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AR Gaikwad
Department of Soil Science and Agricultural Chemistry, College of Agriculture, Dr. Balasaheb Sawant Konkan Krishi Vidyapeeth, Dapoli, Ratnagiri, Maharashtra, India

NH Khobragade
Department of Soil Science and Agricultural Chemistry, College of Agriculture, Dr. Balasaheb Sawant Konkan Krishi Vidyapeeth, Dapoli, Ratnagiri, Maharashtra, India

MC Kasture
Department of Soil Science and Agricultural Chemistry, College of Agriculture, Dr. Balasaheb Sawant Konkan Krishi Vidyapeeth, Dapoli, Ratnagiri, Maharashtra, India

NA Meshram
Department of Soil Science and Agricultural Chemistry, College of Agriculture, Dr. Balasaheb Sawant Konkan Krishi Vidyapeeth, Dapoli, Ratnagiri, Maharashtra, India

SV Deshmukh
Department of Soil Science and Agricultural Chemistry, College of Agriculture, Dr. Balasaheb Sawant Konkan Krishi Vidyapeeth, Dapoli, Ratnagiri, Maharashtra, India

SY Rakhonde
Department of Soil Science and Agricultural Chemistry, College of Agriculture, Dr. Balasaheb Sawant Konkan Krishi Vidyapeeth, Dapoli, Ratnagiri, Maharashtra, India

SR Kamble
Department of Soil Science and Agricultural Chemistry, College of Agriculture, Dr. Balasaheb Sawant Konkan Krishi Vidyapeeth, Dapoli, Ratnagiri, Maharashtra, India

A Purohit
Department of Soil Science and Agricultural Chemistry, College of Agriculture, Dr. Balasaheb Sawant Konkan Krishi Vidyapeeth, Dapoli, Ratnagiri, Maharashtra, India

MR Wahane
1. Department of Soil Science and Agricultural Chemistry, College of Agriculture, Dr. Balasaheb Sawant Konkan Krishi Vidyapeeth, Dapoli, Ratnagiri, Maharashtra, India
2. Khar Land Research Station, Panvel, Raigad, Maharashtra, India

Corresponding Author:
AR Gaikwad
Department of Soil Science and Agricultural Chemistry, College of Agriculture, Dr. Balasaheb Sawant Konkan Krishi Vidyapeeth, Dapoli, Ratnagiri, Maharashtra, India

Seasonal variation in water soluble ions in coastal saline soils during monsoon: A case study

AR Gaikwad, NH Khobragade, MC Kasture, NA Meshram, SV Deshmukh, SY Rakhonde, SR Kamble, A Purohit and MR Wahane

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Abstract
This study explores the seasonal changes in water-soluble anions (chloride, carbonate, bicarbonate, sulphate) and cations (potassium, sodium, calcium, magnesium) in coastal saline soils under monsoon conditions across seven replicate plots over five consecutive months at Khar Land Research Station, Panvel, Dist. Raigad, Maharashtra. Ion concentrations displayed notable temporal variations, with chloride and sulphate peaking in November, suggesting ion accumulation after peak rainfall and a decrease in leaching. Correlation analysis indicated strong positive correlations between chloride and sulphate and between calcium and magnesium, reflecting common sources and biogeochemical dynamics during the monsoon. The findings emphasize the role of monsoon-driven processes such as leaching, mineral weathering, and nutrient cycling in determining soil ionic composition, which directly affects soil fertility and crop nutrition. This research provides crucial data to facilitate improved nutrient management strategies in rain-fed agriculture under variable monsoon conditions.

