International Journal of Plant & Soil Science

Volume 37, Issue 10, Page 33-38, 2025; Article no.IJPSS.143804
ISSN: 2320-7035

Distribution of Different forms of Aluminium (Al) under Tea Plantations of Different Age in Eastern Bihar of 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.

Article Information

DOI: https://doi.org/10.9734/ijpss/2025/v37i105759

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/143804

Short Research Article

Received: 26/06/2025
Accepted: 12/09/2025
Published: 27/09/2025

ABSTRACT

On average, aluminium makes up 7–8% of the earth's crust, making it the most prevalent metal on the planet and the third most abundant element (after silicon and oxygen). Al is present and widespread throughout the plant life cycle, although it serves no particular biological purpose. Al is

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Cite as: *Annu Sinha, Sankar Ch. Paul, Vandana Kumari, Adyant Kumar, Basudev Kole, and D P Saha. 2025. "Distribution of Different Forms of Aluminium (Al) under Tea Plantations of Different Age in Eastern Bihar of India". International Journal of Plant & Soil Science 37 (10):33–38. https://doi.org/10.9734/ijpss/2025/v37i105759.*

mostly present in soil as minerals (aluminosilicates and aluminium oxides) therefore, organisms are typically not exposed to significant quantities of it. The paper aims to distribute different forms of aluminium (Al) under different age tea plantation plantations in Eastern Bihar of India. The study was carried out in different age tea plantations in the eastern region of India with the objective to find out the different forms of Al in the plantation. A representative soil sample was taken from each of the three (3) tea plantations that were taken into consideration for each treatment. Free oxides of iron and aluminium were extracted using the citrate-dithionite-bicarbonate (CBD) method. Following the tea plantation age, treatments were taken into consideration, viz. (i) T1: < 10 years old, (ii) T2: 10–20 years old, (iii) 20–30 years old, (iv) 30–40 years old, and (v) > 40 years old tea gardens. Results found that all forms of Al, such as exchangeable Al, Extractable Al, Non-exchangeable Al, Oxide form of Al/CBD extractable-Al, and Amorphous Al/Oxalate extractable Al concentration, increased with increasing the age of the tea plantation. Furthermore, all forms of Al showed significant and positive correlation with each other. Concentration of various forms of Al in tea soils followed in the order of Oxalate-Al > CBD-Al > Exchangeable Al > Extractable Al > Non-exchangeable Al. Forms of Al concentration gradually increase during tea cultivation over the years, which must be the cause of lowering soil acidity and affect nutrient availability to tea plant growth at old age plantations. Clay content of these soils varied from 19.75 to 21.83%, with a mean content of 20.94%. Water holding capacity found to be low due to light-textured soil, having ranged between 27.00 and 35.67% with an average of 30.76%. All soils were found to be moderately acidic, with soil pH ranging between 4.65 and 5.48, with an average of 5.01. From this study, it may be concluded that the content of all fractions of aluminium concentration increases with increasing age of the tea plantation and all exists exist in equilibrium condition conditions in the soil solution.

