International Journal of Plant & Soil Science

Volume 38, Issue 10, Page 352-361, 2026; Article no.IJPSS.167046
ISSN: 2320-7035

Contrasting Temporal Dynamics of Iron and Aluminium under Prolonged Submergence of an Acidic Paddy Soil in Lower Kuttanad, Kerala, India

B. Anusha [a++], Biju Joseph [b#*], B. Rani [c†], Thomas George [d‡], Naveen Leno [a^] and Pratheesh P. Gopinath [e##]

[a] Department of Soil Science and Agricultural Chemistry, College of Agriculture, Vellayani, 695522, India.
[b] FSRS, Sadanandapuram, 691531, India.
[c] RARS, Vellayani, 695522, India.
[d] College of Agriculture, Vellayani,695522, India.
[e] Department of Agricultural Statistics, College of Agriculture, Vellayani,695522, India.

Authors' contributions

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

Article Information

DOI: https://doi.org/10.9734/ijpss/2026/v38i106353

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://pr.sdiarticle5.com/review-history/167046

Original Research Article

Received: 27/07/2026
Accepted: 24/09/2026
Published: 28/09/2026

Abstract

Submergence induces major changes in the chemical environment of paddy soils and can alter the mobility of redox- and pH-sensitive elements. The present study characterised the temporal dynamics of soil acidity and iron (Fe) and aluminium (Al) fractions during 90 days of continuous submergence in an acidic paddy soil of Lower Kuttanad, Kerala, India. A 40 m² field area was maintained under continuous submergence and soil samples were collected from 0–15 and 15–30 cm depths at 0, 15, 30, 45, 60, 75 and 90 days after submergence, together with concurrent floodwater samples. Soil pH, electrical conductivity, potential acidity, cation exchange capacity, HCl-extractable Fe and Al, water-soluble Fe and Al, and total Fe and Al were determined, while

---

[++] Ph. D. Scholar; [#] Professor; [†] Associate Director of Research; [‡] Dean of Faculty; [^] Assistant Professor; [##] Assistant professor and Head;
**Corresponding author: E-mail: biju.joseph@kau.in;*

Cite as: *Anusha, B., Joseph, B., Rani, B., George, T., Leno, N., & Gopinath, P. P. (2026). Contrasting Temporal Dynamics of Iron and Aluminium under Prolonged Submergence of an Acidic Paddy Soil in Lower Kuttanad, Kerala, India. International Journal of Plant & Soil Science, 38(10), 352–361. https://doi.org/10.9734/ijpss/2026/v38i106353*

floodwater pH, EC, total Fe and total Al were analysed. Soil pH increased during the initial and middle stages of submergence, whereas potential acidity declined. Reactive Fe fractions increased, with HCl-extractable Fe reaching 733.00 and 883.50 mg kg^{-1} at 75 days in the 0–15 and 15–30 cm layers, respectively. In contrast, HCl-extractable and water-soluble Al declined progressively, while total Fe and Al showed comparatively limited temporal variation. Floodwater Fe increased from 11.43 to 15.30 mg L^{-1} by 75 days, whereas floodwater Al declined from 5.56 to 0.43 mg L^{-1} by 90 days. The contrasting Fe and Al responses indicate that partial alleviation of soil acidity under prolonged submergence was accompanied by reduced Al mobility but enhanced mobilisation of reactive Fe. The observations provide a temporal baseline for understanding Fe–Al partitioning in submerged acidic soils of Lower Kuttanad and for designing replicated studies on the timing and management of amelioration.

Keywords: Acidic soil; aluminium; iron; Lower Kuttanad; rice soil; submergence; soil acidity; floodwater.

1. Introduction

Submergence is a defining feature of lowland rice production and causes progressive changes in the chemical environment of soil. Following inundation, oxygen is consumed and the soil develops conditions favouring the reduction of oxidised mineral phases. These changes modify proton balance, nutrient transformations and the solubility and mobility of redox-sensitive elements. The magnitude of these responses depends on soil properties, organic matter, duration of flooding and mineral composition (Patrick & Reddy, 1978; Ponnamperuma, 1972; Sahrawat, 2004). Recent experimental work has shown that waterlogging can establish reducing conditions accompanied by reductive Fe dissolution (Kronberg et al., 2024). Field observations in flooded rice paddy soil have also documented redox-driven transformations of Fe oxyhydroxides under inundation (Schulz et al., 2024).

In acidic soils, the response to submergence is particularly important because Fe and Al are controlled by different but interacting processes. Reduction of Fe(III)-bearing phases can increase the proportion of Fe in more soluble Fe(II) forms, whereas Al solubility is strongly dependent on soil reaction and generally decreases as pH rises through hydrolysis and precipitation processes (Kochian *et al*., 2015; Sahrawat, 2004). Consequently, an increase in soil pH during flooding may reduce Al mobility while not necessarily reducing Fe mobilisation. Studies of acidic agricultural soils further indicate that amelioration of soil acidity can alter extractable or exchangeable Al pools under management interventions (Hasana, 2026; Muindi, 2020).

The Kuttanad wetland system of Kerala contains several acid sulphate and strongly acidic paddy soils where acidity and associated Fe and Al constraints are important limitations to rice production. Earlier investigations have documented severe acidity and Fe–Al-related constraints in Kuttanad, while recent studies have continued to highlight the importance of acidity, Fe behaviour and soil–water interactions in these hydromorphic rice systems (Amrutha *et al*., 2023; Ebimol *et al*., 2017; Kamarudheen *et al*., 2025; Rohith *et al*., 2024; Sumayya *et al*., 2025).

