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FERTILIZER USE EFFICIENCY AND SOIL NUTRIENT DYNAMICS UNDER VARYING LEVELS OF FERTIGATION SCHEDULES IN COCOA (*Theobroma cacao* L.) CULTIVATION ON ALFISOL

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ABSTRACT

A field study was conducted to evaluate the fertilizer use efficiency, soil nutrient dynamics and yield of cocoa (*Theobroma cacao* L.) under different levels of fertigation. The study compared different nitrogen, phosphorus, and potassium (NPK) application rates and methods, including conventional soil application and drip fertigation with both water-soluble and normal fertilizers. The results demonstrated that fertigation treatments significantly influenced the soil nutrient levels. Specifically, the application of 125% of recommended fertilizer dose [RFD] (125:50:175 g plant^{-1} year^{-1}) as water-soluble fertilizers through drip irrigation consistently resulted in highest soil organic carbon, available nitrogen, phosphorus, and potassium contents across the vegetative, flowering, pod set, and harvesting stages of crop growth. Available nitrogen and potassium contents showed a slight decrease with increasing soil depth (0-15 cm to 30-45 cm). However, drip fertigation with water-soluble fertilizers maximized available phosphorus at 30-45 cm depth. The findings suggest that drip fertigation with water-soluble fertilizers at 125% RDF enhances soil nutrient availability and distribution, leading to improved nutrient use efficiency in cocoa cultivation. The study recommends the adoption of appropriate fertigation strategy for optimizing the soil fertility during cocoa production under Alfisol conditions.

Keywords: Cocoa, fertigation, fertilizer use efficiency, soil nutrient dynamics, yield

INTRODUCTION

Cocoa (*Theobroma cacao* L.) is a major cash crop in many tropical countries (López *et al*., 2019). In India it is an introduced crop, with Kerala, Andhra Pradesh, Karnataka and Tamil Nadu as the major cocoa cultivating states. As per the Ministry of Agriculture and Family Welfare, Government of India, cocoa in India is grown on an area of 1,14,530 ha with an annual production of 32,910 t. In Tamil Nadu the crop covers an area of 33,610 ha with annual production of 3,120 t (Indiastat, 2026).

The conventional fertilizer application through soil manipulation is associated with low nutrient use efficiency, typically ranging from 30 to 35%, primarily due to the losses from volatilization (N), evaporation (N), and soil fixation (P & K) [Sathya *et al*., 2008; Ravanachandar *et al*., 2025]. Fertigation, defined as the targeted delivery of nutrients dissolved in irrigation water, represents a transformative approach in contemporary agriculture, diverging from conventional broadcast methods (Mote *et al*., 2024). This practice facilitates the precise and timely application of essential nutrients directly to the crop rhizosphere, thereby enhances the nutrient availability and uptake efficiency. In broader context of sustainable agricultural development, fertigation has emerged as a vital tool for optimizing soil nutrient dynamics. By synchronizing the nutrient inputs with crop physiological demands, it effectively reduces nutrient losses via leaching, volatilization, and surface runoff, ultimately improves the fertilizer use efficiency and mitigates environmental degradation (Smith and Jones, 2022).

The adoption of fertigation necessitates a thorough understanding of its effects on soil physico-chemical and biological properties, as these factors collectively govern nutrient cycling and availability. Recent studies have highlighted the complicated relationships between fertigation practices, soil microbial communities, and nutrient transformations, underscoring the need for site-specific management strategies to maximize its benefits (Kurniawan *et al*., 2024). Fertigation methods have a nutrient utilization efficiency of up to 90%, while conventional approaches only have an efficiency of 40-60% (Basavaraju *et al*., 2014). Right combination of water and nutrients are the key for high yield and quality of produce. Fertigation guarantees nutrient application directly to plant roots and has become more popular in almost all horticultural crops (Bandyopadhyay *et al.*, 2019). Cocoa quickly responds to the applied fertilizers to meet plant nutrient requirements. Fertigation techniques supply nutrients to the soil in sufficient amounts and at proper intervals, helps in enhancing the output quality. However, the information on fertilizer use efficiency, and soil nutrient dynamics under different fertigation schedules in cocoa, cultivated on Alfisol soil, is very limited. This study gives information on the process of nutrient delivery through fertigation which can be optimized to improve the nutrient absorption, enhance the soil fertility status, and ensure fertilizer efficiency usage in cocoa farming. Further, this study gives location-based recommendation for sustainable cocoa production under Alfisol soil conditions. With this back-ground, the present study was aimed to assess the impact of fertigation on soil nutrient dynamics and fertilizer use efficiency in cocoa cultivated under Alfisol soil conditions.

MATERIALS AND METHODS

The present field experiments were conducted from June 2012 to June 2014 in the Department of Spices and Plantation Crops, Horticultural College and Research Institute, TNAU, Coimbatore (India). The field tests were executed in a farmer's field in Thappattai Kilavan Pudur, situated in Pollachi Taluk, Coimbatore district, Tamil Nadu (India), 55 km away from the host institute. The research site, located at 10°58′0″ N latitude and 76°56′0″ E longitude, lies at an elevation of 844 m masl. The area has maximum temperatures between 27.9 and 37.5°C, and minimum temperatures between 18.8 and 24.5°C, with mean annual precipitation of ~700 mm. The soil is Alfisol, mostly red sandy loam. The crop was grown under drip irrigation system with specifications as: motor 10 HP, venturi 50 mm, main and sub-mains PVC (polyvinyl chloride) type, main line diameter 75 mm, sub-main diameter 63 mm, screen filter size 25 mm, control valve (ball valve) 63 mm, flush valve 40 mm, laterals LDPE (low density polyethylene) type, and lateral diameter 16 mm. Drippers were used as emitters, with two emitters provided per tree, each having a discharge rate of 8 L h^{-1}.

Experimental details

The field study was carried out for two years on the farms having 30-year-old coconuts (*Cocos nucifera*) inter-planted with 10-year-old cocoa trees. Cocoa was planted at a plant spacing of 3 m x 3 m between the two rows of coconut trees, with supplementary cocoa plants situated between the coconut trees in the same row. The cocoa population comprised of F_1 seedling progenies derived from the planting materials provided by Kerala Agricultural University. A plant density of 315 cocoa plants ha^{-1} was maintained throughout the trial. Cocoa flowered year-round, with two separate peak harvest seasons: March to May and September to November. The lean cropping phase was in March and April (flowering) and July (pod harvest), whereas the peak cropping phase was in September (flowering initiation) and December (pod harvest). The experiment was conducted in a randomised block design with three levels of NPK, replicated three times across the treatments.

