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Assessment of tree biomass and carbon sequestration potential of *Pongamia pinnata* clones under agroforestry system

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ABSTRACT

Global warming driven by rising atmospheric CO_2 has intensified the need for effective carbon sequestration strategies, where trees like Pongamia pinnata play a vital role due to higher biomass production, nitrogen-fixing ability, and soil restoration potential. The study was conducted at UAS, Bengaluru to evaluate the growth performance, biomass production, and carbon sequestration potential of Pongamia clones. The experiment comprised eight pongamia clones, planted at 5 m × 5 m spacing in a randomised block design (RBD) with three replications. Growth parameters, including tree height, diameter at breast height (DBH) and canopy spread were recorded periodically from 2020 to 2026. After six years of planting, RAK-2015-10 consistently performing better in tree height (4.98 m) and DBH (14.25 cm). Maximum canopy spread is noticed in RAK-2015-01 (4.63 m N-S and 4.31 m E-W). Carbon sequestration potential of pongamia clones varied significantly based on growth and biomass production. In the first year, RAK-2015-01 recorded the highest volume, total biomass and carbon sequestration (7.41 m3, 7.66 t ha^{-1} & 14.04 t ha^{-1}). From the 2nd to 6th year, RAK-2015-10 consistently showed the highest volume and carbon sequestration potential, reaching 40.43 m3 and 76.58 t ha^{-1}. RAK-2015-07 exhibited the lowest and non-significant carbon sequestration throughout the study period. RAK-2015-10 pongamia clone significantly enhanced biomass production and carbon sequestration, making it a viable strategy for climate change mitigation under agroforestry systems in the study area.

INTRODUCTION

Global warming is becoming more certain and concerning than ever Increased CO_2 levels from 280 ppm in pre-industrial to 420-425 ppm in recent years were a major driving factor for increased global warming (Choudhary *et al.*, 2025). One-third of the world's land surface is covered by forest and serves as a major carbon sink on Earth. The amount of carbon sequestered and stored in forests varies greatly with factors such as forest type, net primary production, age and overall composition (He *et al.*, 2022). Soil carbon and biomass carbon are two components that contribute to carbon storage in forest ecosystems (Bania *et al.*, 2025). More photosynthesis results in more CO_2 being transformed into biomass, which lowers atmospheric carbon and stores it in plant tissue both above and below ground. Carbon sequestration in trees is significantly influenced by the production of biomass in various forms (Soni *et al.*, 2023). The primary carbon pools in any ecosystem include dead wood, litter, soil organic matter and aboveground and belowground biomass (Sharma *et al.*, 2021).

Degradation of soil fertility is a major limitation to sustainable agricultural productivity, especially in areas affected by erosion, nutrient loss, and poor land management practices. Restoring the productivity of such degraded soils requires environmentally friendly and economically sustainable methods (Leksono *et al.*, 2021). In this context, perennial leguminous tree species have gained more interest due to their ability to enhance soil health through biological processes. *Pongamia pinnata* is a multipurpose, fast-growing, deciduous tree and is indigenous to the Indian subcontinent (Choudhary *et al.*, 2025) and commonly known as honge in Karnataka, Karanja, or Pongam. Pongamia has a strong root system that helps prevent soil erosion, a leading driver of carbon loss (Chen et al., 2025) and the tree offers carbon storage as an additional benefit (Soni *et al.*, 2023).

By anchoring the soil and reducing erosion, Pongamia helps retain soil organic content, which is vital for long-term carbon sequestration. Pongamia can restore soil fertility by fixing atmospheric nitrogen (Gawali *et al.*, 2015),

Table 1: Details of *Pongamia pinnata* clones

Treatments	Clones	Location of clones collected
T_1	RAK-2015-01	MPKV, Rahuri
T_2	RAK-2015-02	
T_3	RAK-2015-03	
T_4	RAK-2015-04	
T_5	RAK-2015-07	
T_6	RAK-2015-08	
T_7	RAK-2015-09	
T_8	RAK-2015-10	

thereby enriching the soil with nutrients and reducing reliance on synthetic fertilisers. These traits make Pongamia a valuable species for restoring degraded lands while also supporting sustainable agroforestry systems. Since climate change is a global problem, studying *Pongamia* is crucial for several reasons, including estimating carbon sequestration potential, which can support efforts to mitigate the effects of climate change in India and around the world (Zeng *et al.*, 2024).