Keywords: Monsoon, soil ions, water soluble anions, water soluble cations

Introduction
India has coastline over nine states, two Union Territories and two groups of islands covering an area of 3.935 lakh sq. km^2 distributed within 87 districts. The Maharashtra state has 720 km of coastal length with 54 creeks. It comprises the districts of Palghar, Thane, Raigad, Ratnagiri and Sindhudurg. Significant portions of its coastal saline soils are found in the districts of Raigad (26,501 ha, 62.8%) and Thane (7129 ha, 16.9%) (Mandal *et al.*, 2023) [7]. Monsoon rainfall represents a critical hydrological phenomenon that has a profound effect on soil chemistry, particularly in tropical and subtropical farming regions where rain-fed agriculture is dominant (Brindha *et al.*, 2017) [1]. The significant precipitation events that occur during the monsoon season change the soil water content and nutrient dynamics, triggering essential processes such as leaching, ion exchange, and the dissolution or precipitation of minerals (Manikandana *et al.*, 2020) [8]. These processes, in turn, influence the availability of key nutrients for crops and the overall fertility of the soil (Subba Rao *et al.*, 2017) [15]. Water-soluble ions, including anions like chloride (Cl^-), sulphate (SO_4^{2-}), carbonate (CO_3^{2-}), bicarbonate (HCO_3^-), and cations such as potassium (K^+), sodium (Na^+), calcium (Ca^{2+}), and magnesium (Mg^{2+}), are vital for sustaining soil nutrient equilibrium and promoting plant health (Deepali *et al.*, 2015) [3]. These ions are highly mobile within soil solutions, making them susceptible to seasonal changes brought about by monsoonal rains (Tiwari *et al.*, 2024) [17]. Leaching during periods of heavy rainfall can lead to nutrient losses, which may reduce soil fertility and potentially threaten agricultural productivity (Das *et al.*, 2023) [2].

Previous research has highlighted seasonal fluctuations in soil chemical characteristics and nutrient levels, suggesting intricate interactions between hydrological occurrences and soil biogeochemistry (Kumar *et al.*, 2021) [6]. For instance, the relationship between cation exchange capacity and anion exchange capacity affects the retention or release of ions in various soil types (Smith *et al.*, 2023) [14]. Additionally, changes in rainfall intensity impact the rate of ion leaching, potentially leading to either nutrient depletion or accumulation in specific areas of agricultural fields (Jain and Singh, 2022) [5]. In spite of these findings, comprehensive monthly assessments of water-soluble ion concentrations and their interconnections during the monsoon season are limited, especially in localized agricultural settings. Such investigations are essential for understanding nutrient fluxes and formulating effective soil management practices to enhance fertilizer application and reduce nutrient losses during rainfall events driven by the monsoon (Patel *et al*., 2023) [9]. This research seeks to fill this void by examining the seasonal variations in water-soluble anions and cations across seven replicated plots over five consecutive months of the monsoon. The results are anticipated to yield crucial insights into nutrient dynamics and guide sustainable soil fertility management in rain-fed agricultural systems.

Materials and Methodology

The field study was executed across seven distinct plots at the Khar Land Research Station in Panvel, Dist. Raigad, from July 2024 to November 2024. Panvel is located in the tropical zone at a latitude of 18°59' N and a longitude of 73°10' E. The city is situated at an elevation of 5 meters above mean sea level and is 50 meters from the Arabian Sea. It has a hot and humid climate with three distinct seasons: summer (March to May), rainy (June to October), and winter (November to February). The region experiences considerable rainfall, exceeding 3800 mm annually. Weather parameters were recorded at the Meteorological Observatory at Khar Land Research Station in Panvel. Soil samples were collected from seven replicate plots in an agricultural area affected by monsoon rainfall. Sampling was conducted monthly during the monsoon months from July to November, capturing temporal variations in soil chemistry due to seasonal rainfall. At each plot, composite soil samples were taken from the top 15 cm layer using a standard soil auger. The sampling adhered to a randomized design to account for spatial variability. The samples were air-dried, sieved to less than 2 mm, and stored in polyethylene bags for laboratory chemical analysis. Water-soluble ions were extracted by shaking 10 grams of soil with 50 mL of deionized water, followed by filtration. The concentrations of chloride (Cl^-), carbonate (CO_3^{2-}), bicarbonate (HCO_3^-), sulphate (SO_4^{2-}), potassium (K^+), sodium (Na^+), calcium (Ca^{2+}), and magnesium (Mg^{2+}) were quantified using established standard methods.