The present study involved seven treatments, *viz*., T_1 (control) - 100% recommended fertilizer dosage (RFD) - 100:40:140 g NPK $plant^{-1}$ annually administered to the soil via flood irrigation (TNAU, 2004), T_2 - 75% RFD through drip irrigation using water-soluble fertilizers [WSF] (75:30:105 g NPK $plant^{-1}$ annually), T_3 - 100% RFD through drip irrigation using water-soluble fertilizers (100:40:140 g NPK $plant^{-1}$ annually), T_4 - 125% RFD through drip irrigation using water-soluble fertilizers (125:50:175 g NPK $plant^{-1}$ annually), T_5 - 75% RFD through drip irrigation employing conventional (straight) fertilizers (75:30:105 g NPK $plant^{-1}$ annually), T_6 - 100% RFD through drip irrigation employing conventional (straight) fertilizers (100:40:140 g NPK $plant^{-1}$ annually), and T_7 - 125% RFD through drip irrigation employing conventional (straight) fertilizers (125:50:175 g NPK $plant^{-1}$ annually). The fertilizers were applied in the form of urea (46% N), di-ammonium phosphate (18% N & 46% P) and muriate of potash (60% K), with sulphate of potash (50% K). The water-soluble fertilizers included urea (46% N), All-19 (19% N, 19% P, & 19% K), and Multi 'K', a proprietary water-soluble nitrogen and potassium fertilizer with 13% N and 45% K.

Soil application and irrigation [T_1 (control)]

Each cocoa tree received an annual allocation of 100 g N, 40 g P and 140 g K, in two equal splits. The first dosage was administered in the 1st week of April, and the second dose in the 1st week of September. Fertilizers were uniformly applied within a 60 cm radius around the base of each tree, gently forked, and meticulously mixed into the soil. Flood irrigation was conducted at weekly intervals to facilitate nutrient absorption and maintain ideal soil moisture levels.

Drip fertigation (fertigation: T_2 to T_7)

Fertilizers for treatments T_2 to T_7 were applied through a drip irrigation system (fertigation). The designated amount of fertilizers was dissolved in water and injected into the sub-main via a venturi, followed by distribution to the lateral lines in accordance with the treatment procedure. The fertilizers were classified based on the crop growth stage and applied biweekly.

Collection and processing of soil samples

A V-shaped cut was executed at each specified soil sampling location, reaching a depth of 15 cm. Soil slices with a thickness of 1.5 cm were extracted and subsequently placed in clean polythene bags for further processing. The samples corresponding to the identical treatments were meticulously homogenised and then reduced in volume through the quartering method to acquire representative aliquots for analysis. For chemical analysis, the representative soil samples from each treatment were crushed by a wooden mallet, dried in shade until they attained a consistent weight, and then sieved through a 2 mm screen. Surface soil samples (0-15 cm) were collected prior to the experimentation to assess baseline soil fertility status. The initial available NPK was 100.8, 18.85 and 195.02 kg ha^{-1}, respectively.

Nutrient analysis in soil samples

The soil organic carbon was determined by wet oxidation method (Walkley and Black, 1934). The available nitrogen was estimated as per alkaline potassium permanganate method (Subbiah and Asija, 1956). The available phosphorus was analysed calorimetrically using a Klett Summerson colorimeter fitted with a red filter at 600 nm (Olsen *et al*., 1954), while available potassium was measured flame photometerically (Hanway and Heidal, 1952).

Nutrient dynamics

To assess the nutrient dynamics, the soil samples were extracted with the help of a screw drill at 0-15, 15-30, and 30-45 cm depths in vertical direction, as well as at 0, 15, 30, and 45 cm depth from the irrigation emitter on the side. The samples were dried in an oven at 105°C for 24 h and NPK levels estimated. Contour mapping was performed using "Surfer" software package for Windows (Achat *et al*., 2009) to decipher the nutrient distribution in soil.

Statistical analysis

The data was statistically analysed as per Panse and Sukhatme (1978). Treatment-effects were evaluated for significance at 1% ($p \leq 0.01$) and 5% ($p \leq 0.05$) probability levels. Pooled analysis was performed across the four seasonal trials conducted over two-year period using the pooled RBD Module of TNAU Stat Software (Manivannan, 2011).

RESULTS AND DISCUSSION

Effect of fertigation on soil organic carbon

Fertigation treatments exhibited significant effects on soil organic carbon content (Table 1 and 2). Treatment T_4 consistently showed the highest soil organic carbon content across all the growth stages *viz*., vegetative, flowering, pod set, and harvesting during both the seasons of 1st year, with the values of 0.821, 0.828, 0.836, and 0.848%, respectively, in the first season, and 0.842, 0.849, 0.857,

Table 1: Effect of fertigation on soil organic carbon (%) in cocoa field at various growth stages (1st year)

Treatments	1st season				2nd season			
	Vegetative stage	Flowering stage	Pod set stage	Pod harvesting stage	Vegetative stage	Flowering stage	Pod set stage	Pod harvesting stage
T_1	0.722	0.728	0.736	0.752	0.748	0.755	0.762	0.773
T_2	0.758	0.763	0.775	0.795	0.794	0.802	0.808	0.819
T_3	0.786	0.791	0.804	0.820	0.815	0.820	0.829	0.837
T_4	0.821	0.828	0.836	0.848	0.842	0.849	0.857	0.865
T_5	0.730	0.737	0.745	0.767	0.763	0.767	0.776	0.782
T_6	0.752	0.760	0.769	0.783	0.776	0.781	0.790	0.799
T_7	0.758	0.765	0.772	0.796	0.793	0.800	0.810	0.817
SE$\pm$	0.024	0.024	0.025	0.025	0.025	0.025	0.025	0.026
$CD_{0.05}$	0.053	0.053	0.054	0.055	0.055	0.055	0.055	0.056

T_1 (control) - 100% RFD [100:40:140 g NPK plant^{-1} annually] applied to soil via flood irrigation, T_2 - 75% RFD through drip irrigation using water-soluble fertilizers, T_3 - 100% RFD through drip irrigation using water-soluble, T_4 - 125% RFD through drip irrigation using water-soluble fertilizers, T_5 - 75% RFD through drip irrigation via conventional fertilizers, T_6 - 100% RFD through drip irrigation via conventional fertilizers, and T_7 - 125% RFD through drip irrigation via conventional fertilizers; SE$\pm$ - Standard error deviation; CD = Critical difference.