RAK Pongamia clones represents a genetically diverse collection of *Pongamia pinnata* selected from superior trees across varied agro-climatic regions. RAK Pongamia clones plays a crucial role in enhancing soil fertility through biological nitrogen fixation and organic matter addition. Integration of RAK accessions in agroforestry systems contributes to improved soil health, nutrient cycling, and long-term sustainability of degraded lands. Some elite RAK genotypes have shown superior performance in biomass accumulation and carbon sequestration, supporting climate change mitigation efforts. The present study evaluates the performance of different Pongamia clones with respect to growth, biomass, carbon sequestration and soil improvement under an agroforestry system.

MATERIALS AND METHODS

Experimental Location

The experiment was conducted at the Agroforestry unit, ZARS, Gandhi Krishi Vignana Kendra, University of Agricultural Sciences, Bengaluru, situated in the Eastern Dry Zone (Zone – 5) of Karnataka. The experimental site is located between 12° 51' N Latitude and 77° 35' E Longitude at an altitude of 930 m above mean sea level (MSL). The experimental plot was established in July 2017, observations were recorded from 2020-21 to 2025-26 with eight Pongamia clones collected from MPKV, Rahuri. The experiment was laid out in a block plantation of *Pongamia pinnata* with a spacing of 5 m × 5 m. A randomized block design is used for the experiment layout with eight treatments and three replications. The eight Pongamia clones are given in Table 1.

Tree growth observations

The tree biomass was calculated by a non-destructive method by taking the measurements of height and girth of the standing trees and then the volume was calculated. The height, diameter at breast height (DBH) and crown spread of the tree were recorded from 2020 to 2026. The total tree height was measured with an altimeter, and the girth at breast height (1.37 m) from the ground level was measured with the help of a measuring tape. The crown spread of the tree was measured in east - west and north - south direction with the help of a measuring tape. The tree volume was calculated with the following formula, given by Chaturvedi and Khanna (1981) and expressed in cubic meters.

Volume (m^3)

The tree volume was calculated with the following formula

V=4πg2×h

Where 'g' is girth at breast height (cm), 'h' is height in (m), πis 3.142 (Chaturvedi and Khanna, 1981).

Estimation of tree biomass

The tree above ground biomass was estimated by multiplying the mean volume by specific wood density and expressed in kg tree^{-1} (Brown and Lugo, 1982).

Above-ground biomass = Volume x Specific wood density.

Volume = Basal area × Height × Form factor

Basal area = $(\pi d^2) / 4$

Form factor is the ratio of its volume to the volume of a specified geometric solid of similar basal diameter and height. The form factor for Pongamia is 0.33.

Below-ground biomass (BGB) of the tree

The below-ground biomass of Pongamia trees was calculated by multiplying 26 per cent by the above ground biomass (Ravindranath and Ostwald, 2008) and expressed in t ha^{-1}.

BGB = AGB X 0.26

Total biomass (TB)

Total biomass of Pongamia trees was calculated by adding the above-ground and below ground biomass. Usually, total biomass is expressed in t ha^{-1}.

Total biomass (TB) = AGB + BGB

Carbon sequestration potential

Fixed carbon content in wood was determined by multiplying the total biomass with dry weight of wood. The dry weight of Pongamia was taken as 45% (Ravi *et al.*, 2025). Usually expressed in t ha^{-1}.

Fixed carbon = TB X 0.45

CO_2 is composed of one molecule of carbon and two molecules of oxygen. The atomic weight of carbon, oxygen and carbon dioxide is 12.00, 16.00 and 44.00, respectively. The ratio of the atomic weight of CO_2 to C is 3.66. To determine the carbon dioxide sequestered in the tree, multiply the weight of carbon in the tree by 3.66 and expressed in t ha^{-1}.

Carbon sequestration = Fixed carbon content in wood × 3.66

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Table 2: Tree height of different *Pongamia pinnata* clones from 2020-21 to 2025-26

Clones	Tree height (m)					
	1st year	2nd year	3rd year	4th year	5th year	6th year
RAK-2015-01	2.67	2.97	3.17	3.35	3.83	4.49
RAK-2015-02	2.42	2.58	2.83	3.25	3.55	4.10
RAK-2015-03	2.30	2.52	2.79	2.98	3.37	3.74
RAK-2015-04	2.11	2.47	2.98	3.30	3.42	3.84
RAK-2015-07	2.21	2.53	2.93	3.31	3.51	3.82
RAK-2015-08	2.42	2.78	3.28	3.53	4.15	4.76
RAK-2015-09	2.13	2.49	3.01	3.62	4.27	4.86
RAK-2015-10	2.89	3.41	3.56	3.66	4.21	4.98
S.Em±	**0.27**	**0.16**	**0.01**	**0.04**	**0.28**	**0.26**
CD(P=0.05)	**0.80**	**0.50**	**0.02**	**0.11**	**0.87**	**0.78**