Although the general chemistry of submerged soils is well established, field-based information describing the concurrent temporal behaviour of operationally extractable and water-soluble Fe and Al fractions, together with floodwater chemistry, during prolonged submergence of acidic paddy soils in Lower Kuttanad remains limited. Examining reactive and total pools together with floodwater chemistry can distinguish changes in elemental mobility and partitioning from changes in the total soil Fe pool. The present study therefore characterised temporal changes in soil pH, EC, potential acidity and CEC; HCl-extractable, water-soluble and total Fe and Al; and floodwater pH, EC, Fe and Al during 90 days of continuous submergence in an acidic paddy soil of Lower Kuttanad.

2. Materials and Methods

2.1 Study Site and Sampling

The study was conducted at the Regional Agricultural Research Station (RARS), Moncompu, Kerala, India, during the puncha season of 2022–23. A 40 m^2 field area was enclosed with approximately 15-cm-high bunds and maintained under continuous submergence. Soil and floodwater samples were collected at 0, 15, 30, 45, 60, 75 and 90 days after submergence. Soil samples were collected from 0–15 and 15–30 cm depths and composited separately for each sampling date and depth. Floodwater samples were collected concurrently.

2.2 Soil and Floodwater Analysis

Soil pH and electrical conductivity (EC) were determined in a 1:2.5 soil-to-water suspension following Jackson (1973). Potential acidity was estimated using the $BaCl_2$–TEA buffer method of Page *et al*. (1982), while cation exchange capacity (CEC) was determined by the ammonium acetate saturation method (Rhoades, 1982). Total Fe and Al were determined following acid digestion with HNO_3–H_2SO_4–HF–$HClO_4$, followed by estimation using atomic absorption spectrophotometry (AAS) (Loeppert & Inskeep, 1996). Water-soluble Fe was extracted with distilled water and estimated by AAS (Miller *et al.,* 1986). HCl-extractable Fe and Al were determined using 0.1 N HCl extraction followed by AAS (Sims & Johnson, 1991). Water-soluble Al was determined by aqueous extraction and AAS following Drabek *et al*. (2005).

Floodwater pH and EC were measured potentiometrically and by conductometry, respectively. Total Fe and Al in floodwater were determined using AAS following Osiname *et al*. (1973), and concentrations were expressed as mg L^{-1}.

2.3 Data Analysis

Temporal variation in soil and floodwater properties was assessed using observations recorded at the seven sampling dates. Mean values and standard deviations were calculated. Pearson correlation analysis was performed separately for the two soil depths to

examine associations among soil pH, EC, potential acidity, CEC and Fe and Al fractions. Correlations among floodwater pH, EC, total Fe and total Al were also determined. As the study involved a single monitored field and composite samples, the observations were interpreted as temporal changes within the field rather than replicated treatment effects.

3. Results and Discussion

3.1 Changes in Soil Acidity and CEC during Submergence

The soil was strongly acidic at the onset of submergence, with pH values of 4.45 and 4.33 in the 0–15 and 15–30 cm layers, respectively. Soil pH increased through the initial and middle stages, reaching 5.32 and 5.17 at 75 days before declining slightly at 90 days. The mean pH was 5.07 ± 0.34 in the surface layer and 4.89 ± 0.29 in the subsurface layer (Table 1). The response therefore represented partial alleviation of acidity rather than neutralisation.

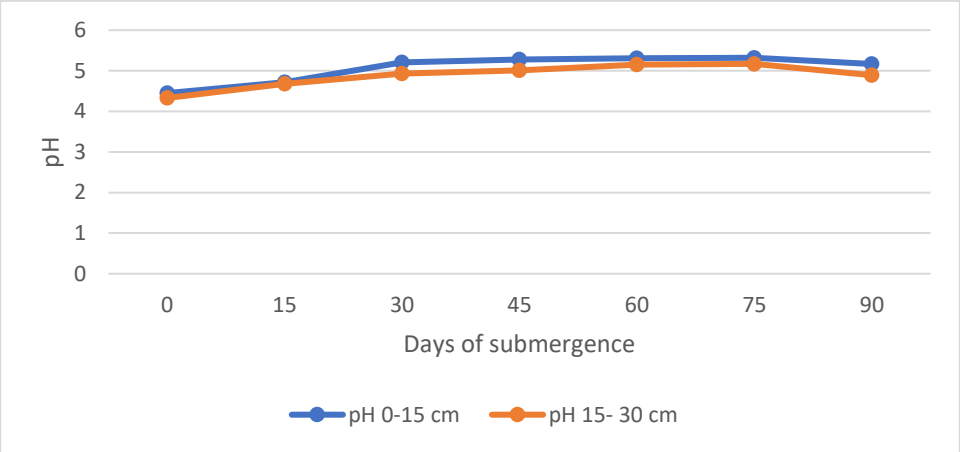

Fig. 1. Temporal variation in soil pH (0-15 cm and 15-30 cm depth) during submergence

