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RESEARCH ARTICLE

Fertigation effects on productivity, soil nutrients and microbial population of cocoa (*Theobroma cacao* L.) plantation in the Western Ghats of Tamil Nadu, India

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Abstract

An experimental study was conducted to analyze the impact of fertigation with nitrogen (N), phosphorus (P) and potassium (K) fertilizers on soil nutrients and microbial communities in a cocoa (*Theobroma cacao* L.) plantation in the Western Ghats of Pollachi. The experiment followed a randomized block design with seven Fertigation treatments. Treatments included soil application (control) and twice-weekly applications of conventional fertilizers at 75 %, 100 % and 125 % of the recommended doses, along with equivalent water-soluble fertilizers (WSF). The experiment was replicated three times. With 125 % recommended dose of fertilizer (RDF) applied as a water-soluble fertilizer by fertigation, the soil provided the highest levels of N, P and K throughout the year. Applying water-soluble fertilizer and conventional fertilizers through the drip system at lower levels (75 %) resulted in much higher values of soil microbial activity. Plants receiving 100 % RDF as water-soluble fertilizer through drip fertigation recorded the highest pod counts (31.74 and 25.97 in the first year; 32.41 and 26.18 in the second year) and maximum dry bean yields (1931.69 and 1501.84 g per tree) during the respective seasons. Compared with ring basin irrigation, drip irrigation reduced N, P and K fertilizers requirements for cocoa by up to 25 % of the recommended dose.

Keywords: cocoa plantation; fertigation; microbial population; soil nutrient; yield attributes

Introduction

Cocoa is indigenous to South America and was introduced to India in the 20th century. Also referred to as the "*Food of God*. Cocoa has been cultivated commercially in India since the early 1970s (1). It was primarily cultivated as an intercrop, comprising 70 % of the total cocoa area, within coconut and areca nut plantations rather than as a monocrop (2). Cocoa is cultivated in tropical regions between 10° and 20° latitude, both north and south of the equator. Kerala, Andhra Pradesh, Karnataka and Tamil Nadu are the main states in India. Cocoa reacts quickly to fertilizers provided to it to meet its nutritional needs (3). A high yield potential in cocoa can be achieved by applying nutrients while considering the many stages of crop growth, such as vegetative, blooming, pod set, pod development and maturity (4). In addition, factors such as the weight of a single bean and the quantity of beans in a pod determine the price of cocoa beans (5). Growers can increase their income by implementing well-balanced fertigation techniques.

Qualitative improvement can also be achieved effectively by adding nutrients to the soil at appropriate intervals and doses through fertigation practices. Farmers can enhance their income potential by producing high-quality cocoa beans. Precise and uniform application of nutrients and water to the productive root zone led to excellent cocoa yield and quality. Consequently, more cocoa growers use the fertigation approach daily (6).

For cocoa in Tamil Nadu, a dose of 100 g N, 40 g P and 140 g K tree /year is typically advised (7). The 1.2 m-deep tap roots provide structural support in cocoa, while the 20-30 cm lateral roots absorb nutrients and moisture. Cocoa is a cauliflorous tree that produces huge pods with a woody husk. The pods contain 20-60 beans in a sticky pulp and mature in 140-

180 days (8). Cocoa is highly susceptible to waterlogging and moisture stress; thus, optimal irrigation is necessary for higher yield and growth. The crop is irrigated every 5-7 days, depending on the soil and meteorological conditions. Research on cocoa indicated that applying fertilizers at 125 % of the recommended dose through fertigation improved yield and quality metrics (9)."

Through organic matter decomposition in the soil ecosystem, soil microorganisms perform important biochemical roles (10, 11). Because of crop rotation, additives and tillage, the soil microbial population is susceptible to changes in the soil environment. Agricultural management strategies have been found to dramatically alter the soil's microbial composition (12, 13). In this context, the present study evaluated the impact of fertigation on soil nutrients and microbial communities in cocoa plantations.

