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ANALYTICAL STUDY OF INTEGRATED NUTRIENT MANAGEMENT ON YIELD OF ARECANUT AND SOIL NUTRIENT STATUS UNDER ASSAM CONDITIONS OF NORTH EAST REGION OF INDIA

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ABSTRACT

Arecanut (*Areca catechu* L.) is a vital plantation crop in Assam and the North Eastern region of India, yet its productivity remains low due to poor nutrient management. A ten-year field experiment (2015-2024) was conducted at ICAR-CPCRI, Kahikuchi, Assam, to evaluate the impact of integrated nutrient management (INM) on yield and soil nutrient dynamics in adult arecanut palms. Treatments included varying combinations of vermicompost and chemical fertilizers. Results revealed that the combined application of 2/3rd vermicompost and 1/3rd recommended dose of fertilizers (T_7) consistently produced the highest chali yield, with yield increment of about 46% over the control. Soil analyses showed that INM enhanced organic carbon, balanced macro and micronutrient availability, and reduced soil acidification compared to sole fertilizer use. Correlation and PCA analyses highlighted strong associations among available N, P, and K with yield, while micronutrients exhibited treatment-specific interactions. The study concludes that INM is a sustainable strategy for improving arecanut productivity, maintaining soil fertility, and supporting long-term ecological and economic sustainability of the crop under Assam conditions.
***Keywords* :** Arecanut, nutrient combination, soil fertility status, chali yield.

Introduction

Arecanut is an important plantation crop grown in Assam and other parts of North East region of India. Area under this crop in Assam is estimated to be 67,000 hectares with a production of 50,040 tonnes and productivity of 747 kg/ha (DASD, 2021). Though Assam contributes significantly to the arecanut sector (22% of area and 17% of production), the productivity is very low compared to the national average of 1.20 tonnes per hectare (Ray *et al*., 2008; DASD, 2021). Traditional practices of non-application of manures and fertilizers and lack of awareness on technological developments lead to poor production in the region. It is also worth to mention here that, arecanut being a perennial crop, provides economic return for 60 to 70 years, it is important and wise to adopt integrated nutrient management practices depending upon the availability of nutrient resources. Integrated nutrient management involves maintaining soil fertility and ensuring an optimal supply of plant nutrients to sustain desired productivity, by effectively managing all sources-organic, inorganic, and biological in a coordinated and integrated way. Integrated nutrient management not only reduces the use of chemical fertilizers by incorporating organic materials, but also help in enriching the soil with essential micronutrients and enhancing microbial activity. In recent years, the growing emphasis on sustainable agricultural practices has brought integrated nutrient management to the forefront as an effective approach to combat soil degradation, nutrient depletion, and environmental pollution caused by excessive use of synthetic fertilizers (Davari and Mirzakhani, 2009). Integrating the system, not only support long term crop productivity but also minimize negative environmental impacts. Impact of integrated nutrient management practices in enhancing soil nutrient status, providing balance nutrient lost and increasing yield have been reported in different agricultural crops (Singh *et al*., 2004; Mohandas, 2012). Studies also showed that no single source of plant nutrients, such as chemical fertilizers, organic manures, crop residues, and bio-fertilizers, can meet the entire nutrient need of a crop in today's intensive agriculture systems (Mahajan and Gupta, 2009). Taking this into consideration, a long term field experiment was conducted in an adult arecanut palm with different doses of fertilizer and vermicompost to study the yield of arecanut and fertility status of soil to ascertain the extend of improvement in arecanut through soil nutrient management.

Materials and Methods

Experimental site

A field experiment was conducted for a period of ten years (2015-2024) at ICAR-Central Plantation Crops Research Institute, Research Centre, Kahikuchi, Assam situated at 20° 18' N latitude and 91° 78' E longitude with an altitude of 50 m above the mean sea level (MSL). The mean maximum temperature varies from 15 to 32°C and the mean minimum temperature ranges between 8 and 22°C. The climate is sub-tropical with an annual average rainfall of about 1,500 mm. The soil of the experimental site was alluvial clay loam, with a pH range of 4.8 to 5.0.