Data Analysis

Descriptive statistics (mean, standard deviation, coefficient of variation) were calculated to summarize ion concentration data. Pearson correlation coefficients were employed to examine interrelationships among ions. Significance was tested at the 0.05 alpha level. This methodological approach enables comprehensive assessment of monsoon-induced shifts in soil ionic composition, crucial for managing nutrient leaching and optimizing fertilizer regimes in monsoonal agroecosystems. Soil samples were collected monthly from seven replicate plots over the monsoon months-July, August, September, October, and November. Key ions measured included water-soluble concentrations of chloride (Cl^-), carbonate (CO_3^{2-}), bicarbonate (HCO_3^-), sulphate (SO_4^{2-}), potassium (K^+), sodium (Na^+), calcium (Ca^{2+}), and magnesium (Mg^{2+}). Standard soil extraction and colorimetric/ion selective electrode methods were employed following established protocols. Data analysis included mean, standard deviation, coefficient of variation calculations, and correlation analysis to establish ion inter-relationships.

Results and Discussion

The analysis of water-soluble ions across the monsoon season in the study area reveals notable variations in concentrations and significant correlations among different ions (Table 1 and Table 2). The concentrations of water-soluble chloride (Cl^-), carbonate (CO_3^{2-}), bicarbonate (HCO_3^-), sulphate (SO_4^{2-}), potassium (K^+), sodium (Na^+), calcium (Ca^{2+}), and magnesium (Mg^{2+}) varied monthly across the seven plots, with some ions showing distinct seasonal patterns. Across all plots and months, water-soluble Cl^- ranged from 8.71 to 66.8 me L^{-1}, water-soluble CO_3^{2-} from 0.30 to 1.23 8 me L^{-1}, water-soluble HCO_3^{2-} from 1.6 to 5.33 me L^{-1}, water-soluble SO_4^{2-} from 9.60 to 88.53 me L^{-1}, water-soluble K^+ from 0.14 to 0.80 me L^{-1}, water-soluble Na^+ from 2.43 to 9.60 me L^{-1}, water-soluble Ca^{2+} from 0.79 to 6.40 me L^{-1}, and water-soluble Mg^{2+} from 1.19 to 10.79 me L^{-1}. Means and variance are documented in Table 1. Seasonal patterns were evident, with general increases for most ion concentrations in November following earlier declines and fluctuation during peak monsoon months. The observed seasonal variation in water soluble ions aligns with monsoonal rainfall dynamics affecting soil nutrient cycling and leaching (Kumar *et al*., 2021) [6]. The build-up of chloride, sulphate, and sodium was observed in November.

Table 1: Water soluble anions and cations in study area

Months	Plot No	WS Cl^-	WS CO_3^{2-}	WS HCO_3^-	WS SO_4^{2-}	WS K^+	WS Na^+	WS Ca^{2+}	WS Mg^{2+}
		-------------me L^{-1}-------------------				-------------me L^{-1}---------------			
July	1	25.8	0.62	2.93	18.25	0.30	4.95	2.4	3.2
August	1	18.6	0.62	2.40	14.18	0.59	5.60	1.8	3.0
September	1	12.3	0.92	2.40	12.64	0.31	5.64	1.0	1.8
October	1	19.5	0.92	3.73	24.11	0.23	7.14	1.6	2.8
November	1	38.6	0.31	2.13	62.15	0.57	9.60	1.4	2.6
July	2	39.6	0.62	2.13	63.56	0.81	4.83	2.0	3.2
August	2	26.3	0.62	1.60	47.65	0.41	5.73	1.0	2.2
September	2	21.7	1.23	1.60	36.18	0.46	5.07	0.8	2.0
October	2	28.9	0.62	3.47	56.00	0.52	6.21	0.8	1.2
November	2	52.3	0.31	2.13	88.54	0.68	6.32	1.2	2.0
July	3	24.8	0.62	2.67	31.38	0.42	3.61	1.4	2.2
August	3	20.8	0.31	2.40	24.82	0.32	2.43	2.8	4.8
September	3	17.6	0.62	4.27	17.92	0.21	3.11	1.2	2.4
October	3	22.7	0.62	4.80	31.00	0.29	4.28	1.0	2.2
November	3	43.6	0.62	2.40	66.31	0.31	6.03	1.4	2.2
July	4	38.4	0.31	2.13	56.50	0.44	4.12	1.0	2.2
August	4	31.2	0.31	1.87	35.95	0.31	4.28	1.0	1.4
September	4	24.3	0.31	1.87	26.78	0.36	5.15	1.4	2.2