Materials and Methods

Study area

The research area was situated at ThappattaiKilavanPudur, Pollachi Taluk, Coimbatore District, about 55 Km from the Horticultural College and Research Institute, TNAU, Coimbatore. The research field is located at an altitude of 258 m above MSL between 10°58'0" North latitude and 76°56'0" East longitude. The average annual rainfall of Pollachi is 844 mm and the average highest and lowest temperatures are 30 °C to 36 °C and 19 °C to 25 °C, respectively. The soil texture is sandy loam with initial soil nutrient status: Soil pH: 7.5, EC: 0.29, available N 100.8 $kg.ha^{-1}$, P 18.85 $kg.ha^{-1}$ and K 195.08 $kg.ha^{-1}$. The study was conducted on ten-year-old cocoa trees interplanted in 30-year-old coconuts.

Cocoa was spaced at 3 × 3 m between coconut rows. In addition, a single cocoa plant was positioned in the coconut row between two coconut trees. According to the varietal description of cocoa, these were progenies of F1 seedlings, produced on seedlings provided by Kerala Agricultural University. A population of 500 cocoa trees per hectare was maintained. Cocoa plants flowered year-round, with two distinct peak harvest seasons: March-May and September-November. During those two seasons, the lean cropping phase is thought to occur from March to April (flowering) - July (pod harvest), whereas the high cropping period is believed to initiate from September (flowering) - December (pod harvest).

Experimental details

The experimental layout was established following a RBD, incorporating seven distinct treatment regimens, each replicated three times. The treatments included: T_1 - control group receiving 100 % of the RDF (100:40:140 g NPK/plant/year) applied through soil application using flood irrigation; T_2 - 75 % of the RDFdelivered as WSF via drip irrigation (75:30:105 g NPK/plant/year); T_3 - 100 % RDF as WSF through drip irrigation (100:40:140 g NPK/plant/year); T_4 - 125 % RDF as WSF via drip irrigation (125:50:175 g NPK/plant/ year); T_5 - 75 % RDF using conventional straight fertilizers through drip irrigation (75:30:105 g NPK/plant/year); T_6 - 100 % RDF using conventional fertilizers via drip irrigation (100:40:140 g NPK/plant/ year); and T_7 - 125 % RDF with conventional fertilizers through drip irrigation (125:50:175 g NPK/plant/year). The trial was conducted in a one-acre field accommodating 126 cocoa trees.

Nutrient applications across the various treatment protocols were administered using conventional and WSF. Conventional fertilizers included urea, di-ammonium phosphate, muriate of potash and sulfate of potash, the latter applied exclusively at the pod-setting stage. Water-soluble fertilizers comprised urea (46 % N), a proprietary NPK blend containing 19 % N, 19 % P and 19 % K and a specialized K formulation containing 13 % N and 45 % K (Multi-K). For treatments T_2 to T_7, fertilizer was applied through drip irrigation (fertigation). The prescribed quantities of fertilizers were accurately weighed, dissolved in water and delivered through the sub-main line using a venturi injector, subsequently distributed via lateral lines per the treatment layout. Fertilizer application was performed biweekly, with dosages tailored to the crop's developmental stage. In the control treatment (T_1), corresponding to soil application and flood irrigation, the recommended nutrient dose of 140 g potassium oxide (K_2O), 40 g phosphorus pentoxide (P_2O_5) and 100 g N per tree annually was split into two equal portions: the first applied in the 1st week of April and the second in the 1st week of September. Fertilizers were evenly distributed within a 60 cm radius around the tree base and manually incorporated into the soil. Flood irrigation was conducted at weekly intervals.

Sample collection and soil parameter analysis

A 'V'-shaped cut to a depth of 15 cm was made at each soil sample location. Earth slices (1.5 cm thick) were collected in sterilized polythene bags. After carefully combining samples of the same treatments, the volume was divided into quarters for analysis. After shade drying, the soil samples were ground into a powder using a wooden hammer, sieved through a 2 mm sieve and analyzed for chemicals.