Experimental design and treatments

The adult arecanut palms, aged 25 years old (*var*. Kahikuchi) were planted at the recommended spacing of 2.7 m x 2.7 m. The experiment was laid out in Randomized Blocks Design (RBD) with three replications and six palms per replication. The different treatments are T_1 (Control), T_2 (100% vermicompost @ 8 Kg/palm), T_3 (200% vermicompost @ 16 Kg/palm), T_4 (100% chemical fertilizer @ 220:250:240 g/palm/year), T_5 (50% vermicompost and 50% chemical fertilizer), T_6 (1/3rd vermicompost and 2/3rd chemical fertilizer) and T_7 (2/3rd vermicompost and 1/3rd chemical fertilizer). The chemical fertilizer including vermicompost was applied in two split dose at the base of each palm, once during the pre-monsoon season (April-May) and again during the post-monsoon season (Spetember-October), by placement in circular basins around the palm and subsequent incorporation into the soil. Fifty-gram borax were also applied in two split doses to maintain the homogeneity due to less or limiting content of boron in soil.

Soil Sampling and laboratory analyses

The soil samples were collected from three different palms from each replication during March before the onset of monsoon. Soil samples were collected from two opposite sides of the base of the palm 100 cm away from the bole at two different depths *viz*., 0-30 cm and 30-60 cm depth using an auger. The soil samples were cleaned; shade dried and kept in polythene bag for analysis. The soil samples were grinded and sieved in 2mm sieve. The samples were examined for soil pH, organic carbon (SOC), available N, available P, available K content and micro nutrient like zinc, copper, iron and manganese.

Available nitrogen in the soil was estimated using Kel-plus nitrogen distillation unit through alkaline potassium permanganate oxidation method (Subbiah and Asija, 1956), available phosphorus by following the procedure described by Bray and Kurtz (1945) and available potassium by using flame photometer through neutral normal ammonium acetate extraction method (Hanway and Heidel, 1952). The pH of the soil was measured using digital pH meter 335 (Jackson, 1973) and organic carbon by Walkley and Black (1934) chromic acid digestion method. Micro nutrients like Mn, Zn, Fe and Cu were analysed using Atomic Absorption Spectrometry (AAS) Plus.

Data analysis

The data for chali yield of arecanut, macro and micro nutrient were analyze using SPSS software version 26. Principal Component Analysis (PCA) and correlation chart computations were conducted using R software version 4.5.1.

Results and Discussion

Chali yield of arecanut

Chali yield per palm under different treatments is presented in Table 1. A significant variation in yield was observed across the years. The control consistently recorded lower yields; however, it remained statistically at par with T_4, T_6 and T_2 during 2015, 2017 and 2018, respectively. Notably, although the yield under T_7 was slightly lower than T_3 in the initial year (2015), it remained consistently higher in the subsequent years. The pooled mean revealed that palms receiving two-thirds vermicompost and one-third of the recommended dose of chemical fertilizer (T_7) produced significantly higher yields than other treatments, with an average increase of approximately 46%.These findings clearly demonstrate the benefits of integrated nutrient management over the exclusive use of inorganic fertilizers. The positive effect of T_7 may be attributed to the synergistic role of vermicompost in improving soil physical properties, enhancing microbial activity and facilitating the slow and sustained release of nutrients, thereby complementing the readily available nutrients from chemical fertilizers. Such combinations ensure balanced nutrient availability, reduce nutrient losses, and improve soil organic matter content, which are critical for perennial crops like arecanut that have a long reproductive cycle. Kumbar *et al.*, (2025) similarly reported yield enhancement in arecanut under integrated nutrient management in Uttara Kannada district of Karnataka. Long-term adoption of such integrated approaches is expected to not only sustain yield but also improve soil health and resource-use efficiency, making the system more resilient under changing climatic conditions. This positive response corroborates earlier findings in Arecanut where integrated nutrient management significantly enhanced yield and soil fertility (Bhat and Sujatha, 2013; Hebbar *et al.*, 2015)