Carbon stock in the soil

Carbon sequestration in soil is determined at the depths of 15, 30 and 45 cm using the following formula

Carbon Stock (Mg C ha^{-1}) = BD (g/cc) x OC (%) x depth (m)

Collection and analysis of soil samples

The soil samples were collected at 0-15 cm, 15 -30 cm and 30-45 cm depth to estimate the soil organic carbon at various depths. Whereas, soil samples were collected 0-15 cm to estimate pH, EC and NPK. Soil samples were dried under shade and gently crushed in mortar and sieved using 2 mm sieve. Soil samples were analyzed for chemical properties such as pH, EC, NPK and organic carbon using standard protocols. pH and electric conductivity were estimated using 1:2.5 soil water suspension (Jackson, 1973). Organic carbon in soil was estimated by rapid titration (Walkley and Blacky, 1938), available nitrogen by alkaline potassium permanganate method given by Subbiah and Asija (1956), available phosphorus by Olsen extraction using spectrophotometer and available potassium by flame photometric method (Jackson, 1973).

Statistical analysis

The experimental data generated from the experiment was subjected to statistical analysis using Fisher's method of analysis of variance. The level of significance used in "F'' test was 5 % agroforestry studies. Critical difference (CD) values were calculated at 5 per cent level of significance whenever "F" test was found significant.

RESULTS AND DISCUSSION

In the first year of planting, there was no significant changes in the tree height (Table 2). During the second year after planting, RAK-2015-10 recorded a higher tree height (3.41m), followed by RAK-2015-01, which was superior over the other clones. After the 3rd and 4th year of planting, RAK-2015-10 recorded higher tree height, whereas in the 5th year, RAK-2015-09 recorded higher tree height (4.27 m), followed by RAK-2015-10 and RAK-2015-08. After 6th year of planting among different clones, RAK-2015-10 recorded higher tree height (4.98 m), followed by RAK-2015-09 and RAK-2015-08. There were variations with respect to the tree increment rate over the years.

Diameter at breast height varied significantly among the different clones (Table 3). Significantly higher diameter upto 4 years of planting was recorded by RAK-2015-10. The minimum diameter at breast height was recorded in all years by RAK-2015-07. During 5th and 6th year of planting RAK-2015-01 recorded higher diameter (14.25 cm) followed by RAK - 2015-08 and RAK-2015-10.

The inherent genetic variability among the different clones, which controls their growth potential, resource efficiency, and environmental adaptability, is the main cause of the observed variation in growth and increment rates among *Pongamia pinnata* clones across different years (Chen *et al.*, 2025). A similar observation was also made by Ravi *et al.*, 2025 states that RAK-2015-10 performed better in terms of height compared to other clones.

Clones of Pongamia performed differently with respect to canopy cover due to variations in their genetic characteristics. However, the changes were significant in the initial two years of planting. After 2 years, there were no significant changes in the crown cover. Clonal selection RAK-2015-10 recorded better spread in North-South and East-West directions (3.47 m, 3.17 m and 4.15 m and 3.71 m) during the 2 years of establishment. RAK-2015-01 recorded maximum canopy cover during the 3rd, 4th and 5th years of establishment (Table 4). Variations in the canopy cover in N-S and E-W directions were monitored to evaluate the clones for their growth and performance over the years. Different *Pongamia* clones exhibit inherent genetic variations that regulate growth habit, crown architecture and branching pattern. Canopy spread increases as Pongamia trees mature, driven by increased branching and crown expansion (Danu *et al.*, 2024).