Table 2: Effect of fertigation on soil organic carbon (%) in cocoa field at various growth stages (2nd year)

*Treat-ments	1st season				2nd season				Pooled mean (1st and 2nd year)			
	Vege-tative stage	Flowe-ring stage	Pod set stage	Pod harvesting stage	Vege-tative stage	Flowe-ring stage	Pod set stage	Pod harvesting stage	Vege-tative stage	Flowe-ring stage	Pod set stage	Pod harvesting stage
T_1	0.769	0.775	0.781	0.789	0.780	0.784	0.790	0.803	0.754	0.761	0.767	0.779
T_2	0.817	0.821	0.827	0.830	0.832	0.835	0.843	0.855	0.800	0.805	0.813	0.824
T_3	0.833	0.837	0.845	0.851	0.849	0.858	0.866	0.878	0.821	0.827	0.836	0.846
T_4	0.858	0.865	0.873	0.883	0.880	0.889	0.901	0.912	0.850	0.858	0.867	0.877
T_5	0.775	0.783	0.792	0.797	0.798	0.803	0.807	0.815	0.767	0.773	0.780	0.790
T_6	0.789	0.798	0.807	0.816	0.812	0.817	0.828	0.836	0.782	0.789	0.798	0.809
T_7	0.800	0.819	0.825	0.833	0.831	0.839	0.847	0.858	0.795	0.806	0.814	0.826
SE$\pm$	0.025	0.026	0.026	0.026	0.026	0.027	0.027	0.027	0.025	0.026	0.026	0.026
$CD_{0.05}$	0.055	0.056	0.056	0.057	0.057	0.058	0.058	0.059	0.051	0.051	0.052	0.052

*See Table 1 for treatment details

and 0.865%, respectively, in the second season. A similar trend was observed in 2nd year where T_4 registered peak values of 0.858, 0.865, 0.873, and 0.883% during the first season, and 0.880, 0.889, 0.901, and 0.912% during the second season (Table 1 and 2). In contrast, control treatment consistently had lowest soil organic carbon levels, with values of 0.722, 0.728, 0.736, and 0.752% in the first season, and 0.748, 0.755, 0.762, and 0.773% in the second season of 1st year. This trend persisted in the 2nd year seasons as well. Pooled mean analysis revealed that the application of 125% RFD through fertigation using water-soluble fertilizers via drip irrigation (T_4) had the highest soil organic carbon content, with values of 0.850, 0.858, 0.867, and 0.877% across the respective growth stages. These values were at par with those observed in T_3 (100% RFD via fertigation), which showed the corresponding values of 0.821, 0.827, 0.836, and 0.846%. The control treatment consistently exhibited lowest soil organic carbon levels throughout the study period.

Effect of fertigation on available soil nitrogen

The available soil N, collected throughout all four stages of crop growth and during seasons, demonstrated a consistent decreasing trend from vegetative stage to pod harvest stage (Table 3 and 4). All treatments depicted a notable impact on soil N levels during vegetative, flowering, pod set, and pod harvesting stages. Among the treatments, T_4 (125% RFD as WSF through fertigation by drip irrigation) demonstrated highest available soil N content, recording values of 141.70, 145.31, 149.74, and 155.75 kg ha^{-1} during the first season, and 145.60, 148.11, 159.01 and 162.34 kg ha^{-1} in the second season of 1st year (Table 3). Additionally, it showed values of 141.32, 148.25, 151.60 and 158.01 kg ha^{-1} in first season, and 151.00, 157.76, 162.11 and 169.79 kg ha^{-1} in the second season

Table 3: Effect of fertigation on available soil nitrogen (kg ha^{-1}) in cocoa field at various growth stages (1st year)

Treatments	1st season				2nd season			
	Vegetative stage	Flowering stage	Pod set stage	Pod harvesting stage	Vegetative stage	Flowering stage	Pod set stage	Pod harvesting stage
T_1	107.49	109.20	115.63	120.53	113.32	116.85	120.67	123.81
T_2	117.10	121.85	124.33	128.85	125.66	127.97	130.59	134.99
T_3	132.56	136.53	141.89	147.98	138.73	142.85	147.43	155.21
T_4	141.70	145.31	149.74	155.75	145.60	148.11	159.01	162.34
T_5	105.13	115.85	119.80	124.75	116.00	120.80	125.85	130.27
T_6	120.88	124.98	128.50	132.43	123.02	126.66	134.10	139.85
T_7	125.41	129.39	130.31	136.72	129.56	133.71	139.00	144.76
SE$\pm$	3.990	4.123	4.242	4.415	4.144	4.245	4.482	4.617
$CD_{0.05}$	8.693	8.983	9.242	9.619	9.031	9.249	9.764	10.059

* See Table 1 for treatment details

Table 4: Effect of fertigation on available soil nitrogen (kg ha^{-1}) soil organic carbon (%) of cocoa at different growth stages in 2nd year and the mean of two-years data

Treat-ments	1st season				2nd season				Pooled mean (1st and 2nd year)			
	Vege-tative stage	Flowe-ring stage	Pod set stage	Pod harvesting stage	Vege-tative stage	Flowe-ring stage	Pod set stage	Pod harvesting stage	Vege-tative stage	Flowe-ring stage	Pod set stage	Pod harvesting stage
T_1	115.00	119.75	121.74	125.41	119.33	123.84	128.79	132.21	113.78	117.41	121.70	125.49
T_2	120.60	122.01	125.63	130.99	128.43	133.95	136.31	140.81	122.94	126.44	129.22	133.90
T_3	135.84	141.87	146.85	149.31	139.22	145.89	149.87	159.82	136.59	141.78	146.51	153.08
T_4	141.32	148.25	151.60	158.01	151.00	157.76	162.11	169.79	144.90	149.85	155.61	161.47
T_5	117.51	120.88	125.72	128.05	122.40	128.42	130.42	133.81	115.26	121.49	125.45	129.22
T_6	126.75	130.65	133.99	137.83	131.05	136.43	140.55	144.75	125.42	129.68	134.28	138.71
T_7	131.89	135.17	138.43	142.88	136.24	141.39	143.63	149.88	130.77	134.91	137.84	143.56
SE$\pm$	4.093	4.255	4.362	4.515	4.309	4.498	4.612	4.810	4.136	4.282	4.426	4.592
$CD_{0.05}$	8.918	9.270	9.504	9.838	9.388	9.799	10.048	10.481	8.313	8.607	8.897	9.229

*See Table 1 for treatment details

of 2nd year at vegetative, flowering, fruit development, and fruit maturity stages, respectively. The treatment T_3 (100% RFD as WSF through drip irrigation) demonstrated the available soil N content of 132.56, 136.53, 141.89, 147.98 kg ha^{-1} and 138.73, 142.85, 147.43, 155.21 kg ha^{-1} in the first and second season of 1st year; and 135.84, 141.87, 146.85, 149.31 kg ha^{-1} and 139.22, 145.89, 149.87, 159.82 kg ha^{-1} in the first and second season of 2nd year, respectively, across all crop growth stages. The control group had lowest available soil N content of 107.49, 109.20, 115.63 and 120.53 kg ha^{-1} during the first season and 113.32, 116.85, 120.67 and 123.81 kg ha^{-1} during the second season of 1st year. In 2nd year, the first season yields were 115.00, 119.75, 121.74, and 125.41 kg ha^{-1}, while the second season yields were 119.33, 123.84, 128.79 and 132.21 kg ha^{-1}.