The soil's organic carbon content was calculated and reported as a percentage using the wet oxidation method (14). The alkaline permanganate method assessed the amount of available N (15). Using a modified Olsen approach, the amount of available P was estimated (16). Flame photometry was used to measure available K (17, 18).

Enumeration of rhizosphere soil microbial population

A rhizospheric soil sample from cocoa was analyzed using the serial dilution plate count method to quantify populations of actinomycetes, fungi and bacteria (19). To prepare an initial 10^{-1} dilution, 10 g of the collected soil was suspended in 100 mL of sterile water and briefly agitated. Successive serial dilutions were performed up to 10^{-10} by transferring 1 mL of the previous dilution into 9 mL of sterile water (beginning from 10^{-2}). For microbial enumeration, 0.2 mL aliquots from selected dilutions 10^{-6} for bacteria, 10^{-4} for fungi and 10^{-5} for actinomycetes were spread onto respective selective media: nutrient agar (NA) for bacteria, Rose Bengal agar for fungi and Ken Knight's medium for actinomycetes. The inoculated plates were incubated under controlled conditions: fungi at 25 °C for 5-7 days, bacteria at 30 °C for 1-2 days and actinomycetes at 30 °C for 12-14 days. Microbial counts were expressed in colony-forming units (CFU) per gram of soil on a moisture content basis.

Statistical analysis

The statistical analysis of the experimental data was conducted using the data underwent statistical analysis using the R software (R version 4.3.1). The critical differences were calculated for 1 % (0.01) and 5 % (0.05) probabilities. The pooled analysis of four seasons and two years was conducted using pooled RBD software and the findings were tabulated and reviewed.

Results and Discussion

Effect of fertigation on soil nutrient status

Across the two study years, different fertigation treatments showed a significant difference in soil organic carbon (Table 1). T_4 recorded the highest soil organic carbon content (0.848 % and 0.865 %) in the first and second seasons in the first year. During the second year, T_4 registered the highest soil organic carbon content, 0.883 % in the first season and during the second season, 0.912 %. The lowest soil organic carbon content was recorded in control T_1 (0.752 % and 0.773 %) during the first and second seasons of the first year. During the second year, the same trend was noted.

All treatments significantly influenced the available soil N content. Among them, treatment T_4 (125 % of the RDF applied as water-soluble fertilizer via drip fertigation) consistently recorded the highest N levels, with values of 155.75 kg/ha (first season) and 162.34 kg/ha (second season) in first year and 158.01 kg/ha (first season) and 169.79 kg/ha (second season) in second year. These results were comparable to those of Treatment T_3 (100 % RDF as water-soluble fertilizer through drip irrigation), which yielded N levels of 147.98 kg/ha and 155.21 kg/ha in the first year and 149.31 kg/ha and 159.82 kg/ha in the second year. The lowest N availability was recorded in the control treatment (T_1), with 120.53 kg/ha and 123.81 kg/ha during the first and second seasons of the first year and 125.41 kg/ha and 132.21 kg/ha in the second year (Table 1).

Similarly, T_4 exhibited the highest levels of available soil P across seasons, reaching 39.25 kg/ha and 42.72 kg/ha in the first year and 42.84 kg/ha and 46.15 kg/ha in the second year. T_3 also demonstrated high P accumulation, though slightly less than T_4. In contrast, the control treatment T_1 showed the lowest P content: 22.81 kg/ha and 25.43 kg/ha in the first year and 28.91 kg/ha and 30.01 kg/ha in the second year.

In terms of available K, treatment T_4 again recorded the maximum levels 288.47 kg/ha and 310.17 kg/ha in the respective seasons of the first year and 322.78 kg/ha and 330.72 kg/ha in the second year. The lowest K values were observed in the control treatment T_1, which yielded 230.21 kg/ha and 246.33 kg/ha in the first year, 251.99 kg/ha and 255.76 kg/ha in the second year (Table 2).