Different clones of Pongamia differed significantly over the years on volume of biomass produced year after year (Table 5). During the 1st year, RAK-2015-01 produced more biomass and volume of 7.41 m^3 compared to other clones, with a minimum biomass of 0.89 m^3 produced by RAK-2015-07. Further, with the incremental rate, RAK-2015-10 performed better with volume in the 2nd, 3rd, 5th and 6th year except during the 4th year. Clonal selection RAK-2015-07 recorded a lesser volume per hectare over the years. Superior clones convert assimilates more efficiently into the stem, branches and root biomass, resulting in higher wood volume. Age-related accumulation, genetic potential, effective photosynthesis, canopy growth, and favourable climatic conditions are the main causes of increased volume and to-

Table 3: Diameter at breast height (DBH) of *Pongamia pinnata* clones

Clones	Diameter at breast height (cm)					
	1st year	2nd year	3rd year	4th year	5th year	6th year
RAK-2015-01	9.78	10.11	11.07	12.13	12.96	14.25
RAK-2015-02	9.29	9.95	10.21	10.37	10.77	11.21
RAK-2015-03	9.53	9.79	10.31	11.16	12.22	13.04
RAK-2015-04	9.29	9.96	10.76	11.14	11.69	12.03
RAK-2015-07	3.97	4.57	5.14	5.70	6.39	6.97
RAK-2015-08	8.64	9.98	10.91	12.19	12.95	13.51
RAK-2015-09	8.83	9.58	10.04	11.08	11.62	12.60
RAK-2015-10	9.98	10.56	11.61	12.26	12.82	13.27
S.Em±	**0.03**	**0.04**	**1.09**	**0.01**	**2.41**	**1.35**
CD (P=0.05)	**0.12**	**0.13**	**3.73**	**0.05**	**NS**	**4.13**

Table 4: Canopy cover (m) of *Pongamia pinnata* as influenced by different clones

Clones	1st Year		2nd Year		3rd Year		4th Year		5th Year	
	N-S	E-W	N-S	E-W	N-S	E-W	N-S	E-W	N-S	E-W
RAK-2015-01	2.59	2.46	2.84	2.73	3.83	3.39	4.30	3.70	4.63	4.31
RAK-2015-02	2.62	2.41	2.96	2.69	3.23	2.64	3.63	3.00	3.94	3.27
RAK-2015-03	2.68	2.49	3.11	2.84	2.38	2.41	3.97	3.35	3.57	3.52
RAK-2015-04	3.01	2.77	3.43	3.38	2.56	2.89	3.03	3.20	3.50	3.78
RAK-2015-07	2.75	2.79	3.56	3.30	3.07	2.78	3.47	3.22	3.85	3.75
RAK-2015-08	2.51	2.51	2.73	2.58	3.69	3.02	4.15	3.38	4.50	3.88
RAK-2015-09	2.24	2.12	2.69	2.47	3.05	3.15	3.40	3.45	3.72	3.81
RAK-2015-10	3.47	3.17	4.15	3.71	3.22	3.38	3.58	3.67	4.04	4.14
S.Em±	0.19	0.20	0.01	0.01	0.54	0.54	0.49	0.52	0.58	0.54
CD (P = 0.05)	0.58	0.62	0.03	0.03	NS	NS	NS	NS	NS	NS

tal biomass throughout time (Sahoo *et al.*, 2021). Clones with superior growth features and more effective resource utilisation result in higher biomass and volume production (Chen *et al.*, 2025).

Total biomass produced by pongamia clones over the years was measured periodically and the results showed significant differences (Fig. 1). During the 1st year of RAK-2015-01, it recorded significantly higher biomass (7.66 t ha^{-1}) over all the other clones. In the second and third year, RAK-2015-10 recorded higher biomass (12.96 and 15.77 t ha^{-1}). During the 3rd year, RAK-2015-08 recorded significantly higher biomass (17.04 t ha^{-1}), followed by RAK-2015-01 and RAK-2015-10. There was non-significant biomass production by the pongamia clones during the 5th year. In the recent year (2025-26), RAK-2015-10 produced significantly higher biomass (41.77 t ha^{-1}), followed by RAK-2015-01 and RAK-2015-08. However, the performance of RAK-2015-07 clone was found to be the least biomass production and not comparable to any of the clones in all the years.

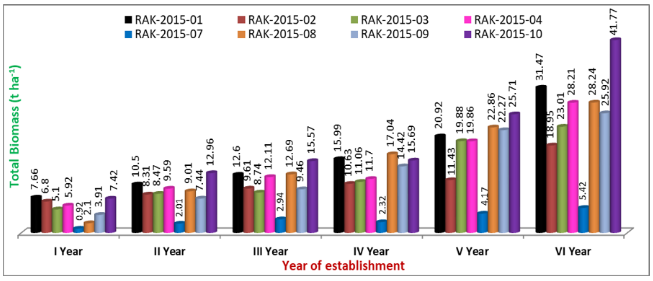

Figure 1: Total biomass (t ha-1) of Pongamia pinnata as influenced by different clones