Effect of fertigation on available soil phosphorus

The available phosphorus content observed during four stages, *viz*., vegetative, flowering, pod set, and harvesting, of 1st and 2nd year are given in Table 6 and 7. The treatment fertigation application of 125% RDF as WSF (T_4) showed the highest accessible soil phosphorus content, with values of 35.10, 37.43, 36.50, 39.25 kg ha^{-1} and 33.56, 36.63, 39.85, 42.72 kg ha^{-1} in the 1st year, and 35.74, 38.11, 41.54 and 42.84 kg ha^{-1} in the first season and 34.09, 36.66, 41.08, and 46.15 kg ha^{-1} in the second season of 2nd year at the vegetative, flowering, pod set, and harvesting stages, respectively. Treatment (T_3), involving 100% RDF as WSF through fertigation, demonstrated the highest available soil phosphorus content. The lowest available soil phosphorus content was observed in control (T_1) in both the years.

Table 5: Effect of fertigation on available soil phosphorus (kg ha^{-1}) in cocoa field at different growth stages (1st year)

Treatments	1st season				2nd season			
	Vegetative stage	Flowering stage	Pod set stage	Pod harvesting stage	Vegetative stage	Flowering stage	Pod set stage	Pod harvesting stage
T_1	21.00	21.94	22.34	22.81	20.82	23.01	24.39	25.43
T_2	22.43	23.49	25.72	27.12	24.06	26.53	28.10	30.24
T_3	33.84	35.58	36.01	37.54	31.74	34.91	37.52	40.47
T_4	35.10	37.43	36.50	39.25	33.56	36.63	39.85	42.72
T_5	20.56	21.85	23.17	24.27	22.45	25.58	26.76	27.19
T_6	26.10	27.74	28.81	30.14	28.33	31.10	32.33	33.45
T_7	28.89	30.89	32.76	33.70	30.14	32.81	34.11	36.84
SE±	0.93	0.99	1.00	1.06	0.92	1.01	1.08	1.16
$CD_{0.05}$	2.03	2.16	2.18	2.30	2.01	2.21	2.36	2.52

*See Table 1 for treatment details

Table 6: Effect of fertigation on available soil phosphorus (kg ha^{-1}) in cocoa field at different growth stages in 2nd year and the mean of two year's data

Treat-ments	1st season				2nd season				Pooled mean (1st and 2nd year)			
	Vege-tative stage	Flowe-ring stage	Pod set stage	Pod harvesting stage	Vege-tative stage	Flowe-ring stage	Pod set stage	Pod harvesting stage	Vege-tative stage	Flowe-ring stage	Pod set stage	Pod harvesting stage
T_1	24.30	26.43	27.31	28.91	21.33	24.01	28.65	30.01	21.86	23.84	25.68	26.80
T_2	26.01	29.85	30.63	31.74	25.85	27.41	29.84	33.46	24.58	26.82	28.57	30.64
T_3	32.87	36.43	39.22	40.01	32.43	35.17	39.75	43.51	32.72	35.52	38.12	40.38
T_4	35.74	38.11	41.54	42.84	34.09	36.66	41.08	46.15	34.62	37.20	39.74	42.74
T_5	24.21	29.00	29.88	30.52	23.82	25.50	27.44	32.01	22.77	25.48	26.81	28.49
T_6	28.65	35.19	36.37	37.85	28.31	31.42	34.66	39.35	27.84	31.36	33.04	35.20
T_7	30.14	36.10	37.71	38.10	31.43	33.01	36.58	40.10	30.15	33.20	35.30	37.18
SE±	0.98	1.09	1.16	1.19	0.95	1.02	1.14	1.27	0.95	1.03	1.10	1.17
$CD_{0.05}$	2.12	2.36	2.52	2. 06	2.06	2.22	2.48	2.77	1.90	2.07	2.20	2.35

*See Table 1 for treatment details

Effect of fertigation on available soil potassium

The potassium content in soil showed an increase from the vegetative stage to the pod set stage, followed by a significant decrease during the harvesting stage (Table 8 and 9). Among the various treatments, T_4 (125% RDF as WSF through fertigation by drip irrigation) showed the highest available soil potassium content of 258.65, 270.66, 279.42 and 288.47 kg ha^{-1} during the first season and 274.47, 295.01, 301.14, and 310.17 kg ha^{-1} in the second season. Additionally, it showed values of 287.84, 301.55, 313.70, and 322.78 kg ha^{-1} in the first season and 300.79, 314.18, 321.13, and 330.72 kg ha^{-1} in the second season for the 1^{st} and 2^{nd} year, respectively, at the vegetative, flowering, fruit development and fruit maturity stages, which was equivalent to the treatment T_3 (100% RDF as WSF delivered via drip irrigation). The control (T_1) exhibited lowest available soil potassium content in both 1^{st} and 2^{nd} year.

The nutrient availability in soil is a crucial factor affecting the optimal plant growth and yield. Maintaining sufficient nutrient levels promotes the optimisation of fertilizer use, reduces nutrient loss, and improves plant health and nutrient utilisation (Goudsmit *et al*., 2023). Soil samples were analysed at critical crop growth stages to assess nutrient dynamics. Soil organic carbon is essential for maintaining and improving a range of soil physicochemical properties (Sudhakaran *et al*., 2018, 2023). The present study revealed that the use of water-soluble fertilizers via drip irrigation notably enhanced soil organic carbon levels. The hike in soil organic carbon in fertigation treatments may be attributed to the improved litter deposition. Comparable trends have been noted in forest plantation systems by Paul *et al*. (2002), Laganière *et al*. (2010) and Just *et al*. (2024). The study also assessed

Table 7: Effect of fertigation on available soil potassium (kg ha^{-1}) in cocoa field at different growth stages (1^{st} year)

Treatments	1^{st} season				2^{nd} season			
	Vegetative stage	Flowering stage	Pod set stage	Pod harvesting stage	Vegetative stage	Flowering stage	Pod set stage	Pod harvesting stage
T_1	200.85	215.40	223.65	230.21	229.25	235.52	240.01	246.33
T_2	216.97	226.31	234.11	241.13	238.61	243.62	251.53	257.72
T_3	240.23	252.79	260.30	266.15	265.08	272.31	277.65	282.65
T_4	258.65	270.66	279.42	288.47	274.47	295.01	301.14	310.17
T_5	205.11	217.32	228.53	233.52	232.10	239.00	245.68	249.72
T_6	223.72	230.63	236.76	245.73	240.88	246.92	258.45	265.66
T_7	230.64	236.79	243.84	252.26	249.90	255.66	261.34	273.17
SE$\pm$	7.35	7.69	7.94	8.18	7.95	8.34	8.54	8.79
$CD_{0.05}$	16.01	16.74	17.29	17.83	17.32	18.18	18.61	19.15

*See Table 1 for treatment details

Table 8: Effect of fertigation on available soil potassium (kg ha^{-1}) in cocoa field at different growth stages in 2^{nd} year and the mean of two year's data