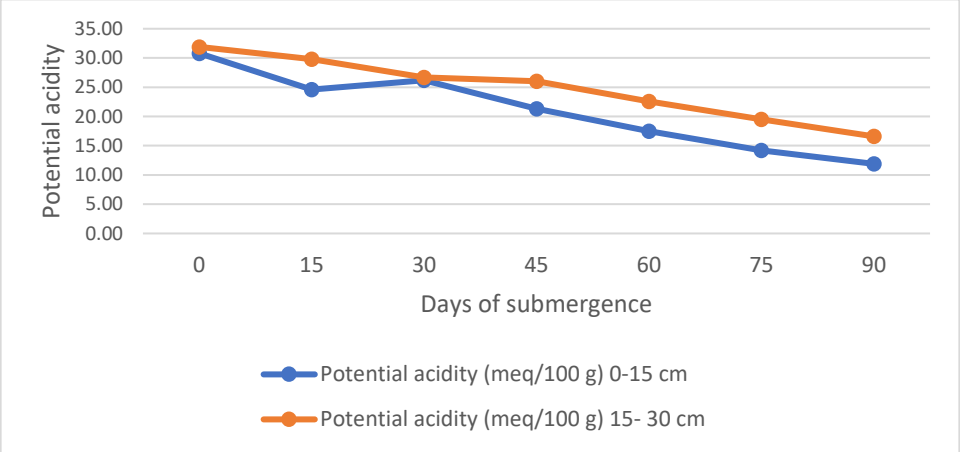

Fig. 2. Temporal variation in potential acidity (0-15 cm and 15-30 cm depth) during submergence

The increase in pH is consistent with the established response of submerged acidic soils, in which oxygen depletion and reduction of oxidised Fe and Mn phases contribute to proton consumption and alkalinity generation (Patrick & Reddy, 1978; Ponnamperuma, 1972). Similar increases in pH have been reported in Kuttanad acid sulphate soils (Ebimol *et al*., 2017). The persistence of pH below 5.5 even at 90 days indicates that submergence alone did not remove the acidity constraint.

EC showed comparatively limited temporal variation, with mean values of 0.35 ± 0.03 and 0.30 ± 0.02 dS m^{-1} in the two layers. The temporary increase during the early period was followed by a decline, suggesting redistribution or retention of soluble constituents rather than progressive salt accumulation. The relatively low EC throughout the monitoring period is consistent with observations reported for Kuttanad soils (Amrutha *et al*., 2023; Rohith *et al*., 2024).

Potential acidity declined from 30.80 to 11.90 meq 100 g^{-1} in the surface layer and from 31.90 to 16.60 meq 100 g^{-1} in the subsurface layer by 90 days. This coincided with the increase in pH and indicates a progressive reduction in the measured acid reserve during submergence. CEC increased during the initial and middle stages, reaching 25.50 and 22.60 meq 100 g^{-1} at 75 days

before a slight decline at 90 days. The increase may reflect changes in surface charge characteristics and ion exchange processes accompanying changes in soil reaction, although these mechanisms were not directly evaluated in the present study; comparable relationships between CEC, soil reaction and Fe status have been reported in hydromorphic rice soils of Kerala (Amrutha *et al*., 2023; Kamarudheen *et al*., 2025).

3.2 Temporal Redistribution of Soil Fe Fractions

HCl-extractable Fe increased markedly during submergence, reaching 733.00 mg kg^{-1} in the 0–15 cm layer and 883.50 mg kg^{-1} in the 15–30 cm layer at 75 days (Table 2). Water-soluble Fe also increased, reaching 22.10 mg kg^{-1} in the surface layer at 75 days and 29.80 mg kg^{-1} in the subsurface layer at 90 days. In contrast, total Fe changed comparatively little. The greater response of the reactive fractions relative to the total Fe pool indicates redistribution among Fe pools rather than a major change in the overall soil Fe reserve.

Flooding promotes reduction of Fe(III) minerals to Fe(II), which can increase dissolved and operationally extractable Fe fractions under oxygen-limited conditions (Kirk et al., 2022; Ponnamperuma, 1972; Sahrawat, 2004). The present temporal pattern is consistent with this established mechanism and with recent observations of changing Fe fractions under soil submergence (Lai & Wang, 2025). However, Eh was not measured in the present study; therefore, the data demonstrate temporal Fe mobilisation associated with submergence but do not independently quantify the redox mechanism.

The consistently higher reactive Fe concentrations in the 15–30 cm layer suggest greater accumulation of these forms at depth. Differences in mineral Fe pools, organic matter and local soil–water conditions may contribute, but these mechanisms cannot be separated with the present sampling design. The decline in HCl-extractable Fe after 75 days, together with continued high concentrations of soluble Fe in the subsurface layer, also indicates that Fe mobilisation was not strictly linear through time.

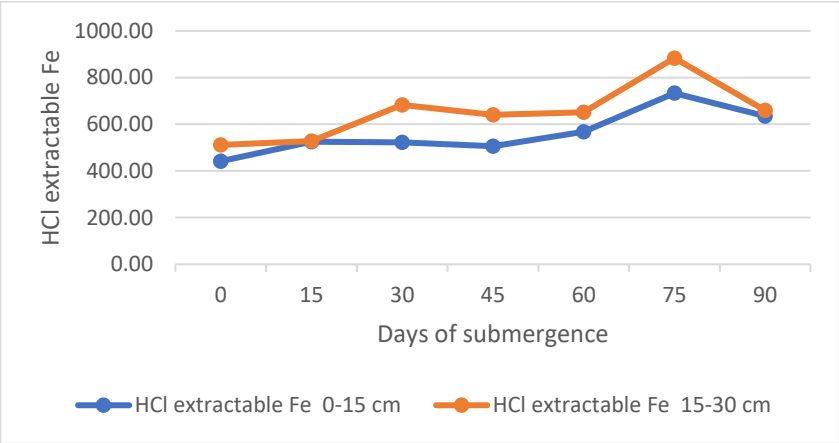

Fig. 3. Temporal variation in HCl extractable Fe (0-15 and 15-30 cm depth) during submergence