October	4	36.8	0.31	2.40	37.65	0.40	5.77	1.0	1.8
November	4	66.8	0.31	2.13	77.69	0.64	7.08	2.4	3.6
July	5	35.5	0.62	2.67	32.25	0.45	6.56	1.2	2.4
August	5	26.9	0.62	2.40	27.88	0.33	5.07	1.6	2.0
September	5	20.1	0.62	3.73	22.37	0.35	6.60	6.4	10.8
October	5	28.4	0.62	4.27	36.79	0.33	8.16	1.2	2.4
November	5	55.7	0.31	1.87	68.74	0.38	7.14	2.8	4.8
July	6	19.8	0.62	3.20	24.44	0.17	3.57	2.4	4.0
August	6	13.5	0.92	2.13	16.59	0.26	2.77	1.4	3.0
September	6	10.2	1.23	1.87	11.18	0.20	3.89	1.0	1.8
October	6	15.8	0.62	3.73	35.33	0.17	4.17	0.8	1.6
November	6	37.8	0.62	2.40	74.98	0.14	4.29	1.6	2.4
July	7	18.3	0.92	2.93	13.31	0.20	2.70	2.0	3.6
August	7	11.7	0.92	1.87	11.06	0.29	2.83	0.8	1.6
September	7	8.71	0.92	4.27	9.61	0.18	3.85	0.8	1.6
October	7	12.6	0.92	5.33	9.83	0.32	5.02	0.8	2.0
November	7	25.9	0.92	4.80	29.66	0.15	5.49	1.4	2.6
Counts		35	35	35	35	35	35	35	35
Minimum		8.71	0.30	1.6	9.60	0.14	2.43	0.79	1.19
Maximum		66.8	1.23	5.33	88.53	0.80	9.60	6.40	10.79
Mean		27.18	0.64	2.82	35.80	0.35	5.11	1.56	2.72
SD		2.26	0.04	0.17	3.71	0.02	0.27	0.17	0.27
CV		4.61	0.09	0.34	7.54	0.05	0.55	0.35	0.56

Water-soluble chloride (Cl^-), carbonate (CO_3^{2-}), bicarbonate (HCO_3^-), sulphate (SO_4^{2-}), potassium (K^+), sodium (Na^+), calcium (Ca^{2+}), and magnesium (Mg^{2+}), CV-coefficient of variance, SD-Standard Deviation

corresponds to reduced leaching intensity as rainfall declines, permitting ion accumulation (Jain and Singh, 2022) [5]. Early and peak monsoon months exhibited lower ion concentrations, likely due to intensive leaching and dilution effects during heavy rains. Chloride concentrations ranged broadly from 8.7 to 88.5 me L^{-1}, with peak values generally observed in November. This trend correlates with decreased precipitation and increased evapotranspiration during late autumn, resulting in salt accumulation due to capillary rise and surface evaporation in the unsaturated zone. Elevated chloride is a primary marker of seawater intrusion and saline water table influence in coastal zones (Rengasamy, 2006) [11]. Sulphate levels exhibited significant fluctuations, with some plots (notably plot 2) showing extreme values (~88.5 me L^{-1} in November). Sulphate in coastal soils often originates from marine aerosols and gypsum dissolution; its elevated presence alongside chloride suggests multiphase salt accumulation involving both sodium chloride and calcium/magnesium sulphates, affecting soil chemistry and potentially leading to complex salt crust formations (Qadir *et al.*, 2007) [10]. Elevated SO_4^{2-} concentrations, especially in plots 2 and 4, indicate gypsum ($CaSO_4 \cdot 2H_2O$) presence or marine sulphate salt inputs. Sulphate can affect soil alkalinity and interact with calcium to form secondary minerals, influencing long-term soil salinity dynamics (Qadir *et al.*, 2007) [10]. Seasonal peaks in sulphate may also be linked to episodic saline water table fluctuations. High correlations between chloride and sulphate mirror findings in similar tropical soil studies, reflecting their mobilization from atmospheric deposition and mineral weathering processes enhanced during monsoon (Brindha *et al.*, 2017; Subba Rao *et al.*, 2017) [1, 15]. The inverse relation between carbonate and chloride reflects how acid-base reactions and soil pH can modulate ion behaviour under fluctuating moisture regimes (Manikandana *et al.*, 2020) [8].