The soil's nutrient availability is crucial for maximum development and productivity. This will help to standardize nutrient delivery and limit the possibility of nutrient waste, enhancing plant potential and nutrient use efficiency. Nutrient analysis was performed at various crop growth stages to determine the availability of different nutrients in the soil (20). Soil organic carbon is critical in maintaining and improving several soil properties. Applying WSF in the drip system showed enhanced soil organic carbon content. The effect was prominent in fertigation treatments involving drip, in which more litter fall was observed and further decomposition of these materials led to increased soil organic carbon (21).

The current study examined the variation in nutrient availability due to varied fertigation levels during different seasons. The investigation found that fertilizer with 125 % RDF using drip irrigation systems produced the maximum accessible NPK in soil. This supports the idea that increased soil nutrient availability increases growth and yield. Nutrient mobility was significantly improved using the drip fertigation technology. Nutrients were transported by the water and concentrated near the wetness zone's edge. Similar findings were reported in other studies (22, 23).

Effect of fertigation on rhizosphere soil microbial population

Data collected during the first and second year (four seasons) indicated a significant impact of the treatments on soil bacterial populations. Fertilization with 75 % of the RDF via drip irrigation (T_2) resulted in the highest bacterial counts, registering

Table 1. Effect of fertigation on soil organic C (%) and available N in different seasons

Treatments	Soil organic C (%)				Available Nitrogen (kg ha^{-1})			
	First Year		Second Year		First Year		Second Year	
	1st Season	2nd Season	1st Season	2nd Season	1st Season	2nd Season	1st Season	2nd Season
T_1	0.752	0.762	0.789	0.790	120.53	123.81	125.41	132.21
T_2	0.795	0.808	0.830	0.843	128.85	134.99	130.99	140.81
T_3	0.820	0.829	0.851	0.866	147.98	155.21	149.31	159.82
T_4	0.848	0.857	0.883	0.901	155.75	162.34	158.01	169.79
T_5	0.767	0.776	0.797	0.807	124.75	130.27	128.05	133.81
T_6	0.783	0.790	0.816	0.828	132.43	139.85	137.83	144.75
T_7	0.796	0.810	0.833	0.847	136.72	144.76	142.88	149.88
Sed	**0.025**	**0.025**	**0.026**	**0.027**	**4.42**	**4.62**	**4.52**	**4.81**
CD (0.05)	**0.055**	**0.055**	**0.057**	**0.058**	**9.62**	**10.06**	**9.84**	**10.49**

Table 2. Effect of fertigation on available soil P and available K in different seasons

Treatments	Available Phosporous(kg ha^{-1})				Available Potassium (kg ha^{-1})			
	First Year		Second Year		First Year		Second Year	
	1st Season	2nd Season	1st Season	2nd Season	1st Season	2nd Season	1st Season	2nd Season
T_1	22.81	25.43	28.91	30.01	230.21	246.33	251.99	255.76
T_2	27.12	30.24	31.74	33.46	241.13	257.72	263.81	272.27
T_3	37.54	40.47	40.01	43.51	266.15	282.65	298.65	295.49
T_4	39.25	42.72	42.84	46.15	288.47	310.17	322.78	330.72
T_5	24.27	27.19	30.52	32.01	233.52	249.72	259.80	263.65
T_6	30.14	33.45	37.85	39.35	245.73	265.66	266.52	277.64
T_7	33.70	36.84	38.10	40.10	252.26	273.17	287.96	289.82
Sed	**1.06**	**1.16**	**1.20**	**1.27**	**8.18**	**8.79**	**9.13**	**9.31**
CD (0.05)	**2.30**	**2.52**	**2.60**	**2.77**	**17.83**	**19.15**	**19.89**	**20.29**

50.25××10^{-6} CFU.g^{-1} soil and 48.92××10^{-6} CFU.g^{-1} soil during the first and second seasons of the first year, respectively. Similarly, in the second year, Treatment T_2 continued to show peak bacterial populations at 47.13××10^{-6} CFU.g^{-1} and 43.85××10^{-6} CFU.g^{-1} soil during the respective seasons. In contrast, the control treatment (T_1) consistently recorded the lowest bacterial populations, with values of 30.11××10^{-6} and 26.58××10^{-6} CFU.g^{-1} soil in the first year and 26.25××10^{-6} and 20.72××10^{-6} CFU.g^{-1} soil in the second year across the first and second seasons (Fig.1).