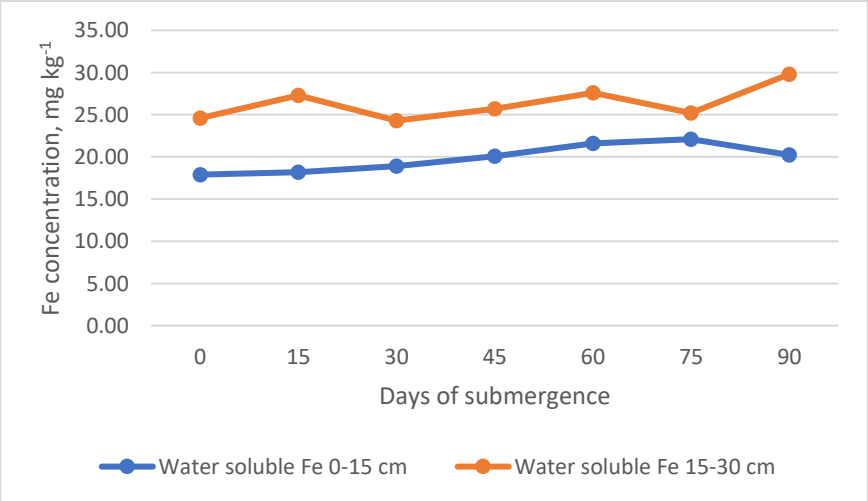

Fig. 4. Temporal variation in Water soluble Fe (0-15 and 15-30 cm depth) on submecrgence

Table 1. Temporal variation of soil pH, EC, Potential acidity and CEC in submergence

Days after submergence	pH		EC (dS m⁻¹)		Potential acidity (meq 100 g⁻¹)		CEC (meq 100 g⁻¹)	
	0-15 cm	15- 30 cm	0-15 cm	15- 30 cm	0-15 cm	15- 30 cm	0-15 cm	15- 30 cm
0	4.45	4.33	0.32	0.28	30.80	31.90	22.50	19.80
15	4.72	4.68	0.35	0.30	24.60	29.80	23.20	20.40
30	5.21	4.93	0.39	0.32	26.20	26.70	24.00	21.00
45	5.28	5.01	0.38	0.33	21.30	26.00	24.80	21.30
60	5.31	5.15	0.34	0.30	17.50	22.60	25.20	22.00
75	5.32	5.17	0.35	0.28	14.20	19.50	25.50	22.60
90	5.17	4.89	0.31	0.29	11.90	16.60	24.90	22.10
Mean±SD	5.07± 0.34	4.888± 0.29	0.35± 0.03	0.30± 0.02	20.93± 6.80	24.73± 5.49	24.30±1.11	21.31±1.00
Range	4.45-5.32	4.33-5.17	0.31-0.39	0.28-0.33	11.90-30.80	16.60-31.90	22.50-25.50	19.80-22.60

Table 2. Temporal variations of Fe fractions at 0-15 and 15-30 cm depth on submergence

Days of submergence	HCl extractable Fe (mg kg⁻¹)		Water soluble Fe (mg kg⁻¹)		Total Fe (mg kg⁻¹)	
	0-15 cm	15-30 cm	0-15 cm	15-30 cm	0-15 cm	15-30 cm
0	441.80	511.50	17.90	24.60	13030.00	15281.00
15	525.50	528.00	18.20	27.30	13160.00	15170.00
30	522.50	682.50	18.90	24.30	13233.00	15420.00
45	505.60	640.05	20.10	25.70	13640.00	15447.00
60	568.05	651.50	21.60	27.60	13782.00	15487.00
75	733.00	883.50	22.10	25.20	13981.00	15773.00
90	634.50	659.50	20.22	29.80	13769.00	15593.00
Mean	561.56 ± 95.79	650.94 ± 122.36	19.86± 1.62	26.36± 1.97	13513.57 ± 367.28	15453.00 ± 197.46
Range	441.80 - 733.00	511.50 - 883.50	17.90-22.10	24.30-29.80	13030.00 - 13981.00	15170.00 - 15773.00

3.3 Temporal Redistribution of Soil Al Fractions

The temporal behaviour of Al contrasted with that of Fe (Table 3). HCl-extractable Al declined from 387.00 to 288.00 mg kg^{-1} in the 0–15 cm layer and from 458.40 to 307.00 mg kg^{-1} in the 15–30 cm layer. Water-soluble Al showed a stronger decline, from 6.87 to 1.31 mg kg^{-1} and from 6.31 to 1.43 mg kg^{-1}, respectively. Thus, the readily mobile Al pool decreased substantially as submergence progressed.