Soil nutrient status

The soil nutrient status *viz*., pH, organic carbon and available N, P, K at two different depths are presented in Table 2. Soil pH in surface showed that treatment with T_4 and T_6 was found to be comparatively less than other treatments. Application of more inorganic fertilizer might have added acidic properties to the soil. High rainfall and humid nature might also lead to the binding of cations and organic acids resulting in leaching of soluble solids, thereby increasing the acidity of the soil. The sub-surface soils were found to be less acidic irrespective of the treatments. Organic carbon content in soil was found to be higher in surface soil as compared to sub surface soil which was due to more plant litters and root debris accumulation (Lungmuana and Lalparmawii, 2023). Higher organic carbon content was found in the treatment, 200% vermicompost (T_3) both in surface and sub-surface soil. This might be due to direct addition of water soluble carbon through vermicompost in a higher proportion. Similar findings were also reported by Singh *et al.*, (2009). Organic carbon content was generally higher in treatments that received organic inputs, with T_3 (1.30%) and T_5 (1.24%) at 0-30 cm showing a marked improvement over the control (1.05%). This highlights the role of vermicompost in enhancing soil organic matter and sustaining microbial activity. Available soil nitrogen in surface soils differed significantly among the treatments. Build up available nitrogen was observed more in surface soil than the sub surface soil. Higher available nitrogen was observed in the treatment with 50% chemical fertilizer and 50% vermicompost (T_5). However, was found to be statistically at par with T_6 and T_7. Study also showed that combined application of organic and inorganic fertilizer was found to produced higher available nitrogen than fully organic and chemical. Available nitrogen (N) content was significantly higher in T_5 (228.24 and 219.23 kg ha^{-1} at 0–30 and 30–60 cm, respectively), followed by T_6 and T_7, while the control (T_1) recorded the lowest values. The increase in available nitrogen (N) under integrated nutrient management treatments may be attributed to better synchronization of N release from vermicompost with that of chemical fertilizers (Hebbar *et al.*, 2015). Available phosphorus (P) was highest under T_4 (17.0 and 14.8 kg ha^{-1}), which could be due to enhanced solubilization of P in the presence of organic matter and sustained release from rock phosphate (Sujatha and Bhat, 2012). Similarly, available potassium (K) content was significantly higher in T_4 and T_5 (>230 kg ha^{-1} at surface depth) compared to the control (157.66 kg ha^{-1}), indicating the positive contribution of organic inputs in releasing exchangeable K through mineral weathering and organic acid production (Srinivasan *et al.*, 2010).

Overall, the results suggest that combined application of vermicompost and chemical fertilizers improves soil fertility by enhancing organic carbon and nutrient availability compared to chemical fertilizer application alone. These findings corroborate earlier reports of improved nutrient status under integrated nutrient management in arecanut and other plantation crops (Bhat and Sujatha, 2013; Singh *et al.*, 2018)

With respect to available phosphorus and potassium content in the soil, treatment with 100% chemical fertilizer was found to increase the availability of both the minerals. Lowest available phosphorus and potassium was observed in control (T_1). Continuous application of straight fertilizer might have resulted in buildup of more available phosphorus and potassium. Similar trend was observed in sub-surface soil with comparatively less available phosphorus and potassium as compared to surface soil.

Table 1 : Yield of chali (Kg/palm/year)

Treatment	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	Pooled mean
T_1	2.08	1.79	1.62	1.69	1.67	1.59	1.57	1.54	1.56	1.52	1.66
T_2	2.50	2.37	1.78	1.77	2.27	1.80	1.75	1.81	1.79	1.83	1.97
T_3	2.57	2.39	2.05	2.26	2.38	1.95	1.87	2.11	2.09	2.03	2.17
T_4	2.27	2.19	1.91	2.36	2.31	2.06	2.02	2.06	2.14	2.19	2.15
T_5	2.25	2.26	1.89	2.49	2.42	2.30	2.29	2.39	2.33	2.28	2.29
T_6	2.18	2.14	2.16	2.21	2.51	2.22	2.15	2.27	2.21	2.31	2.24
T_7	2.52	2.62	2.28	2.56	2.65	2.34	2.30	2.43	2.37	2.35	2.43
CD (0.05%)	0.25	0.17	0.21	0.11	0.11	0.10	0.13	0.17	0.17	0.18	0.08

Table 2 : Soil chemical properties at different depth under integrated nutrient management