Treat-ments	1^{st} season				2^{nd} season				Pooled mean (1^{st} and 2^{nd} year)			
	Vege-tative stage	Flowe-ring stage	Pod set stage	Pod harvesting stage	Vege-tative stage	Flowe-ring stage	Pod set stage	Pod harvesting stage	Vege-tative stage	Flowe-ring stage	Pod set stage	Pod harvesting stage
T_1	219.91	230.60	240.00	251.99	229.18	237.66	246.01	255.76	219.80	229.79	237.42	246.07
T_2	232.74	242.54	250.91	263.81	247.81	255.85	265.46	272.27	234.03	242.08	250.50	258.73
T_3	261.01	277.11	288.54	298.65	266.82	276.01	283.51	295.49	258.29	269.56	277.50	285.74
T_4	287.84	301.55	313.70	322.78	300.79	314.18	321.13	330.72	280.44	295.35	303.85	313.03
T_5	225.51	235.76	243.81	259.80	241.64	250.90	259.87	263.65	226.09	235.74	244.48	251.68
T_6	239.82	248.60	254.52	266.52	254.99	264.54	270.55	277.64	239.85	247.68	255.06	263.89
T_7	246.60	255.83	263.17	287.96	265.41	272.41	280.10	289.82	248.13	255.17	262.11	275.80
SE$\pm$	8.06	8.43	8.74	9.13	8.48	8.81	9.04	9.31	7.97	8.33	8.57	8.86
$CD_{0.05}$	17.56	18.37	19.05	19.89	18.47	19.19	19.69	20.29	16.01	16.73	17.23	17.82

*See Table 1 for treatment details

the availability of nutrients under various fertigation techniques during different phases of crop growth. The maximum amounts of accessible N, P and K were obtained by applying drip fertigation using water-soluble formulations at 125% of RFD. The nutrients were transported along the water flow route and concentrated at the borders of wetted region, thus drip irrigation improved the nutrient mobility. These results are in conformity with previous works on mango (Karthick, 2011), and capsicum (Sureshkumar, 2000; Kumar *et al*., 2020).

Effect of fertigation on nitrogen dynamics

The levels of essential soil nutrients, specifically N, P and K, were assessed at three depths *viz*., 0-15, 15-30, and 30-45 cm. In drip fertigation treatments, N levels available in soil showed a progressive increase with the application of higher fertilizer doses, specifically ranging from 75 to 125% of RFD.

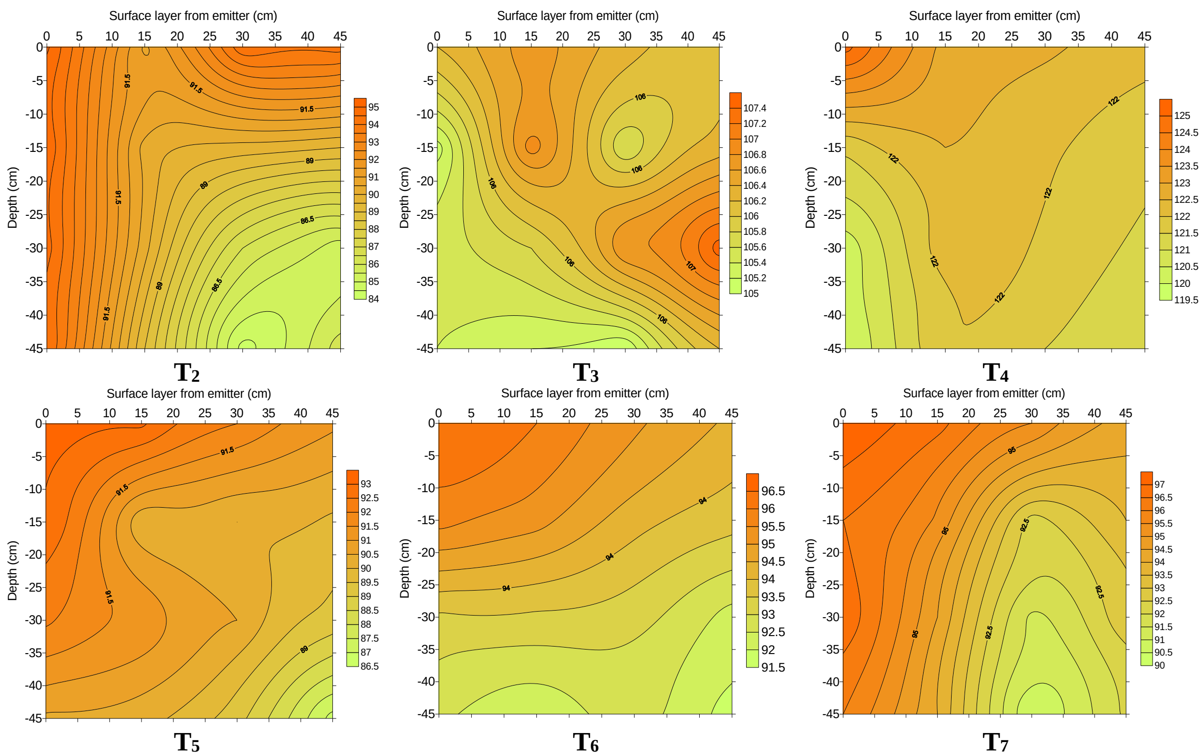

Fig. 1: Effect of fertigation on horizontal distribution of nitrogen dynamics in cocoa fields; T_1 (control) - 100% RFD [100:40:140 g NPK plant^{-1} annually] applied via flood irrigation, T_2 - 75% RFD applied through drip irrigation using water-soluble fertilizers, T_3 - 100% RFD applied through drip irrigation using water-soluble, T_4 - 125% RFD applied through drip irrigation using water-soluble fertilizers, T_5 - 75% RFD applied through drip irrigation via conventional fertilizers, T_6 - 100% RFD applied through drip irrigation via conventional fertilizers, and T_7 - 125% RFD applied through drip irrigation via conventional fertilizers.

At 75% application level, the N content was highest in top layer (0-15 cm) especially beneath the dripper, with a subsequent decrease laterally up to 30 cm from the emitter. The available N depicted a gradual decrease from surface to deeper layers (30-45 cm). A similar distribution pattern, both horizontally and vertically, was noted at 100% RFD. At 125% RFD, the highest N content was observed at dripper point (125.2 kg ha^{-1}), decreasing to 121.2 kg ha^{-1} at a lateral distance of 45 cm in deepest layer. The spatial nutrient dynamics is depicted in Fig. 1 and 2. A key element affecting crop output is the soil's ability to supply essential plant nutrients. The leaching, volatilization, and nutrient fixation activities in soil matrix significantly impact nutrient availability. The impact of drip fertigation on soil fertility dynamics and effectiveness of nutrient mobility has been established. However, to understand these interactions, a solid grasp of nutrition transport and transformation is necessary. In drip fertigation systems, soil N content increased as one moved away from the emitter until they reached a threshold, at which point they started to decline (Kurniawan *et al*., 2024). Generally, N content in deeper layer (15-30 cm) was higher than that in the surface layer (0-15 cm). With a depth of 15-30 cm and a lateral distance of 20 cm from the emitter, the highest N content of 125.2 kg ha^{-1} was obtained by applying 125% RDF using water-soluble fertilizers by drip irrigation. Owing to its rapid mobility and poor adsorption to soil colloids, urea showed efficiency in both vertical and lateral movement. Fan *et al*. (2020) reported a consistent distribution of moisture beneath the emitter that extended up to 15 cm radially, which facilitates the nutrient movement. Due to their mobility, nitrate ions have a propensity to move toward outer edge of wetted zones, which may make them less accessible to the plants. However, the present findings support Bhattarai *et al*. (2018) by showing that N did not accumulate at wetting front's edge or leak past the root zone.