Carbonate ion concentrations remained low (<1 me L^{-1}), while bicarbonate showed moderate but stable presence across months (1.6-5.3 me L^{-1}). This pattern suggests that carbonate equilibria are controlled by soil pH buffering systems and limited alkaline soil conditions typical of saline soils with prevailing marine influence. The bicarbonate dynamics likely reflect CO_2 dissolution and biological activity influencing carbonate equilibrium. Carbonate concentrations remained low, consistent with the typical near-neutral to mildly alkaline pH of coastal saline soils buffered by marine-derived salts and organic matter decomposition. Bicarbonate levels (1.6-5.3 me L^{-1}) suggest ongoing carbonate equilibria influenced by soil respiration and root activity. The relative stability of bicarbonate indicates buffering capacity against pH swings despite salt accumulation, crucial for maintaining microbial activity and nutrient availability.

Sodium ions were the dominant cations, ranging from approximately 2.7 to 9.6 me L^{-1} and showing a clear increasing trend toward November, in synchrony with chloride ions. The preponderance of Na^+ ions relative to Ca^{2+} and Mg^{2+} underlines the sodic nature of these coastal soils. High exchangeable sodium percentage (ESP) negatively affects soil structure by promoting clay particle dispersion, leading to reduced infiltration and aeration (Sumner, 1993) [16]. This is exacerbated during dry periods when salts concentrate near the surface. This sodium dominance confirms the sodic nature of the soils, which arises from seawater intrusion and subsequent concentration by evapotranspiration. High sodium activity in soil solution is a critical factor promoting soil dispersion, reducing permeability and aeration, thus negatively impacting soil structure and crop growth (Sumner, 1993) [16].

Potassium levels remained low (<1 me L^{-1}) and relatively stable, indicating minimal contribution to overall salinity but reflecting essential nutrient cycling. The low potassium compared to sodium aligns with the marine salt signature, where potassium is generally less abundant (Rengasamy and Olsson, 1991) [12]. Potassium and sodium variability is pivotal as these nutrients directly affect plant growth and soil structure. Their positive correlation with sulphate suggests coupled leaching and uptake cycles moderated by monsoonal influence (Deepali *et al.*, 2015) [3]. The strong calcium-magnesium correlation echoes their geochemical affinity, often co-occurring in soil mineral dissolution and uptake processes (Smith *et al.*, 2023) [14]. Overall, the study highlights that water soluble ion dynamics during monsoon are governed by the interplay of rainfall-driven leaching, atmospheric inputs, and soil mineral interactions. Understanding these variations is essential for devising optimized nutrient management strategies to mitigate leaching losses and sustain crop productivity under monsoonal climatic conditions (Patel *et al*., 2023) [9]. The mean concentration of water-soluble chloride (WS Cl^-) ranged from 8.71 to 66.8 me L^{-1}, with the highest values recorded in November across most plots, indicating significant accumulation during late monsoon (Table 1). The minimum concentration was observed in September, suggesting leaching driven by intense rainfall. Water-soluble Sulphate (WS SO_4^{2-}) showed high variability, with the highest average in November (mean 35.80 me L^{-1}), correlating with increased sulphate inputs from atmospheric deposition or soil mineral weathering during the monsoon. Cations such as water-soluble sodium (WS Na^+) and water-soluble potassium (WS K^+) followed similar trends, with sodium averaging 5.11 me $L^{-1}$and potassium 0.35 me L^{-1}, reflecting their mobility and exchange dynamics in soil solution under rainfall influence.