Table 3. Temporal variations of Al fractions at 0-15 and 15-30 cm depth on submergence

Days of submergence	HCl extractable Al (mg kg^{-1})		Water soluble Al (mg kg^{-1})		Total Al (mg kg^{-1})	
	0-15 cm	15-30 cm	0-15 cm	15-30 cm	0-15 cm	15-30 cm
0	387.00	458.40	6.87	6.31	3475.00	3588.00
15	382.00	432.10	4.49	6.70	3213.00	3528.00
30	379.00	383.20	3.39	4.65	3144.00	3590.00
45	365.00	346.90	3.95	4.46	3418.00	3344.00
60	344.00	335.60	1.21	1.49	3333.00	3474.00
75	330.00	336.00	1.23	1.32	3176.00	3536.00
90	288.00	307.00	1.31	1.43	3165.00	3357.00
Mean	353.57±35.71	371.3±55.79	3.21±2.13	3.77±2.34	3274.86±133.37	3488.14±101.98
Range	288.00-387.00	307.00-458.40	1.21-6.87	1.32-6.70	3144.00-3475.00	3344.00-3590.00

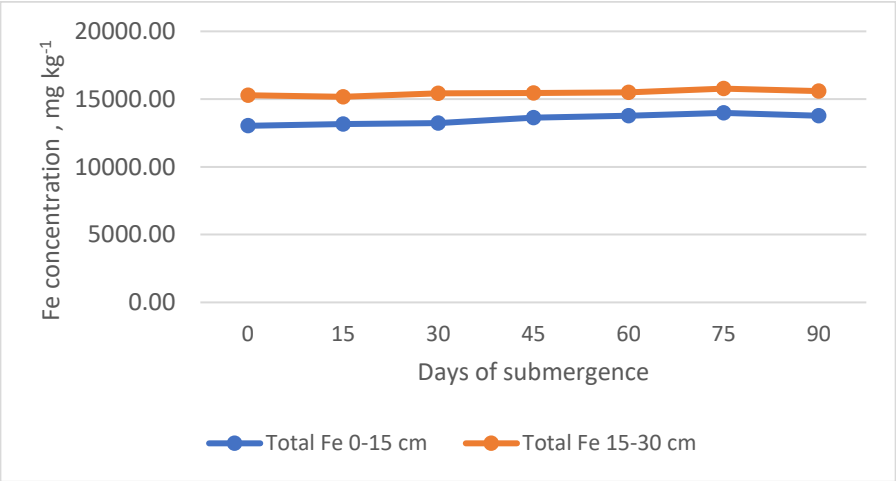

Fig. 5. Temporal variation in Total Fe (0-15 and 15-30 cm depth) during submergence

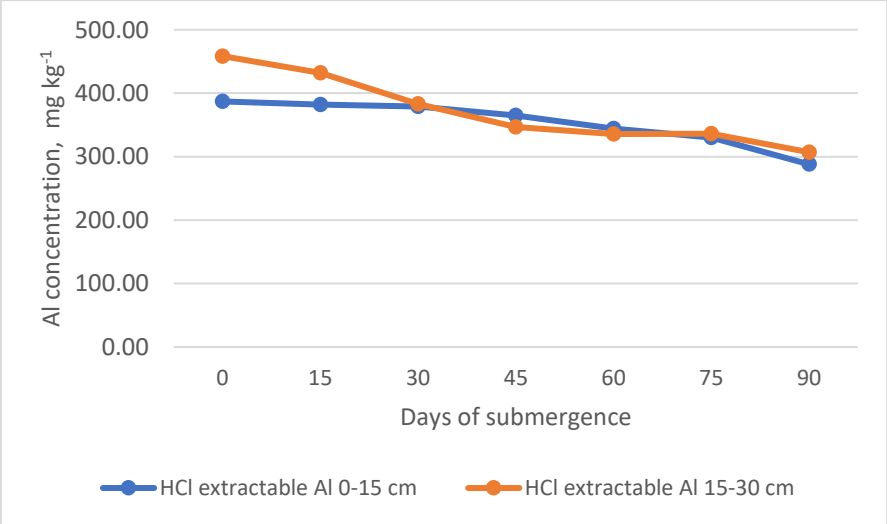

Fig. 6. Temporal variation in extractable Al (0-15 and 15-30 cm depth) during submergence

The decline in soluble and HCl-extractable Al coincided with increasing soil pH and decreasing potential acidity. This temporal association is consistent with the strong pH dependence of Al solubility: as soil pH increases, hydrolysis, polymerisation and precipitation can convert soluble Al into less soluble hydroxy-Al forms (Kochian *et al.,* 2004; Kochian *et al*., 2015). The concurrent increase in soil pH and decline in water-soluble Al further indicate a close temporal association between soil reaction and Al mobility; however, the relationship should not be interpreted as evidence of causation.

Total Al showed comparatively limited temporal variation despite the decline in its extractable fractions. This indicates that submergence primarily altered Al partitioning and mobility rather than substantially removing Al from the soil. The response is relevant to Kuttanad acid sulphate soils, where severe acidity and Fe–Al constraints have been documented (Ebimol *et al*., 2017; Rohith *et al*., 2024; Sumayya *et al*., 2025).

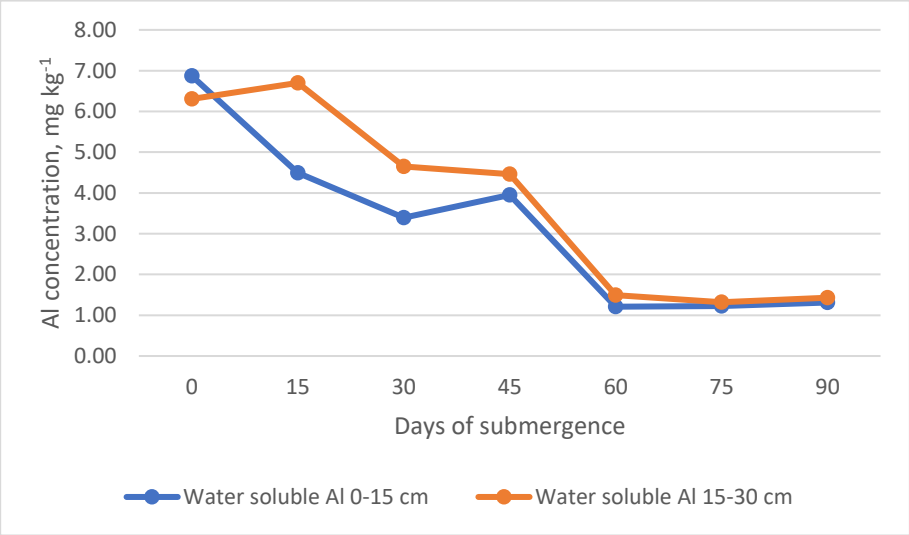

Fig. 7. Temporal variation in water soluble (0-15 and 15-30 cm depth) during submergence