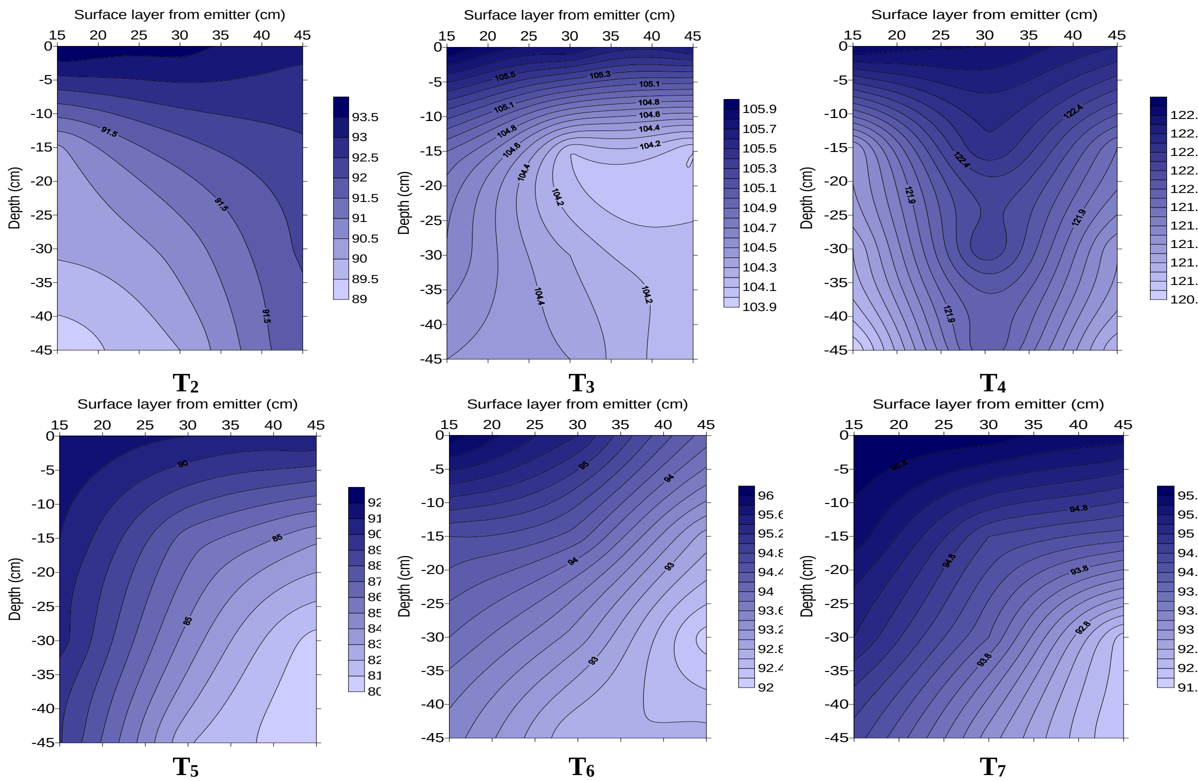

Fig. 2: Effect of fertigation on vertical distribution of nitrogen dynamics in cocoa (For treatment details see Fig. 1)

Effect of fertigation on phosphorus dynamics

Drip fertigation using water-soluble fertilizers demonstrated the highest available P concentration (28.0 kg ha^{-1}) at 30-45 cm depth, directly at dripper point. This concentration decreased progressively with increasing distance from dripper point, both horizontally and vertically, at a rate of 125% RDF. The available P was lower at 75% dosage in comparison to the 100 and 125% dosages (Fig. 3 & 4). Significant phosphorus migration was observed during drip fertigation revealing that the soil ability to adsorb phosphate was the main factor influencing the orthophosphate movement from the emitter. Grewal and Khera (2018) observed that phosphate moved significantly both vertically and horizontally in clay loam soils. Since adsorption sites close to the application point are saturated and subsequently displaced by mass flow with soil water, therefore, phosphate transport was found directly proportional to the application rate (Niu *et al*., 2017; Mohammed *et al*., 2024). Orthophosphate movement often remains restricted to the soil volume close to the emitter, and the saturation of reactive sites in the surrounding soil matrix affects how much it shifts. Because of its low mobility, phosphorus mostly builds up near the application point, which is under the emitter, with little lateral dispersion or leaching to deeper layers (Guo *et al*., 2023; Rezaei *et al*., 2025). Phosphorus availability increased at 15-30 cm depth at all distances from the emitter when 125% of

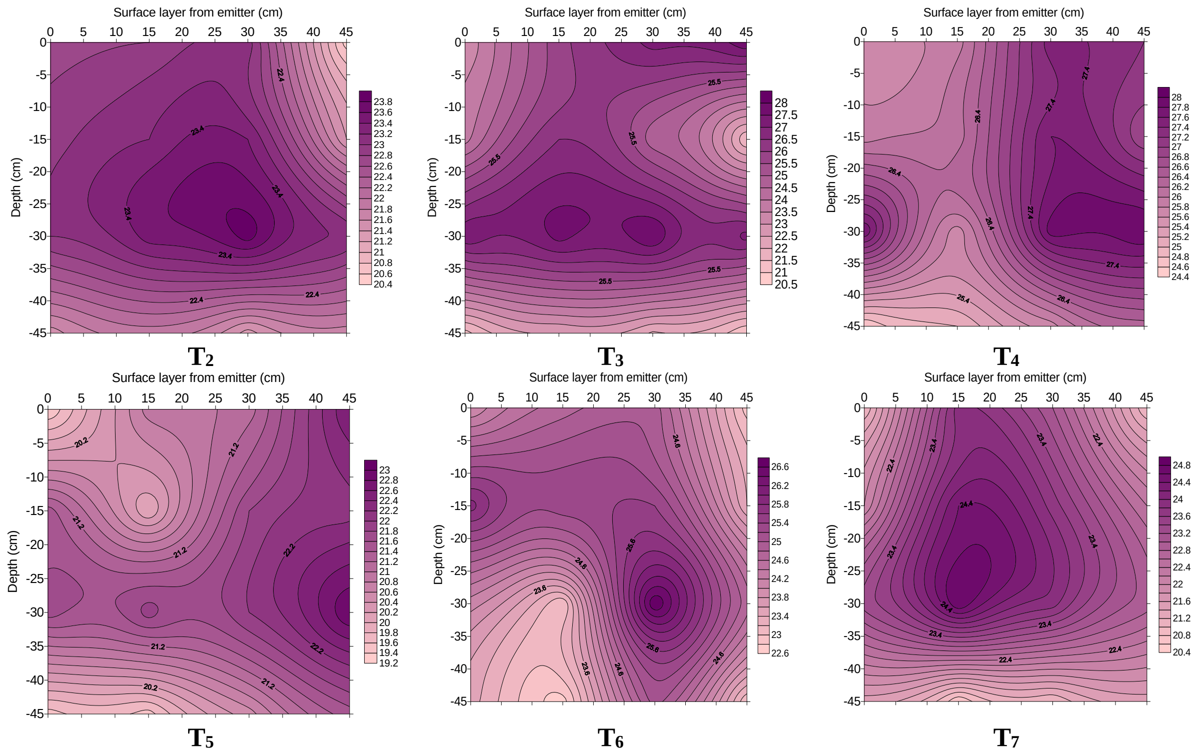

Fig. 3: Effect of fertigation on horizontal distribution of phosphorus dynamics in cocoa field (For treatment details see Fig. 1)