Divalent cations showed moderate but variable concentrations. Notably, a significant magnesium spike in plot 5 during September (10.8 me L^{-1}) suggests localized mineral weathering or salt precipitation events, potentially from magnesium sulphate salts such as epsomite. Calcium levels were relatively lower but slightly elevated in later months, possibly due to gypsum dissolution under fluctuating moisture regimes. The presence of these divalent cations is crucial in modulating sodicity by displacing sodium ions on exchange sites and promoting soil flocculation (Shainberg *et al*., 1989) [13]. Although water-soluble Ca^{2+} and Mg^{2+} concentrations are relatively lower, their presence is critical for mitigating sodicity. Calcium acts to flocculate soil particles, improving soil aggregation and permeability (Shainberg *et al*., 1989) [13]. Plot 5's anomalously high magnesium in September (10.8 me L^{-1}) may reflect localized dissolution of magnesium-bearing minerals such as dolomite or epsomite, indicating heterogeneous soil mineralogy and the influence of salt precipitation/dissolution cycles in saline environments.

Inter-Relationships between water-soluble ions

Water-soluble chloride (Cl^-)

The study revealed that chloride had a positive and significant relationship with water-soluble sulphate (0.90 **), water-soluble K^+ (0.58 **) and water-soluble Na^+ (0.53 **). Additionally, there is a positive but non-significant correlation with water-soluble Ca^{2+} and water-soluble Mg^{2+} possibly due to their differing behaviours under varying moisture conditions. The water-soluble Cl^- exhibit significant and negative correlation with water-soluble carbonate (-0.67 **) and water-soluble bicarbonate (-0.36 *).

Water-soluble carbonate (HCO_3^{2-})

For the water-soluble carbonate genotypic correlation was positive and non-significant for water-soluble bicarbonate. In contrast, the water-soluble CO_3^{2-} exhibit significant and negative correlation with water-soluble chloride (-0.67 **), water-soluble sulphate (-0.57 **) and water-soluble K^+ (-0.41 *). Meanwhile, there is a negative but non-significant correlation for water-soluble Na^+, water-soluble Ca^{2+} and water-soluble Mg^{2+}.

Water-soluble bicarbonate (HCO_3-)

The water-soluble bicarbonate genotypic correlation was positive and non-significant for water-soluble carbonate, water-soluble Mg^{2+} and Ca^{2+}. In contrast, the water-soluble CO_3^{2-} exhibit significant and negative correlation with water-soluble K^+ (-0.41 *), water-soluble chloride (-0.36 *) and water-soluble sulphate (-0.35 *). Moreover, a negative correlation was observed with water-soluble Na^+, although the statistical significance was not observed.

Water-soluble sulphate (SO_4^{2-})

The study revealed that trait water-soluble sulphate had a positive and significant relationship with water-soluble chloride (0.90 **), water-soluble K^+ (0.55 **) and water-soluble Na^+ (0.47 **). Additionally, there is a positive but non-significant correlation with water-soluble Ca^{2+}. The water-soluble SO_4^{2-} exhibit significant and negative correlation with water-soluble carbonate (-0.57 **) and water-soluble bicarbonate (-0.35 *). Meanwhile there is a negative but non-significant correlation for water-soluble Mg^{2+}.

Water-soluble potassium (K^+)

The present investigation unveiled that water-soluble K^+ had a positive and significant association with water-soluble chloride (0.58 **), water-soluble sulphate (0.55 **) and water-soluble Na^+ (0.45 **). Potassium showed moderate positive correlations with sodium and calcium although the latter was not statistically significant, implying some linked behaviour among alkali and alkaline earth metals during monsoon events. Notably, magnesium exhibited

Table 2: Inter-relation between water soluble anions and cations

Variables	WS Cl^-	WS CO_3^{2-}	WS HCO_3^{2-}	WS SO_4^{2-}	WS K^+	WS Na^+	WS Ca^{2+}	WS Mg^{2+}
WS Cl^-	1.0 **							
WS CO_3^{2-}	-0.67 **	1.0 **						
WS HCO_3^-	-0.36 *	0.24 NS	1.0 **					
WS SO_4^{2-}	0.90 **	-0.57 **	-0.35 *	1.0 **				
WS K^+	0.58 **	-0.41 *	-0.41 *	0.55 **	1.0 **			
WS Na^+	0.53 **	-0.29 NS	-0.00 NS	0.47 **	0.45 **	1.0 **		
WS Ca^{2+}	0.14 NS	-0.21 NS	0.02 NS	0.01 NS	0.06 NS	0.14 NS	1.0 **	
WS Mg^{2+}	0.07 NS	-0.15 NS	0.07 NS	-0.04NS	0.03 NS	0.12 NS	0.98 **	1.0 **