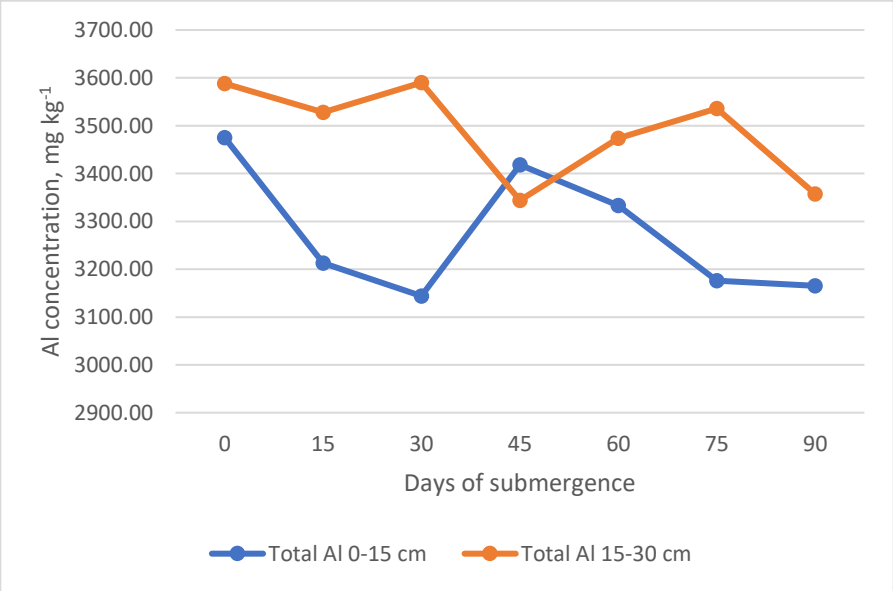

Fig. 8. Temporal variation in Total Al (0-15 and 15-30 cm depth) during submergence

3.4 Contrasting Fe–Al dynamics and Floodwater Chemistry

The combined soil and floodwater observations demonstrate a clear divergence between Fe and Al during prolonged submergence. As soil pH increased and potential acidity declined, reactive Fe fractions increased while HCl-extractable and water-soluble Al decreased. This contrasting behaviour reflects the different dominant controls on the two elements: Fe is strongly influenced by reduction and mineral dissolution under flooding, whereas Al mobility is more strongly governed by soil reaction (Kochian *et al*., 2015; Sahrawat, 2004).

Table 4. Temporal variations of flood water pH, EC, Total Fe and Al on submergence

Days of submergence	pH	EC	Total Fe (mg L^{-1})	Total Al (mg L^{-1})
0	5.65	0.48	11.43	5.56
15	6.21	0.52	11.69	5.15
30	6.25	0.46	12.63	3.13
45	6.74	0.38	12.85	2.83
60	6.68	0.31	14.15	1.96
75	6.66	0.27	15.30	0.47
90	6.63	0.24	15.09	0.43
Mean	6.40 ± 0.39	0.38 ± 0.11	13.31±1.56	2.79 ± 2.04
Range	5.65 - 6.74	0.24 - 0.52	11.43-15.30	0.43 - 5.56

Table 5. Correlation among various parameters at 0-15 cm depth of soil

	pH	EC	PA	CEC	HCl Extractable Fe	Soluble Fe	Total Fe	HCl Extractable Al	Soluble Al	Total Al
pH	1									
EC	0.4	1								
PA	-0.72	0.27	1							
CEC	0.94 **	0.12	-0.88 **	1						
HCl extractable Fe	0.62	-0.16	-0.86 *	0.77 *	1					
Soluble Fe	0.82 *	-0.01	-0.83 *	0.95 **	0.79 *	1				
Total Fe	0.82 *	-0.09	-0.93 **	0.97 ***	0.83 *	0.96 ***	1			
HCl extractable Al	-0.54	0.49	0.93 **	-0.71	-0.76 *	-0.66	-0.79 *	1		
Soluble Al	-0.85 *	0.04	0.91 **	-0.92 **	-0.84 *	-0.87 *	-0.88 **	0.79 *	1	
Total Al	-0.41	-0.13	0.47	-0.35	-0.64	-0.22	-0.27	0.43	0.6	1

Table 6. Correlation among various parameters at 15-30 cm depth of soil

	pH	EC	PA	CEC	HCl Extractable Fe	Soluble Fe	Total Fe	HCl Extractable Al	Soluble Al	Total Al
pH	1									
EC	0.3	1								
PA	-0.71	0.19	1							
CEC	0.89 **	-0.09	-0.94 **	1						
HCl extractable Fe	0.78 *	-0.12	-0.71	0.85 *	1					
Soluble Fe	0.18	-0.16	-0.57	0.38	-0.12	1				
Total Fe	0.72	-0.23	-0.87 *	0.91 **	0.92 **	0.11	1			
HCl extractable Al	-0.84 *	-0.14	0.93 **	-0.93 **	-0.68	-0.5	-0.82 *	1		
Soluble Al	-0.77 *	0.22	0.94 **	-0.95 ***	-0.75	-0.43	-0.9 **	0.91 **	1	
Total Al	-0.38	-0.34	0.53	-0.44	-0.05	-0.64	-0.29	0.68	0.41	1