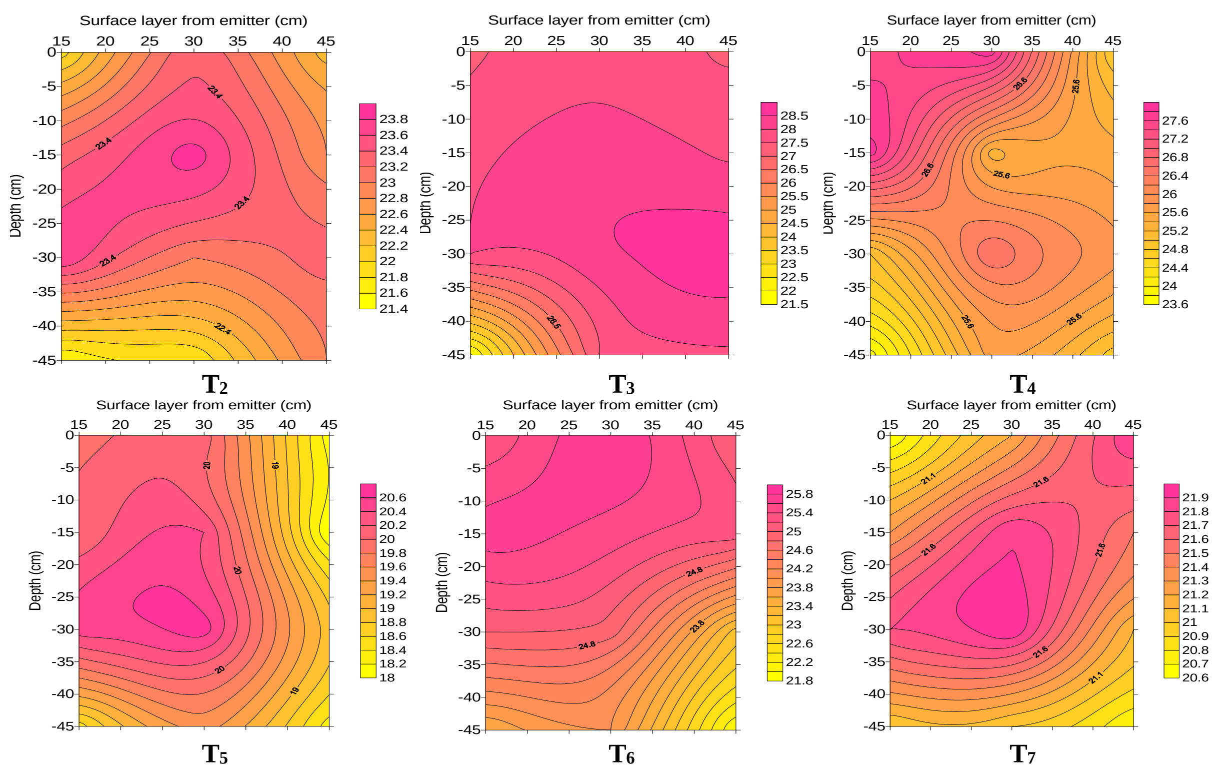

Fig. 4: Effect of fertigation on vertical distribution of phosphorus dynamics in cocoa field (For treatment details see Fig. 1)

the permitted amount of water-soluble fertilizer was applied; this decreased as the fertilizer application was lowered (Ben-Gal *et al.*, 2003).

Effect of fertigation on potassium dynamics

The spatial distribution of potassium beneath the emitter exhibited a trend akin to that of nitrogen, characterised by a progressive increase in concentration with elevated fertilizer dosages and a gradual decline at the outer edges of dripper zone. The maximum potassium level was recorded in 125% RDF treatment, measuring 240.9 kg ha^{-1} at a depth of 15-30 cm directly beneath the emitter. The concentration diminished laterally to 232.4 kg ha^{-1} at a depth of 30-45 cm from the emitter (Fig. 5 and 6). The equilibrium and kinetic interactions between the various forms of soil K, the soil's moisture content, and the amounts of bivalent cations in the solution and exchange phases all affect the concentration of K in soil solution. Because of its interaction with soil binding sites, potassium may appear to be distributed quite uniformly within the wetted soil volume, while having lesser mobility than nitrate (Zhang *et al*., 2017). The highest potassium concentrations were found in all soil layers following fertigation when 125% of the prescribed fertilizers dosage whether applied in water-soluble or straight forms. The highest K content was typically found at a soil depth of 15-30 cm below the emitter, which is consistent with the results of Lavanya *et al*. (2026). Alternating cycles of wetting and drying can cause rapid changes in the amount of K available in the surface layer, particularly during summer when K fixation is encouraged. The results revealed that the subsoil had noticeably higher K concentration which may be attributed to the fact that administered K is retained in surface layer and its downward migration is constrained. Furthermore, vertical transport was probably limited by the net upward movement of soil water, which was impacted by increasing evapotranspiration. Our findings align with Rezaei *et al*. (2025). Similarly, Reethika *et al*. (2025) found that the addition of K ions to the soil exchange complex, which limited their downward mobility, was associated with elevated K levels in subsurface layer.

