils of the Coastal and Eastern Dry Zones of Karnataka and revealed distinct zone-specific soil acidity and fertility constraints. Coastal Zone soils were strongly acidic with high exchangeable aluminium, low calcium and magnesium, low phosphorus availability, and excessive iron and manganese, reflecting intense leaching and advanced weathering under humid conditions. Despite higher organic carbon content, nutrient availability in these soils remained restricted due to acidity-induced fixation and metal toxicity.

In contrast, soils of the Eastern Dry Zone were slightly acidic with comparatively higher base cation status and phosphorus availability but were constrained by low organic carbon and marginal micronutrient availability, particularly zinc, copper, and boron. The inverse relationship between soil pH and exchangeable aluminium and the positive influence of pH on phosphorus availability highlight the dominant role of soil reaction in regulating nutrient dynamics across both zones.

Overall, the findings emphasize the need for zone-specific soil management strategies, with liming and phosphorus

management being critical for Coastal Zone soils, and integrated nutrient management focusing on organic carbon enhancement and micronutrient supplementation for Eastern Dry Zone soils. This study provides a scientific basis for developing location-specific soil fertility management practices to improve soil health and sustain crop productivity in Karnataka.

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