Keywords: Aluminium forms; tea soil; tea plant age

1. INTRODUCTION

Tea (*Camellia sinensis* L.) plant, a potential bio-accumulator of Aluminium (Al) and Fluoride (F) is the most popular beverage in the world, and concentrations beyond threshold levels might cause an adverse effect that otherwise has a beneficial impact on human health (Rajbonshi *et al*., 2025; Shehasen, 2024). On average, aluminium makes up 7–8% of the earth's crust, making it the most prevalent metal on the planet and the third most abundant element (after silicon and oxygen). Al is present and widespread throughout the plant life cycle, although it serves no particular biological purpose (Poschenrieder et al., 2008). Al is mostly present in soil as minerals (aluminosilicates and aluminium oxides), therefore, organisms are typically not exposed to significant quantities of it. However, in aqueous solutions and at varying pH levels, Al hydrolyses water molecules to generate aluminium hydroxide. The pH and the chemical environment of the solution affect both the total amount of Al in the soil and the species of Al (Kisnieriené & Lapeikaité, 2015). The most prevalent form of trivalent aluminium (Al_3^+) and the one that most effects plant growth occurs at a low pH (about 4.3). However, all that has been precipitated or chelated with organic molecules is not harmful to plants (Nogueirol et al., 2015). The amount of Al that is available (both in the soil solution and exchangeable) is crucial for assessing the risk of plant production on acidic soils, where it can occur in toxic concentrations for both microorganisms and plants (Mossor-Pietrasyewska, 2001). Soils contain aluminium (Al), which is liberated during weathering and development and reprecipitates as crystalline or amorphous oxides, hydroxides, or hydras-oxides. Crystalline Fe-oxides like hematite and geothites are believed to be formed by substituting the crystalline form of Al-oxides. However, it can be inferred that the nature, quantity, and distribution of aluminium (Al) oxides in soil influence its specific surface area, surface charge, ionic charge, chemical properties, and ion adsorption, particularly phosphorus (P) sorption. Aluminium ion promoted new root growth in five representative tea varieties with dose-dependent responses to Al3+ availability. In the absence of Al3+, the tea plants failed to generate new roots, and the root tips were damaged within 1 d of Al deprivation. Structural analysis of root tips demonstrated that Al was required for root meristem development and activity (Sun *et al*., 2020). In the presence of amorphous Al oxides, swelling and aggregation formation may be markedly altered. The weathering of Al-containing parent materials releases the Al. They reprecipitate in the soils as aluminium hydroxides and oxyhydroxides. In general, the amount of these alteration products increased with the age of the soil (Dolui & Bera, 2001). In order to better understand, this work was conducted to find out the distribution of various kinds of aluminium in different-aged tea plantations in the eastern part of India.

2. MATERIALS AND METHODS

The study was carried out in the eastern region of India, which is regarded as a subtropical humid region with rainfall exceeding 2000 mm, taking into account different-aged tea plantations. Surface soil (0–30 cm) samples were taken using the appropriate "Z-shaped" sampling technique from five distinct tea age plantation treatments: (i) T1: < 10 years old, (ii) T2: 10–20 years old, (iii) 20–30 years old, (iv) 30–40 years old, and (v) > 40 years old tea gardens. A representative soil sample was taken from each of the three (3) tea plantations that were taken into consideration for each treatment. The soil samples were stored in plastic containers after being allowed to air dry and sieved to a size of 2 mm. The soil pH and Electrical conductivity (EC) were estimated by using soil suspension (1:2.5) (Jackson 1973); organic carbon was determined by the method of Walkley and Black; cation exchange capacity (CEC) by the ammonium saturation method of Jackson (1973). Slit and clay content were estimated by the hydrometer method of Bouyoucos (1962). Exchangeable aluminium was estimated by the 1 N KCl extraction method (Black, 1965) as described in Baruah and Barthakur (1997). Extractable aluminium was determined using 1 N ammonium acetate (NH_4OAc) buffered at pH 4.8, following the method of Olson and Carlson (1950) as described by Baruah and Barthakur (1997). Non-exchangeable aluminium was estimated by calculating the difference between extractable aluminium and exchangeable aluminium as described in Baruah and Barthakur (1997). Ammonium oxalate-extractable aluminium was determined following the method described by Page et al. (1982). Free oxides of iron and aluminium were extracted using the citrate-dithionite-bicarbonate (CBD) method as described by Mehra and Jackson (1960).

3. RESULTS AND DISCUSSION

The results of the physicochemical properties of soil under different tea plantations are presented in Table 1. The texture of soils is sandy loam to sandy clay loam in nature, where the sand fraction is maximum. Clay content of these soils varied from 19.75 to 21.83%, with a mean content of 20.94%. Water holding capacity found to be low due to light-textured soil, having ranged between 27.00 and 35.67% with an average of 30.76%. All soils were found to be moderately acidic, with soil pH ranging between 4.65 and 5.48, with an average of 5.01. Older tea garden soils are found to have lower soil pH. The electrical conductivity (EC) varied from 0.04 to 0.18 with an average of 0.14 dS m^{-1}, which is considered to be low. The light texture of the soil may be the cause of the leaching loss of soluble salts caused by heavy rainfall. The cation exchange capacity (CEC) of the studied soils varied from 7.41-8.94 cmol(p^+)/kg, with a mean value of 8.31 cmol(p^+)/kg. Organic carbon content under different aged tea plantations ranged from 0.92 to 1.14%, with an average of 1.02% indicates that organic carbon content in soil is high. The presence of high organic matter and good drainage conditions may have contributed to the lower pH of the tea soil, which in turn may have enhanced the weathering process and caused bases to leach, resulting in elevated Al levels.