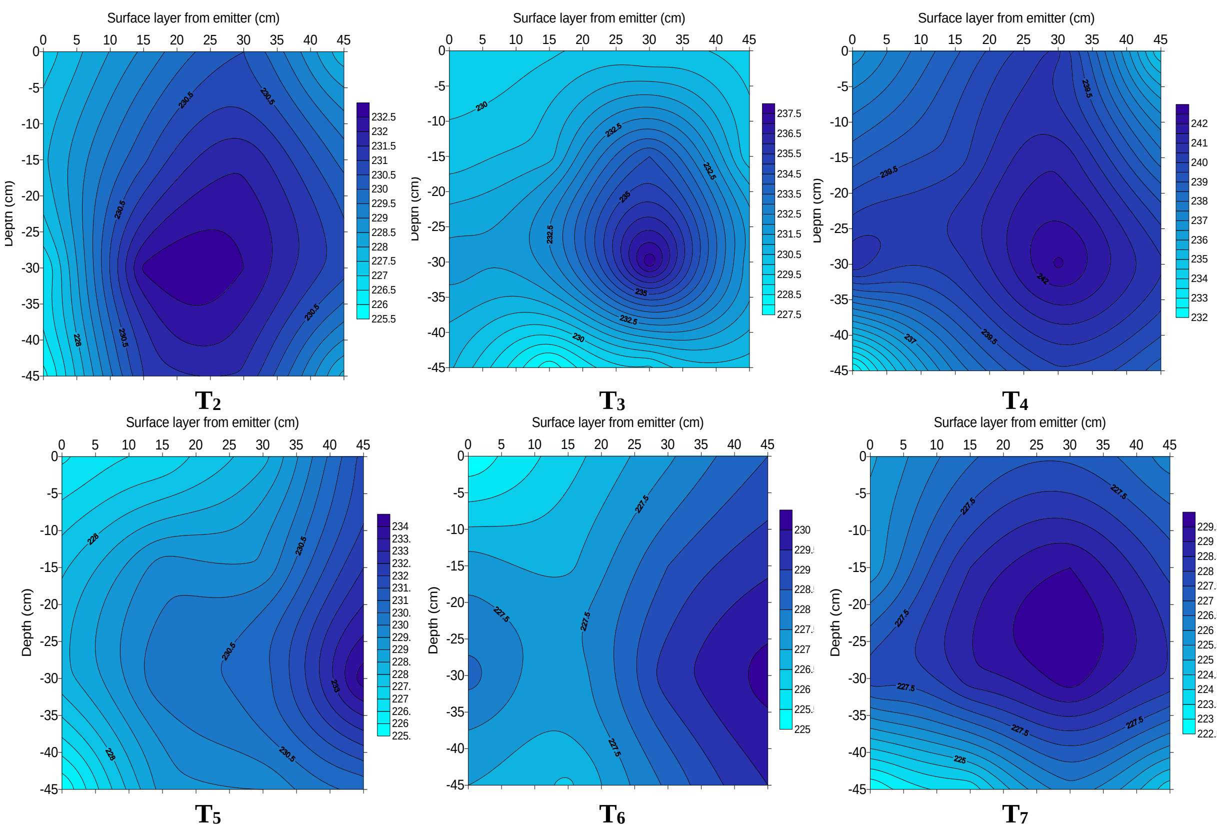

Fig. 5: Effect of fertigation on horizontal distribution of potassium dynamics in cocoa field (For treatment details see Fig. 1)

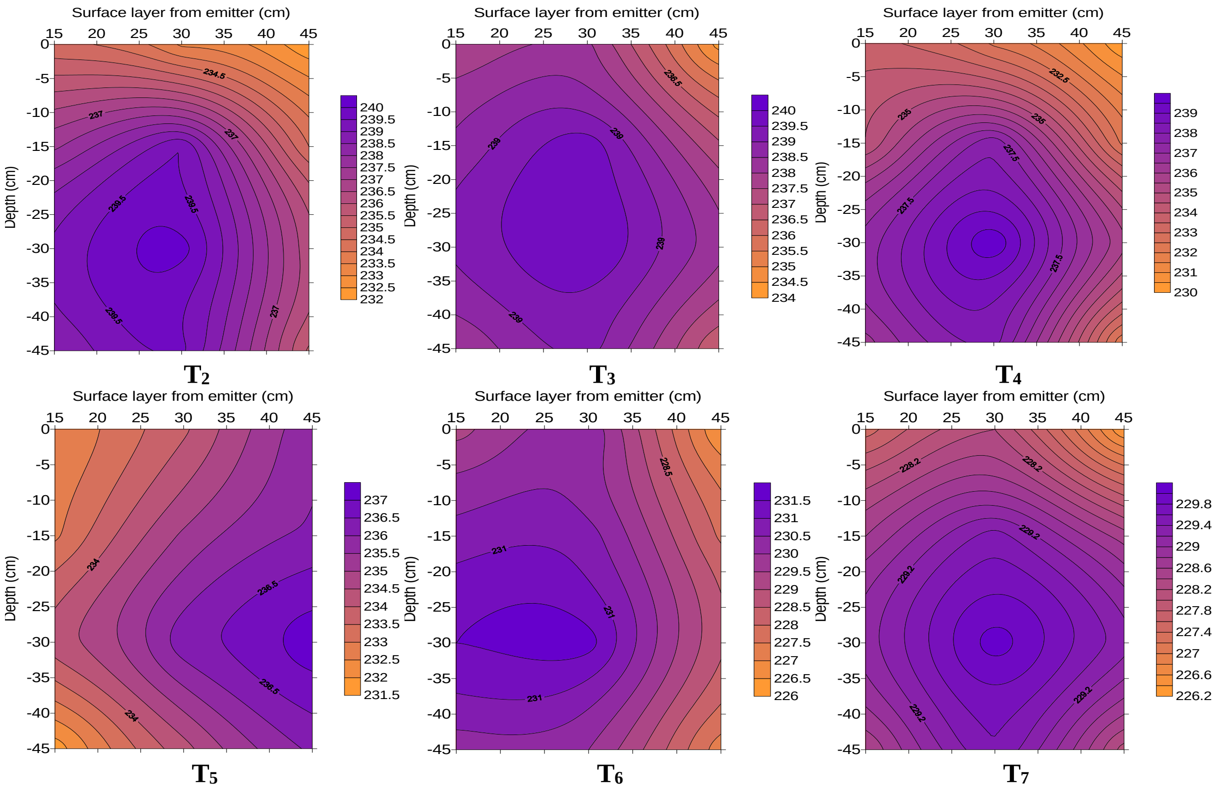

Fig. 6: Effect of fertigation on vertical distribution of potassium dynamics in cocoa field (For treatment details see Fig. 1)

Conclusion: The findings of this two-season study highlight the impact of fertigation treatments on soil nutrient dynamics in cocoa cultivation in Alfisol settings. The highest concentrations of soil organic carbon, available nitrogen, phosphorus, and potassium were consistently obtained over all important phenological stages vegetative, flowering, pod set, and harvesting when 125% of RDF were applied as water-soluble fertilizers (WSF) via drip irrigation (T_4: 125:50:175 g NPK plant^{-1} year^{-1}). Drip fertigation with WSF significantly increased P mobility, allowing its translocation to deeper soil layers and optimizing its availability within 30-45 cm root zone, whereas available N and K levels showed a slight decrease with increasing soil depth (from 0-15 cm to 30-45 cm). These results demonstrate how well drip-based fertigation works to enhance nutrient delivery and retention in Alfisols that grow cocoa. In order to improve soil nutrient status and nutrient use efficiency in cocoa cultivation under Alfisol conditions, it is suggested implement 125% RDF through drip fertigation using water-soluble fertilizers (125:50:175 g NPK plant^{-1} year^{-1}).

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