Floodwater pH increased from 5.65 initially to 6.74 at 45 days and remained above 6.6 thereafter, while EC declined from 0.52 dS m^{-1} at 15 days to 0.24 dS m^{-1} at 90 days (Table 4). Total Fe in floodwater increased from 11.43 mg L^{-1} initially to 15.30 mg L^{-1} at 75 days and remained high at 15.09 mg L^{-1} at 90 days. In contrast, total Al declined from 5.56 to 0.43 mg L^{-1}. The parallel increase in soil reactive Fe and floodwater Fe, together with the decline in soil and floodwater Al, strengthens the interpretation of contrasting Fe and Al mobility during prolonged submergence. The persistence of elevated floodwater Fe after the maximum HCl-extractable Fe at 75 days also indicates that Fe mobilisation and redistribution continued after the peak in the acid-extractable soil fraction.

At 75 days, the divergence was particularly pronounced: HCl-extractable Fe reached 733.00 and 883.50 mg kg^{-1} in the surface and subsurface layers, respectively, whereas HCl-extractable Al had declined to 330.00 and 336.00 mg kg^{-1}. This stage provides a useful temporal point for subsequent replicated investigations of Fe–Al transformations and amelioration timing. Because the study comprised one continuously submerged field and composite samples at each date, these observations should be interpreted as temporal patterns rather than replicated treatment effects.

4. Implications and Study Limitations

The observed temporal divergence indicates that moderation of acidity under prolonged submergence should not be interpreted as simultaneous removal of all metal-related constraints. The decline in soluble Al indicates reduced Al mobility as soil reaction became less acidic, whereas the increase in reactive and floodwater Fe indicates that Fe mobilisation continued during the later stages of submergence. This supports consideration of Fe and Al together when evaluating acidity management in submerged Kuttanad soils.

The study has an important design limitation: observations were obtained from a single monitored field with composite samples and therefore do not provide replicated treatment comparisons or independent statistical tests of temporal effects. Pearson correlations should consequently be regarded as exploratory temporal associations. Nevertheless, the consistency among soil pH, acidity parameters, Fe and Al fractions and floodwater chemistry provides a useful baseline for designing future replicated experiments, particularly those evaluating amendment timing under prolonged submergence.

5. Conclusion

Prolonged submergence produced contrasting temporal changes in Fe and Al in the acidic paddy soil of Lower Kuttanad. Soil pH increased and potential acidity declined, indicating partial alleviation of the initial acid reaction, while HCl-extractable and water-soluble Al decreased progressively. In contrast, reactive Fe fractions increased, particularly during the later stages of submergence, and floodwater Fe increased concurrently. Total Fe and Al showed comparatively limited temporal variation, indicating that submergence primarily altered the partitioning and mobility of these elements rather than their total soil pools. The contrasting Fe and Al responses demonstrate that partial moderation of acidity under flooding does not necessarily correspond to reduced Fe mobilisation and provide a temporal baseline for future replicated studies on Fe–Al management in submerged Kuttanad soils.

Declaration of AI Use

This manuscript was prepared through the intellectual contributions of the author(s) to the study design, data analysis, interpretation of results, and scholarly content. Grammarly and ChatGPT were used solely to assist with grammatical refinement and reference formatting during manuscript revision. The author(s) accept full responsibility for the accuracy, integrity, and final content of the 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.

References

Amrutha, K. K., Beena, V. I., & Geetha, P. (2023). Nutrient status of acid sulphate soils of Upper Kuttanad of Kerala, India. *International Journal of Environment and Climate Change, 13*(9), 1834–1842. https://doi.org/10.9734/ijecc/2023/v13i92414

Drabek, O., Mladkova, L., Boruvka, L., Szakova, J., Nikodem, A., & Nemecek, K. (2005). Comparison of water-soluble and exchangeable forms of Al in acid forest soils. *Journal of Inorganic Biochemistry, 99*(9), 1788–1795. https://doi.org/10.1016/j.jinorgbio.2005.06.024

Ebimol, N. L., Suresh, P. R., Binitha, N. K., & Santhi, G. R. (2017). Management of iron and aluminium toxicity in acid sulphate soils of Kuttanad. *International Journal of Current Microbiology and Applied Sciences, 6*(11), 1496–1503. https://doi.org/10.20546/ijcmas.2017.611.177

Hasana, H. (2026). Coffee husk biochar: A sustainable amendment for soil acidity mitigation and carbon sequestration. *Asian Journal of Agriculture and Allied Sciences, 9*(1), 31–47. https://doi.org/10.56557/ajaas/2026/v9i180

Jackson, M. L. (1973). *Soil chemical analysis*. Prentice-Hall of India.