Treatment	pH		OC (%)		Available N (kg ha^{-1})		Available P (Kg ha^{-1})		Available K (Kg ha^{-1})	
	0-30 cm	30-60 cm	0-30 cm	30-60 cm	0-30 cm	30-60 cm	0-30 cm	30-60 cm	0-30 cm	30-60 cm
T_1	5.01	4.90	1.05	0.92	192.19	183.54	13.4	11.4	157.66	145.64
T_2	5.04	5.01	1.11	1.08	207.45	195.06	14.2	12.4	184.53	176.92
T_3	5.12	5.23	1.30	1.12	208.19	199.79	14.6	13.0	199.82	187.09
T_4	4.46	6.25	1.14	0.98	209.82	203.49	17.0	14.8	248.33	240.61
T_5	5.01	5.12	1.24	1.05	228.24	219.23	16.2	14.2	237.13	226.73
T_6	4.50	5.00	1.06	0.95	223.22	214.52	15.6	12.4	219.16	208.52
T_7	5.00	5.46	1.12	1.01	220.21	213.61	15.2	13.2	205.03	195.28
CD (0.05%)	0.13	0.22	0.06	0.05	8.97	8.51	1.24	1.33	36.19	36.41

Table 3 : Micro nutrient concentration under different treatments

Treatment	Mn (ppm)	Fe (ppm)	Zn (ppm)	Cu (ppm)
T_1	30.14	26.00	0.84	0.98
T_2	21.20	27.80	0.92	0.93
T_3	23.96	26.00	0.83	0.90
T_4	30.84	19.62	0.66	0.72
T_5	28.16	19.80	0.65	1.01
T_6	17.40	20.58	1.02	1.04
T_7	24.88	16.64	0.72	1.08
CD (0.05%)	NS	NS	0.22	NS

Soil micronutrient

Among the treatment, the highest Mn content was obtained in 100% chemical fertilizer (2.27% higher than control) while lowest was observed under combined application of vermicompost and chemical fertilizer. Application of appropriate rates of chemical fertilizers can increase soil Mn availabilities in soil (Li *et al*., 2007). Available Mn was lowered in different treatment over control except under 100% chemical fertilizer. Chemical fertilization with nitrogen as ammonium form results in soil acidification, due to this reason an increases in Mn content was observed. The highest micronutrient availability was observed in soil with the lowest pH (Li *et al*., 2007; Rutkowska *et al*., 2009; Sienkiewicz *et al*., 2009). Micronutrient are more soluble and then availability is higher when pH is low (Howe *et al*., 2024). Application of manure reduced the Mn availability because organic material reduced the concentration of free micronutrient cation in soil solution by forming organometallic complexes that improve phyto-availability and regulate micronutrient mobility in the soil profile (Sukirtee *et al*., 2021). Application of 100% vermicompost (T2) resulted in higher Fe content compared to control. However, other treatment showed decline in Fe content over control with the lowest under combined application of 2/3rd vemicompost and 1/3rd chemical fertilizer. Application of vermicompost increase Fe availability as nutrients are released gradually during decomposition and mineralization process. Organic substances which are released during the mineralization may act as chelates thereby helping in absorption of Fe and other micro-nutrients (Thakur *et al*., 2023). The highest content of available Zn was observed in combine application of 1/3rd vemicompost and 2/3rd chemical fertilizer (T_6) followed by 100% vermicompost while lowest under chemical fertilizer alone (21.4% lower than control). The result indicates that vermicompost is a rich source of Zn as compared to chemical fertilizers alone (Raut *et al*., 2019). Due to organic manure having solubilizing effect on nutrient and chelating effect on metal ions resulted in increased availability (Thakur *et al*., 2023). Available Cu was observed to be higher in the treatment combination of vermicompost with chemical fertilizer (T_5, T_6, T_7) over sole application of vermicompost and chemical fertilizer. The higher content of available Cu with vermicompost might be due to that organic compound promote microbial activity and can chelate Cu^{2+} that increase the concentration and availability (Raut 2017). Combined application of inorganic fertilizers and FYM appears to be no risk of Cu deficiency but sole application poses such a risk (Agbenin and Henningsen 2004). Long-term integrate ion of NPK with FYM regulated the supply of micronutrients in soil-plant system over sole application and correcting the micronutrients deficiencies (Suri *et al*., 2024).