Carbon sequestration potential of all the clones under the study was calculated based on growth characteristics and biomass production (Table 6). During the first year, RAK-2015-01 sequestered significantly higher carbon compared to all other clones (14.04 t ha^{-1}). In the 2nd and 3rd year, RAK-2015-10 recorded higher carbon sequestration potential (23.76 and 28.54 t ha^{-1}) over other clones, and a similar trend was followed during 5th and 6th year (47.13 and 76.58 t ha^{-1}) except during 4th year, wherein RAK-2015-08, which recorded the maximum carbon sequestration potential (31.24 t ha^{-1}). The C sequestration potential by RAK-2015-07 was non-significant in all the years of study.

The potential of tree carbon sequestration is determined by the location and method of tree planting. The results clearly state that older trees sequester more carbon when compared to younger trees. Genetic traits, environment, density and age of the trees were also attributed to variations in carbon sequestration in Pongamia clones (Soni *et al.*, 2023). The trees support a large number of leaves, have a high woody biomass, and enhance carbon fixation, which can eventually sequester more carbon and serve as a long-term carbon sink. This helps in reducing the greenhouse effect and climate change (Norby *et al.* 2024). In the present study, RAK-2015-10 noticed highest height and biomass, which helps in sequestering more carbon and these results are in line with the findings of Ravi *et al.* (2025) wherein, RAK-2015-10 performed better than other clones in terms of carbon sequestration under an agroforestry system.

Carbon stock in soil was assessed after 5 years of study. There were significant changes with respect to different soil depths. Carbon stock varied with depth among the various clones however, RAK-2015-10 recorded higher C stock in all the depths (10608, 6936 and 5100 kg ha^{-1}, respectively). Significantly lower C stock was noticed in RAK-2015-09 clone at 0-15, 15-30 and 30-45 cm depths (Fig. 2). The higher accumulation in the top soil might be due to higher accumulation of organic carbon by the decomposition of leaf litter by

Table 5: Volume (m^3 ha^{-1}) of *Pongamia pinnata* as influenced by different clones

Clones	1st year	2nd year	3rd year	4th year	5th year	6th year
RAK-2015-01	7.41	10.16	12.20	15.48	20.25	30.46
RAK-2015-02	6.58	8.04	9.30	10.29	11.06	18.34
RAK-2015-03	4.93	8.20	8.46	10.70	19.24	22.27
RAK-2015-04	5.73	9.28	11.72	11.32	19.23	27.30
RAK-2015-07	0.89	1.94	2.85	2.24	4.04	5.24
RAK-2015-08	2.03	8.72	12.28	16.49	22.12	27.33
RAK-2015-09	3.79	7.20	9.15	13.96	21.56	25.08
RAK-2015-10	7.18	12.55	15.07	15.18	24.88	40.43
S.Em±	0.06	0.09	0.83	1.31	7.54	5.91
CD (P=0.05)	0.17	0.28	2.53	4.01	NS	18.11

Table 6: CO_2 sequestration (t ha^{-1}) potential of *Pongamia pinnata* at different growth stages as influenced by clones

Clones	1st year	2nd year	3rd year	4th year	5th year	6th year
RAK-2015-01	14.04	19.25	23.10	29.31	38.35	57.68
RAK-2015-02	12.46	15.23	17.62	19.49	20.95	34.73
RAK-2015-03	9.34	15.54	16.02	20.27	36.44	42.18
RAK-2015-04	10.86	17.58	22.19	21.45	36.41	51.71
RAK-2015-07	1.69	3.68	5.39	4.24	7.65	9.93
RAK-2015-08	3.85	16.51	23.25	31.24	41.90	51.77
RAK-2015-09	7.17	13.63	17.33	26.44	40.83	47.51
RAK-2015-10	13.61	23.76	28.54	28.75	47.13	76.58
S.Em±	0.11	0.17	1.57	2.48	14.28	11.20
CD (P=0.05)	0.33	0.53	4.81	7.59	NS	34.31

the Pongamia clones (Negash and Starr, 2021). Similar variations were also noticed by Giweta (2020) that decomposition of leaf litter results in the formation of soil organic matter and nutrient cycling, contributing significantly to topsoil carbon accumulation.