Significant differences in soil fungal populations were observed across treatments during cropping years. Treatment T_5 (125 % RDF applied as straight fertilizers via fertigation) recorded the highest fungal counts of 15.35××10^{-4} and 14.78××10^{-4} CFU.g^{-1} soil during the first seasons of the first and second year, respectively. Fungal populations were maximized under T_5 in the first season and T_2 in the second season, with values of 14.82××10^{-4} and 14.30××10^{-4} CFU.g^{-1} soil. The control treatment (T_1) consistently recorded the lowest fungal counts, ranging from 11.54 to 12.05××10^{-4} CFU.g^{-1} soil in the first year and 11.09 to 11.65××10^{-4} CFU.g^{-1} soil in the second year (Fig. 2). Treatment T_5 consistently achieved the highest soil actinomycetes populations (approximately 8×10^{-3}CFU.g^{-1} soil) across both years (Fig. 3), significantly outperforming the control treatment (ranging from 3.8×10^{-3} to 4.9×10^{-3}CFU.g^{-1} soil).

The study revealed that using 75 % RDF as WSF had a pronounced effect on microbial abundance, particularly under drip irrigation. The rapid leaf litter decomposition within tree basins under these conditions likely stimulated the microbial proliferation. Microbial activity in soil is thought to act as a storehouse, contributing significantly to soil processes determining plant productivity. Higher amounts of inorganic nutrients build up in the soil due to increased fertilizer dosage, which reduces microbial survival and enzyme activity (24). Notably, plant roots release approximately 17 % of the assimilated photosynthates, most of which become available to soil microbes. This exudation fosters microbial colonization and activity, resulting in elevated population densities within fertigation treatments compared to others.

Effect of drip fertigation on yield characters

The number of pods per tree varied significantly among treatments across both years of study. Treatments involving WSF consistently resulted in a higher pod count than those receiving straight fertilizers. Among them, T_3 (100 % of the RDF as water-soluble fertilizer via drip fertigation) recorded the highest number of pods per tree, 31.74 and 25.97 during the first and second seasons of the first year and 32.41 and 26.18 during the corresponding seasons in the second year. This was followed by T_2

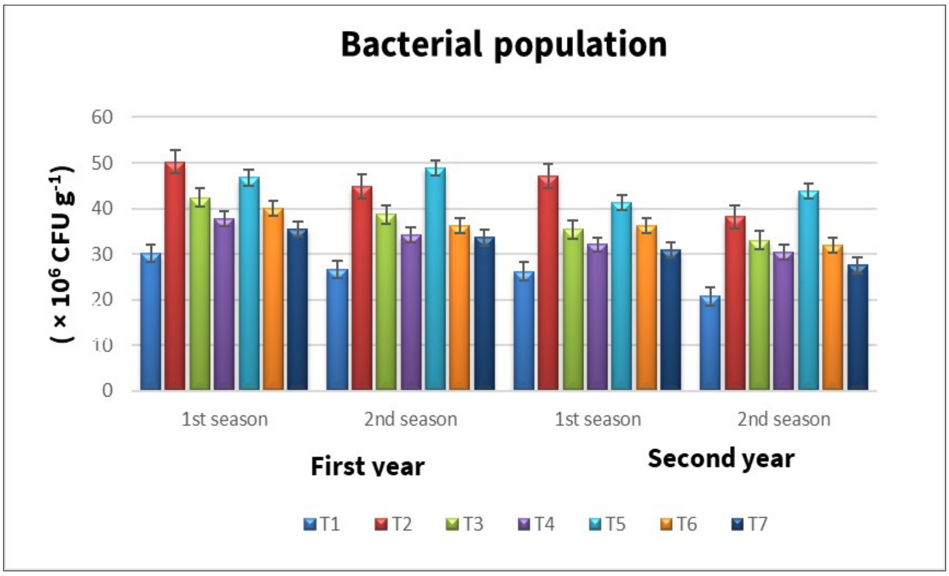

Fig. 1. Effect of fertigation on soil bacterial population in different seasons.