Kamarudheen, P., Mayadevi, M. R., Smitha, J. K., Beena, V. I., Jayasree, P., Sandeep, S., Archana, K., & Aryadevi, J. S. (2025). Iron-acidity interactions in hydromorphic rice systems of south western coastal India. *Discover Soil, 2*, Article 84. https://doi.org/10.1007/s44378-025-00110-y

Kirk, G. J. D., Manwaring, H. R., Ueda, Y., Semwal, V. K., & Wissuwa, M. (2022). Below-ground plant–soil interactions affecting adaptations of rice to iron toxicity. *Plant, Cell & Environment, 45*(3), 705–718. https://doi.org/10.1111/pce.14199

Kochian, L. V., Hoekenga, O. A., & Piñeros, M. A. (2004). How do crop plants tolerate acid soils? Mechanisms of aluminum tolerance and phosphorous efficiency. *Annual Review of Plant Biology, 55*, 459–493. https://doi.org/10.1146/annurev.arplant.55.031903.141655

Kochian, L. V., Piñeros, M. A., Liu, J., & Magalhaes, J. V. (2015). Plant adaptation to acid soils: The molecular basis for crop aluminum resistance. *Annual Review of Plant Biology, 66*, 571–598. https://doi.org/10.1146/annurev-arplant-043014-114822

Kronberg, R., Kanerva, S., Koskinen, M., Polvinen, T., Heinonsalo, J., & Pihlatie, M. (2024). Controlled soil monolith experiment for studying the effects of waterlogging on redox processes. *Geoderma, 452*, Article 117110. https://doi.org/10.1016/j.geoderma.2024.117110

Lai, Y.-R., & Wang, S.-L. (2025). Effects of biochar on the temporal dynamics and vertical distribution of iron and phosphorus under soil submergence. *Agronomy, 15*(6), 1394. https://doi.org/10.3390/agronomy15061394

Loeppert, R. H., & Inskeep, W. P. (1996). Iron. In D. L. Sparks, A. L. Page, P. A. Helmke, R. H. Loeppert, P. N. Soltanpour, M. A. Tabatabai, C. T. Johnston, & M. E. Sumner (Eds.), *Methods of soil analysis: Part 3. Chemical methods* (pp. 639–664). Soil Science Society of America & American Society of Agronomy. https://doi.org/10.2136/sssabookser5.3.c23

Miller, W. P., Martens, D. C., & Zelazny, L. W. (1986). Effect of sequence in extraction of trace metals from soils. *Soil Science Society of America Journal, 50*(3), 598–601. https://doi.org/10.2136/sssaj1986.03615995005000030011x

Muindi, E. M. (2020). Effects of liming on dithionate and oxalate extractable aluminium in acid soils. *Asian Journal of Soil Science and Plant Nutrition, 5*(3), 1–9. https://doi.org/10.9734/ajsspn/2019/v5i330069

Osiname, O. A., Kang, B. T., Schulte, E. E., & Corey, R. B. (1973). Zinc response of maize (*Zea mays* L.) grown on sandy Inceptisols in Western Nigeria. *Agronomy Journal, 65*(6), 875–877. https://doi.org/10.2134/agronj1973.00021962006500060008x

Page, A. L., Miller, R. H., & Keeney, D. R. (Eds.). (1982). *Methods of soil analysis: Part 2. Chemical and microbiological properties* (2nd ed., Agronomy Monograph No. 9). American Society of Agronomy & Soil Science Society of America. https://doi.org/10.2134/agronmonogr9.2.2ed

Patrick, W. H., Jr., & Reddy, C. N. (1978). Chemical changes in rice soils. In *Soils and rice* (pp. 361–379). International Rice Research Institute.

Ponnamperuma, F. N. (1972). The chemistry of submerged soils. *Advances in Agronomy, 24*, 29–96. https://doi.org/10.1016/S0065-2113(08)60633-1

Rhoades, J. D. (1982). Cation exchange capacity. In A. L. Page (Ed.), *Methods of soil analysis: Part 2. Chemical and microbiological properties* (2nd ed., pp. 149–157). American Society of Agronomy & Soil Science Society of America. https://doi.org/10.2134/agronmonogr9.2.2ed.c8

Rohith, A. K., Joseph, B., & Gladis, R. (2024). Probing acid sulphate soils for sustainable rice production in Kuttanad: Challenges and solutions. *Annual Research & Review in Biology, 39*(12), 46–56. https://doi.org/10.9734/arrb/2024/v39i122169

Sahrawat, K. L. (2004). Iron toxicity in wetland rice and the role of other nutrients. *Journal of Plant Nutrition, 27*(8), 1471–1504. https://doi.org/10.1081/PLN-200025869

Schulz, K., Wisawapipat, W., Barmettler, K., Grigg, A. R. C., Kubeneck, L. J., Notini, L., ThomasArrigo, L. K., & Kretzschmar, R. (2024). Iron oxyhydroxide transformation in a flooded rice paddy field and the effect of adsorbed phosphate. *Environmental Science & Technology, 58*(24), 10601–10610. https://doi.org/10.1021/acs.est.4c01519

Sims, J. T., & Johnson, G. V. (1991). Micronutrient soil tests. In J. J. Mortvedt (Ed.), *Micronutrients in agriculture* (2nd ed., pp. 427–476). Soil Science Society of America. https://doi.org/10.2136/sssabookser4.2ed.c12

Sumayya, S., Gladis, R., Rani, B., George, T., Joseph, B., & Bindhu, J. S. (2025). Acid sulphate soils: Characteristics, constraints and integrated management strategies for sustainable utilization. *International Journal of Environment and Climate Change, 15*(10), 621–630. https://doi.org/10.9734/ijecc/2025/v15i105087

Peer-review history:
The peer review history for this paper can be accessed here: https://pr.sdiarticle5.com/review-history/167046