3.1 Forms of Aluminium

Aluminium is a predominant cation involved in exchange equilibria and soil acidification processes, and its excessive concentration is widely recognised as a major constraint to plant growth. The pool of aluminium that exists in the exchangeable form serves as an indicator of soil reserve acidity and plays a significant role in influencing root elongation as well as overall crop productivity. Exchangeable aluminium is generally quantified through extraction with relatively concentrated (0.5-1 M) unbuffered salt solutions such as KCl, $CaCl_2$ or $BaCl_2$, which facilitate the displacement of aluminium ions from exchange sites under equilibrium conditions. This fraction comprises both hydroxy-aluminium monomeric forms and polymeric species, thereby reflecting the dynamic nature of aluminium in acidic soils.

3.2 Exchangeable Al

The results of different forms of aluminium under different aged tea plantations presented in Table 2 indicate that the Exchangeable aluminium content of the soil varied from 1.13 to 1.86 meq $100g^{-1}$ soil, with a mean value of 1.47 meq $100g^{-1}$ soil. Exchangeable aluminium showed a strong negative correlation with soil pH (r = -0.56*), indicating that Al solubility increases with acidity. Exchangeable Al also exhibited correlation (Table 3) with clay content (r = 0.11) and organic carbon (r = –0.16). Among aluminium fractions, exchangeable Al maintained

Table 1. Some important physical properties of soil under different-age tea plantations

Treatment	Silt (%)	Clay (%)	Max. WHC (%)	pH (1:2.5)	EC (dS m^{-1})	CEC [cmol (+)/ kg^{-1}]	OC (%)
T1	19.24	21.64	35.67	5.48	0.16	8.73	1.13
T2	13.28	20.52	32.93	5.03	0.18	7.41	0.98
T3	12.05	21.83	27.45	4.84	0.18	8.17	1.07
T4	21.13	19.75	27.00	4.68	0.04	8.94	0.92
T5	18.95	19.93	33.62	4.65	0.08	8.25	1.14
Mean	16.43	20.94	30.76	5.01	0.14	8.31	1.02
SD	3.583	0.858	3.474	0.305	0.058	0.529	0.085
Range	12.05-21.13	19.75 – 21.83	27.00 -35.67%	4.65 – 5.48	0.04 – 0.18	7.41-8.94	0.92 - 1.14

Table 2. Forms of aluminium under different age tea plantation

Treatment	Exchangeable-Al (meq $100g^{-1}$)	Extractable-Al (meq $100g^{-1}$)	Non-exchangeable-Al (meq $100g^{-1}$)	CBD-Al (%)	Oxalate Al (%)
T1	1.13	0.85	0.22	0.27	0.42
T2	1.01	1.33	0.13	0.29	0.39
T3	1.65	1.31	0.42	0.32	0.41
T4	1.66	1.41	0.78	0.33	0.49
T5	1.86	1.42	0.83	0.32	0.44
Mean	1.36	1.23	0.39	0.30	0.43
SD	0.33	0.21	0.28	0.02	0.04
Range	1.13–1.86	0.85–1.42	0.13 -0.83	0.27 - 0.33	0.39–0.49,

Table 3. Coefficient of correlation between forms of Al and physicochemical properties of soil

	Silt	Clay	Max. WHC	pH	EC	OC
Exch. Al	0.18	0.11	-0.29	-0.57*	-0.20	0.16
Extract. Al	-0.14	-0.32	-0.54*	-0.51*	-0.38	0.07
Non-exch. Al	0.56*	-0.26	-0.31	-0.61*	-0.45	-0.07
Oxalate Al	0.14	-0.13	-0.45	-0.41	-0.15	-0.03
CBD-Al	0.002	-0.07	-0.46	-0.74**	0.14	-0.12

Table 4. Coefficient of correlation value (r) among various forms of aluminium

	Exch. Al	Extract. Al	Oxalate Al	Non-exch. Al
Extract. Al	0.43			
Oxalate Al	0.22	0.28		
Non-exch. Al	0.83**	0.48	0.33	
CBD-Al	0.41	0.38	0.63*	0.39

a strong positive relationship (Table 4) with non-exchangeable Al (*r* = 0.83**), while the correlation with oxalate Al (*r* = 0.22) and CBD extractable Al (*r* = 0.41) were comparatively weaker. Al release is influenced by soil organic matter and pH. Because some amorphous Fe and Al dissolve, the release of Fe and Al increases as pH decreases (Cabrerra & Talibudeen, 1977).