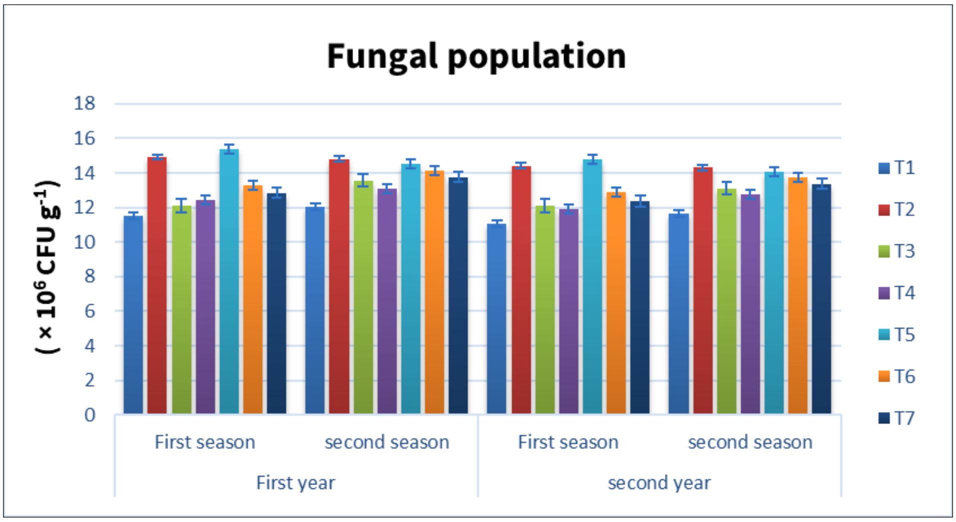

Fig. 2. Effect of fertigation on soil fungal population in different seasons.

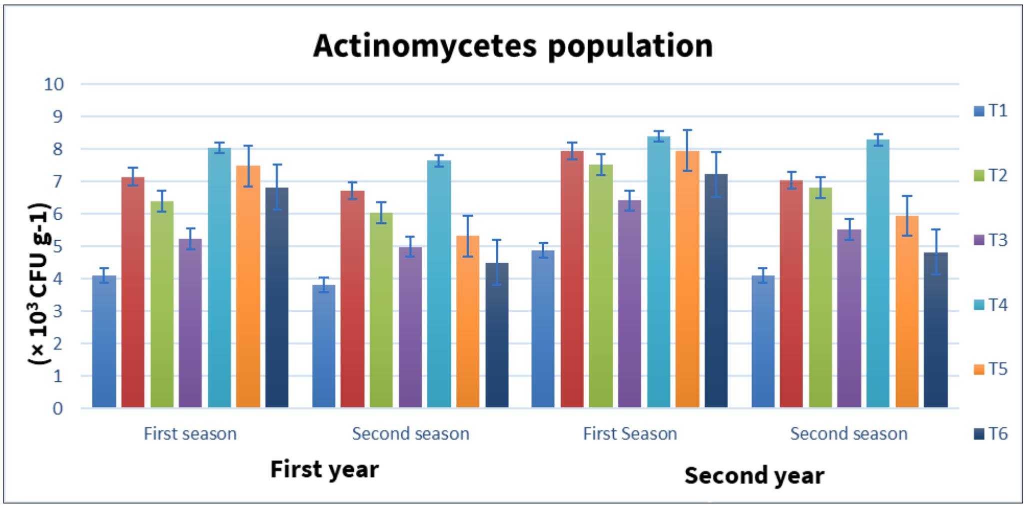

Fig. 3. Effect of fertigation on soil Actinomycetes population in different seasons.