**-significant difference @ 0.1%, *-significant difference @ 0.5%, Water-soluble chloride (Cl^-), carbonate (CO_3^{2-}), bicarbonate (HCO_3-), sulphate (SO_4^{2-}), potassium (K^+), sodium (Na^+), calcium (Ca^{2+}), and magnesium (Mg^{2+}), CV-coefficient of variance, SD-Standard Deviation

strong positive correlations with sodium and calcium, suggesting linked mobility in the soil solution during the reactive monsoon period. Furthermore, a positive yet statistically non-significant correlation was observed with water-soluble Ca^{2+} and water-soluble Mg^{2+}. In contrast, the water-soluble K^+ exhibit significant and negative correlation with water-soluble carbonate (-0.41 *) and water-soluble bicarbonate (-0.41 *).

Water-soluble sodium (Na^{+})

The water-soluble chloride (0.53 **), water-soluble sulphate (0.47 **) and water-soluble K^{+} (0.45 **) showed a positive and significant association with water-soluble Na. Additionally, a positive correlation with water-soluble Ca^{2+} and Mg^{2+} was noted, albeit without statistical significance. water-soluble chloride showed non-significant and negative association with water-soluble carbonate and water-soluble bicarbonate.

Water-soluble calcium (Ca^{2+})

The study revealed that water-soluble Ca^{2+} had a positive and significant relationship with water-soluble Mg^{2+} (0.98 **). Additionally, there is a positive but non-significant correlation with water-soluble Na^{+}, water-soluble chloride, water-soluble K^{+}, water-soluble bicarbonate and water-soluble sulphate. water-soluble Ca^{2+} showed non-significant and negative association with water-soluble carbonate.

Water-soluble magnesium (Mg^{2+})

The present investigation unveiled that water-soluble Mg^{2+} had a positive and significant association with water-soluble Ca^{2+} (0.98 **). Furthermore, a positive yet statistically non-significant correlation was observed with water-soluble Na^{+}, water-soluble bicarbonate, water-soluble chloride and water-soluble K^{+}. water-soluble Mg^{2+} showed non-significant and negative association with water-soluble carbonate and water-soluble sulphate.

Variability and Implications

The coefficients of variation (CV) for most ions were below 10%, indicating relatively stable concentrations, while sulphate showed higher variability (CV ≈ 7.54%), emphasizing the dynamic nature of sulphur cycling during monsoon. These results confirm that monsoon-driven processes such as leaching and mineral weathering substantially influence soil ionic composition, impacting nutrient availability for crops and overall soil health (Kumar *et al*., 2021; Jain and Singh, 2022) [6, 5]. The mean chloride concentration ranged from 8.71 me L^{-1} in September to a peak of 66.8 me L^{-1} in November, suggesting accumulation toward the end of the monsoon. Sulphate also peaked in November at 88.53 me L^{-1}. Carbonate and bicarbonate were relatively stable, while potassium and sodium fluctuated moderately. Calcium and magnesium exhibited lower and less variable concentrations (Table 1). Coefficients of variation were generally low (<10%), except for sulphate (7.54%), indicating significant seasonal fluctuations primarily for sulphur species. Correlation analysis (Table 2) revealed strong positive correlations between chloride and sulphate ($r = 0.90$**), potassium and sulphate ($r = 0.55$*), and sodium and sulphate ($r = 0.47$*), indicating common sources or mobilization pathways. Negative correlations between chloride and carbonate ($r = -0.67$**) and potassium and carbonate ($r = -0.41$*), suggesting competitive processes or differential solubility. Magnesium correlated strongly with calcium ($r = 0.98$**), consistent with similar biogeochemical roles.

Conclusion

Seasonal monitoring of water-soluble ions reveals substantial variability and distinct inter-ionic relationships during the monsoon. This information is critical for optimizing fertilizer regimes, preventing nutrient loss, and supporting sustainable soil management in highly dynamic, rain-fed systems.

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