3.3 Extractable Al

Extractable aluminium is commonly determined using ammonium acetate at pH 4.8, and it represents the fraction of Al released from non-exchangeable sources, including structural components or hydroxy-polymeric interlayers. The Extractable aluminium ranged (Table 2) between 0.85 and 1.42 meq $100g^{-1}$ soil, averaging 1.23 meq $100g^{-1}$ soil. Extractable aluminium recorded a negative correlation (Table 3) with pH (*r* = –0.51*), clay (*r* = –0.32), and a weak positive relation with organic carbon (*r* = 0.07). Among Al fractions, Extractable Al (Table 4) was strongly associated with Exchangeable Al (*r* = 0.42), Non-exchangeable Al (*r* = 0.47) and oxalate Al (*r* = 0.28).

3.4 Non-Exchangeable Al

The non-exchangeable Al ranged from 0.13 to 0.83 meq $100g^{-1}$ soil (Table 2) with a mean of 0.39 meq $100g^{-1}$ soil. Non-exchangeable Al also showed a significant negative correlation (Table 3) with soil pH (r = –0.61*), reflecting its sensitivity to acid soil conditions. Its relationships with clay (*r* = -0.26) and organic carbon (r = 0.071) were weak, but a significant positive correlation was found with silt content. Highly significant positive correlation (Table 4) was also observed with exchangeable Al (r = 0.83**), extractable Al (r = 0.47), and oxalate Al (r = 0.33).

3.5 Oxalate extractable Al / Amorphous Al

The oxalate aluminium varied (Table 2) from 0.39 to 0.49% with an average (Table 2) of 0.43%. The fraction of aluminium distinguished as non-exchangeable is calculated as the difference between extractable Al and exchangeable Al. Oxalate Al exhibited a negative relationship (Table 3) with pH (*r* = –0.41), clay (*r* = –0.12), and organic carbon (*r* = -0.03). Amorphous Al showed significant positive correlations (Table 4) with exchangeable Al (*r* = 0.22), non-exchangeable Al (*r* = 0.33), and extractable Al (*r* = 0.28). Although it did not dissolve crystalline oxide, the acid ammonium oxalate removes aluminium from both organic matter complexes and amorphous inorganic compounds (Parfitt et al., 1988).

3.6 CBD Extractable Al / Al_2O_3

The Free aluminium oxide content of the soil was recorded (Table 2) between 0.27 and 0.33%, with an average of 0.30%, respectively. Older tea plantation soil contained more CBD extractable Al than the younger plantation. Free aluminium oxides exhibited a strong negative correlation (Table 3) with soil pH (r = –0.73**), confirming that their availability increases markedly under highly acidic conditions. The relationship with clay content was weakly negative (r = –0.67**), whereas organic carbon showed a weak positive correlation (*r* = -0.11). Among aluminium fractions (Table 4), free Al showed positive associations with exchangeable Al (r = 0.41), extractable Al (r = 0.37), oxalate Al (r = 0.62*), and non-exchangeable Al (r = 0.39). Citric bicarbonate dithionite Al extractant extracts finely crystalline Al together with the oxalate solution fraction (Borggard, 1998).

4. CONCLUSION

From this study, it may be concluded that the content of all fractions of aluminium concentration increases with increasing age of the tea plantation and all exist in equilibrium conditions in the soil solution. Concentration of various forms of Al in these soils followed the order of Oxalate-Al > CBD-Al > Exchangeable Al > Extractable Al > Non-exchangeable Al.

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 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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Peer-review history:
The peer review history for this paper can be accessed here:
https://pr.sdiarticle5.com/review-history/143804