Table 3. Effect of fertigation on the number of pods per tree

Treatments	Number of pods per tree						
	First Year			Second Year			Pooled mean (First and Second year)
	1st season	2nd season	Total	1st season	2nd season	Total	
T_1	25.44	19.42	44.86	25.55	19.35	44.90	44.88
T_2	30.90	24.95	55.85	31.24	25.22	56.26	56.05
T_3	31.74	25.97	57.71	32.41	26.18	58.59	58.15
T_4	30.84	24.87	55.71	31.00	25.00	56.00	55.85
T_5	26.40	21.15	47.55	27.01	22.11	49.12	48.33
T_6	27.50	23.00	50.50	28.00	23.66	51.66	51.08
T_7	27.14	22.70	49.84	27.89	23.22	51.11	50.47
Sed	**0.9057**	**0.7332**		**0.9173**	**0.7429**		**1.6500**
CD (0.05)	**1.9735**	**1.5976**		**1.9985**	**1.6186**		**3.3990**

(75 % RDFas water-soluble fertilizer via drip fertigation), which yielded 30.90 and 24.95 pods per tree in the first year and 31.24 and 25.22 pods per tree in the second year. The control (T_1) consistently recorded the lowest pod numbers, 25.44 and 19.42 during the first and second seasons of the first year and 25.55 and 19.35 during the respective seasons in the second year (Table 3).

Summed seasonal totals showed T_3 with the greatest number of pods per tree (57.71 in the first year and 58.59 in the second year), while T_1 remained the lowest (44.86 and 44.90, respectively). Pooled mean analysis confirmed the superior pod count under T_3 (58.15), which was statistically comparable to T_2 (56.05), whereas T_1 yielded the lowest mean value (44.88).

Variations in dry bean yield per tree were observed among fertigation treatments in both years of research (Table 4). Fertigation using WSF resulted in a maximum dry bean yield per tree compared to fertilizer application to the soil. In the first year, fertigation with 100 % recommended dose of WSF (T_3) resulted in the maximum dry bean production per tree of 1931.69 and 1501.84 g during the first and second seasons, equivalent to fertigation with 75 % recommended dose of WSF (T_2), which produced a dry bean yield of 1736.88 and 1341.81 g during the first and second seasons. A similar pattern was seen in the second year. During both years, soil fertilizer application produced a lower dry bean yield than all other treatments T_1 (841.80 and 575.41 g, 942.28 and 611.65 g) during the first and second seasons in first and second year respectively.

The annual dry bean yield per tree (sum of two seasons) was highest in T_3 (3433.53 and 3817.42 g) and lowest in T_1 (1417.21 and 1553.93 g) during the first and second year, respectively. Pooled mean analysis indicated that T_3 (100 % RDF as WSF through drip fertigation) achieved the highest yield (3625.47 g), statistically on par with T_2 (3219.48 g). The plant that received 100 % RDF as soil application (T_1) registered the minimum dry bean yield per tree (1485.56 g).

The increased number, size and bean content of pods produced by fertilized trees were most likely due to a higher assimilate availability and increased vegetative growth. Fertigation caused a shift in pod allometry, increasing the bean to husk ratio. This could result in more embryos developing, resulting in a higher number of beans or larger seeds and larger embryos. Previous research showed that treated trees got the

Table 4. Effect of fertigation on dry bean yield per tree (g)

Treatments	Dry bean yield per tree (g)						
	First Year			Second Year			Pooled mean (First and Second year)
	1st season	2nd season	Total	1st season	2nd season	Total	
T_1	841.80	575.41	1417.21	942.28	611.65	1553.93	1485.56
T_2	1736.88	1341.81	3078.69	1930.06	1430.22	3360.28	3219.48
T_3	1931.69	1501.84	3433.53	2168.87	1648.55	3817.42	3625.47
T_4	1629.58	1270.60	2900.18	1795.83	1370.00	3165.83	3033.00
T_5	1041.48	832.25	1873.73	1168.45	826.91	1995.36	1934.54
T_6	1329.62	1069.27	2398.89	1490.44	1134.97	2625.41	2512.14
T_7	1212.07	956.57	2168.64	1342.90	1016.57	2359.47	2264.05
Sed	45.8836	35.7710		50.8977	38.3476		85.5279
CD (0.05)	99.9727	77.9391		110.8975	83.5529		176.1875

exact nutrients in the functional root zone with negligible leaching, resulting in higher fertilizer efficiency. This could explain the largest number of pods produced in 125 % RDF by fertigation. Continuous wetting in the root zone caused by fertigation with desired fertilizer and irrigation schedules reduces moisture stress and increases cocoa pod setting percentage (25, 26). Similar results were observed in sweet orange (27).