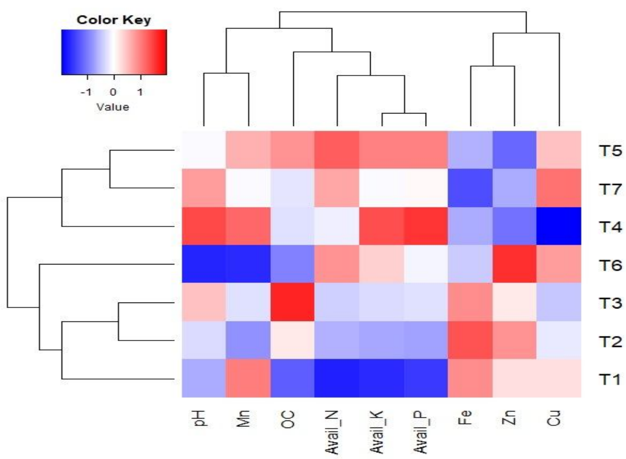

Fig. 1 : Heatmap showing the correlation among macro and micro nutrients

The heatmap illustrates the clustering of treatments (T_1-T_7) and soil properties based on their relative association. Treatments clustered into two major groups: (i) T_5, T_7, and T_4, and (ii) T_6, T_3, T_2, and T_1. The first group (T_5, T_7, T_4) was characterized by higher levels of soil organic carbon (OC), available nitrogen, phosphorus, and potassium, while the second group showed comparatively lower nutrient availability. This suggests that treatments incorporating organic amendments (T_5: 50% vermicompost + 50% chemical fertilizers, T_7: ⅔ vermicompost + ⅓ chemical fertilizers, and T_4: integrated treatments with organics) had a more positive impact on soil fertility than treatments receiving only chemical fertilizers (T_1, T_2).

Clustering of soil properties also revealed interesting associations. Organic carbon (OC) grouped closely with available N, P, and K, indicating the central role of organic matter in sustaining soil fertility. In contrast, pH and micronutrients (Zn, Cu, Fe, Mn) formed a separate cluster, suggesting that their variation was influenced more by soil chemical environment than by organic inputs. Notably, available potassium and phosphorus showed strong positive association with integrated nutrient management treatments, supporting the role of organics in enhancing nutrient release through mineral weathering and organic acid production. The consistently higher nutrient availability in T_7, followed by T_5, highlights the benefits of combining vermicompost with inorganic fertilizers, ensuring both immediate nutrient supply and long-term soil health. Similar findings were reported in arecanut-cocoa systems where integrated nutrient management improved soil organic carbon, available NPK, and microbial activity (Sujatha and Bhat, 2012). Earlier studies in arecanut also confirmed that partial substitution of chemical fertilizers with organics enhanced yield and improved nutrient cycling efficiency (Bhat and Sujatha, 2013; Hebbar *et al.*, 2015). These results align with broader plantation crop research, where balanced use of organics and inorganics has been shown to sustain productivity and soil health (Singh *et al.*, 2018; Srinivasan *et al.*, 2010). Thus, the clustering analysis corroborates the quantitative soil data, underscoring that integrated nutrient management strategies (particularly T_7) promote superior soil quality compared to sole reliance on chemical fertilizers

Principal Component Analysis

Principal Component Analysis (PCA) explained 73.3% of the total variance with Dim1 and Dim2 contributing 46.6% and 26.7%, respectively (Fig. 2). The distribution of treatments along these axes clearly indicated contrasting influences on soil properties. Treatments T_5 and T_7 were strongly associated with higher availability of macronutrients (N, P, K) and organic carbon, while treatments T_1, T_2, and T_3 clustered on the positive side of Dim1, showing strong association with micronutrients such as Fe, Zn, and Mn. Treatment T_6 was positioned towards the positive end of Dim1 and aligned with Cu availability. In contrast, T_4 was placed on the negative side of both axes, correlating with soil pH and Mn.

The biplot thus revealed that macronutrient enrichment (N, P, K, OC) and micronutrient enrichment (Fe, Zn, Cu, Mn) are differentially influenced by treatments, with no single treatment optimizing all nutrient pools. This highlights the importance of treatment-specific nutrient management strategies, where T_5 and T_7 can be preferred for enhancing soil fertility and organic matter build-up, while T_1-T_3 and T_6 favor micronutrient availability.