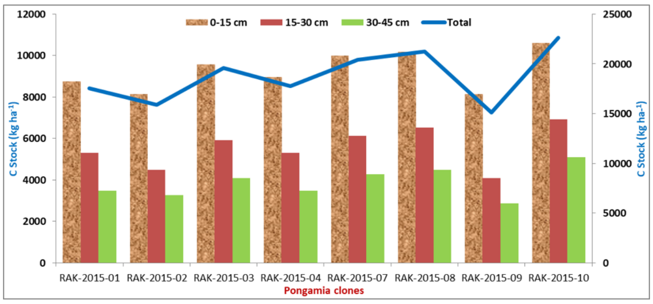

Figure 2: Carbon stock in soil (kg ha-1) influenced by Pongamia pinnata clones at different growth stages

Pongamia growth over the years influenced a few soil chemical properties (Table 7). There was improvement in soil properties due to pongamia clones, with respect to soil pH, electrical conductivity and organic carbon status, there was a slight positive variation recorded. However, Primary nutrient status in soil differed significantly among the clones when compared to initial values. Significantly higher availability N was recorded under RAK-2015-10 (278.18 kg ha^{-1}) over the other clones. Soil under RAK-2015-10 clone recorded significantly higher availability of P_2O_5 and availability of K_2O over the other clones (29.65 and 211.09 kg ha^{-1}), followed by RAK-2015-09 and RAK-2015-08 clones. Irrespective of clones, major nutrient availability was improved due to the litter fall, carbon sequestration and nodulation potential of different clones. Pongamia is a fast-growing tropical legume tree that accumulates biomass quickly and is ideal for the sequestration of carbon. The crop has its ability to form symbiotic associations with beneficial soil microbes, such as rhizobia and mycorrhiza that provide the tree with critical nutrients (Kumar *et al.*, 2017). The increased availability of nutrients resulted in increased production of photosynthates and their translocation into leaves and branches. The higher amount of nitrogen in the soil might be due to the addition of organic, manures, fertilizers. However, *Pongamia pinnata* is nitrogen fixing tree species, which helps to accumulation of more nitrogen; this may be one of the reasons for increased available nitrogen under *Pongamia pinnata* plantation. These results are in conformity with the findings of Parasuram, 2013. The litter fall and its decomposition over the years might have accounted for the improved availability of carbon and other major nutrients in soil.

CONCLUSION

The present study was conducted to assess the growth, biomass and carbon sequestration potential of various Pongamia clones along with soil carbon stock, including nutrient status of soil. The study found that *Pongamia pinnata* clones vary significantly in growth, biomass and carbon sequestration within an agroforestry system. RAK-2015-01 performed better in the early growth stage, but RAK-2015-10 consistently outperformed the other clones in height, biomass accumulation and carbon sequestration over time. Carbon sequestration was increased with age of the tree and biomass, emphasizing the significance of choosing high-performing clones for long-term climatic benefits. Pongamia also increased soil carbon storage and nutritional status, showing its importance in soil fertility. Overall, *Pongamia pinnata* is a good species for sustainable agroforestry and climate change mitigation, as RAK-2015-10 is shown to be the most promising clone for maximizing production of biomass and carbon sequestration.

Table 7: Soil chemical properties and soil nutrient status as influenced by Pongamia clones (2025-26)

Clones	pH (1:2.5)	EC (dS m^{-1})	Organic Carbon (%) (0–15 cm)	Organic Carbon (%) (15–30 cm)	Organic Carbon (%) (30–45 cm)	Available N (kg ha^{-1})	Available P_2O_5 (kg ha^{-1})	Available K_2O (kg ha^{-1})
RAK-015-01	5.32	0.46	0.46	0.28	0.18	242.56	23.58	191.52
RAK-015-02	5.26	0.47	0.42	0.24	0.17	232.47	23.72	190.46
RAK-015-03	5.39	0.38	0.48	0.31	0.22	253.14	24.41	200.76
RAK-015-04	5.27	0.39	0.45	0.27	0.20	242.28	23.48	191.78
RAK-015-07	5.46	0.36	0.50	0.32	0.22	254.28	25.39	207.25
RAK-015-08	5.51	0.36	0.52	0.33	0.21	274.26	25.69	208.19
RAK-015-09	5.24	0.48	0.45	0.23	0.18	235.28	22.25	190.26
RAK-015-10	5.57	0.35	0.54	0.36	0.27	278.18	29.65	211.09
S.Em ±	0.08	0.07	0.06	0.05	0.04	0.93	0.50	2.99
C.D @ 5%	NS	NS	NS	NS	NS	3.13	1.62	9.04
Initial	5.28	0.41	0.43	0.26	0.17	232.94	18.46	182.88

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