Applying 100 % RDF by fertigation increased the bean's length and girth. This increased length and width of the bean may have resulted from the maximum rate of photosynthesis, which in turn may have improved assimilate partitioning. Increased nutrient uptake of N, P and K and increased fertilizer usage efficiency may cause the higher values found for these features with fertigation treatments. Growth hormones such as gibberellins, cytokinins and auxins are produced at optimal nutrient distribution, increasing assimilation, nutrient uptake, water translocation and yield. These results concur with previous studies (28, 29).

The low yield in the control (soil applied with 100 % RDF) may result from insufficient nutrient availability, which lowers the efficiency of photosynthetic assimilate accumulation and reduces the formation of dry matter. In the aforementioned treatment, the yield-attributing traits-bean length, bean girth, number of beans/ pods, wet bean weight/pod, single bean dry weight, single bean wet weight, number of pods /trees and dry bean yield /tree were also low. Similar results were observed on yield reduction resulting from lower nutritional levels in mango, kiwifruit and papaya (30-32).

In cocoa, the main characteristics contributing to the produce's economic value are the bean's length, girth, weight and yield per tree. In addition to these financial characteristics, a lower pod value results in a higher bean yield, while a higher pod value increases the farmer's realizable produce. The fertigation treatments in the current investigation directly impacted these parameters. A 100 % nutrient fertilization increased the necessary nutrients available in the soil, enhancing growth and leaf area. It also improved nutrient uptake, improved photo assimilation and improved assimilate translocation from source to sink, all of which contributed to an increase in pod yield. he opinions about mango, capsicum and nutmeg are all in agreement with the current study (33-36).

Numerous physiological processes, such as more nutrients and water intake, a higher rate of photosynthetic activity and accelerated cell division and expansion, support rapid development by producing more protoplasm. Thus, biometric characteristics such as leaf area, dry matter content, pod weight, pod volume, number of pods per tree and dry weight of a single bean increased. The rapid differentiation of vegetative buds into reproductive ones may be due to fertigation treatment, which accelerated the production of photo assimilates required for the tree to increase sink strength (37, 38). The study's findings indicated that using 100 % RDF through fertigation offered the best outcomes in terms of yield characteristics, quality and nutrient utilization efficiency. This may be due to increased photosynthetic rate promoted by higher availability of nutrients, leading to enhanced formation of protoplasm, cell division and cell enlargement, complementing vigorous growth (39).

Conclusion

The study found that different fertigation treatments substantially impacted soil nutrients and microbial populations in cocoa plantations. In terms of major nutrients and accessible nutrients, it was observed that the content was high throughout the seasons in trees treated with 125 % RDF as water-soluble fertilizer by fertigation (T_4). Soil microbial activities were much higher after applying a lower level (75 %) of nutrients using WSF and straight fertilizers by drip irrigation. Regarding yield attributes, applying a larger level (100 %) of WSF via the drip system resulted in a higher yield. The study showed that when drip irrigation is used instead of the ring basin type of irrigation, there is excellent potential to reduce the N, P and K fertilizers by up to 25 % of the current recommended dose of fertilizers for cocoa. Practically, this means that drip fertigation can help cocoa farmers enhance nutrient-use efficiency, sustain soil microbial activity and achieve higher yields while reducing fertilizer costs by up to 25 %, thereby ensuring both economic benefits and environmental sustainability in cocoa production.

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Authors' contributions

AR carried out the research, analysis and drafting of the research article. GV and KP were involved in correcting and proofreading the manuscript. BG and MS helped in statistical analysis and the design of charts. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: All authors do not have any conflict of interest to declare.

Ethical issues: None

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