The scree plot (Fig. 2) illustrates the percentage of variance explained by each principal component (PC). The first two components together accounted for 73.3% of the total variation, with PC1 contributing 46.6% and PC2 contributing 26.7%**.** This indicates that the majority of variability in soil and nutrient parameters is effectively captured by the first two dimensions. PC3 and PC4 explained 13.4% and 9.8% of the variance, respectively, while the remaining components (PC5 and PC6) contributed marginally (<5%). According to the Kaiser criterion (eigenvalues >1) and the elbow rule visible in the scree plot, only the first two components were retained for further interpretation, as they captured the maximum variation and showed a sharp drop in explained variance thereafter. This suggests that Dim1 and Dim2 are sufficient to summarize the multidimensional dataset**,** allowing meaningful visualization of the relationship between treatments and soil properties. The dominance of the first two components is consistent with findings from multivariate analyses in soil fertility studies, where PCA effectively reduces data complexity while retaining key nutrient interactions (Jolliffe and Cadima, 2016; Sahoo *et al*., 2021).

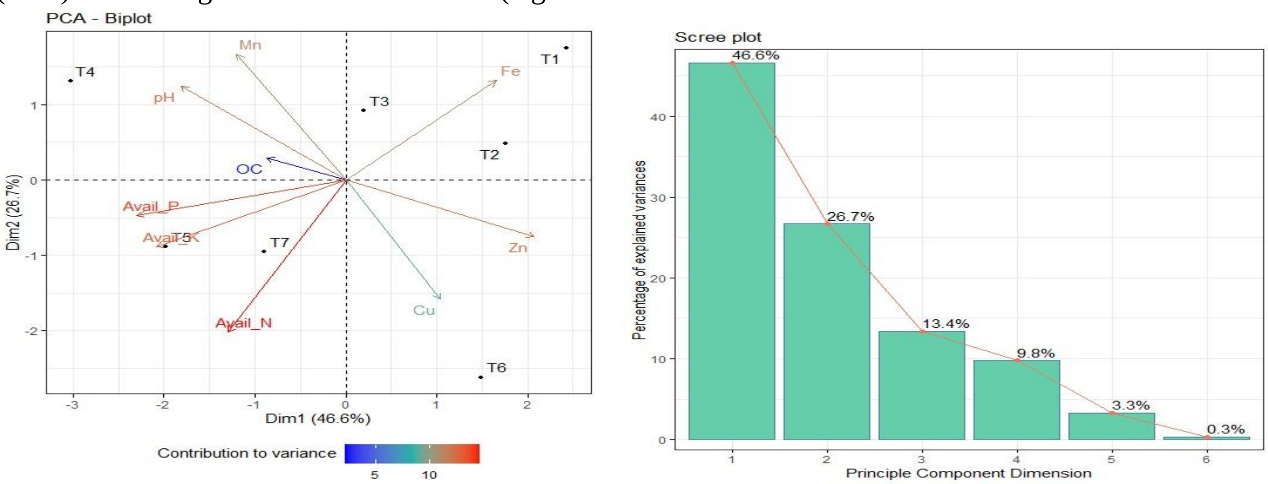

Fig. 2 : Principal component Biplot and Scree plot

Conclusion

The long-term study clearly demonstrates that integrated nutrient management (INM) significantly enhances both yield performance of arecanut and soil nutrient status under Assam conditions. Among the treatments, the combined application of 2/3rd vermicompost with 1/3rd chemical fertilizer (T_7) consistently produced the highest chali yield, reflecting nearly 46% improvement over control. The findings further highlight that blending organic and inorganic nutrient sources not only sustains higher productivity but also improves soil organic carbon, balances nutrient availability, and minimizes soil acidification compared to sole reliance on chemical fertilizers. Nutrient interaction analyses revealed that available N, P, and K were strongly correlated and positively associated with yield, while micronutrients such as Fe and Zn exhibited contrasting patterns, underscoring the need for balanced nutrient supplementation. The PCA and clustering analyses further emphasized that INM fosters favourable macronutrient enrichment while also regulating micronutrient availability, ensuring long-term soil fertility. Overall, the results confirm that integrated use of organic and inorganic inputs offers a sustainable strategy for improving arecanut productivity in the North Eastern region. Adoption of such practices will not only boost farmer income but also safeguard soil health, ensuring ecological and economic sustainability of arecanut cultivation in Assam.

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