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RESEARCH ARTICLE

Smart fertigation effects on groundnut (*Arachis hypogaea* L.) yield, nutrient uptake and soil health

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Abstract

Precise application of water and nutrients is crucial for sustainable groundnut cultivation. Field experiments were conducted to evaluate the performance of smart fertigation systems on groundnut yield, nutrient uptake, soil microbial population and soil enzyme activities. The experiments were conducted at two locations. Location I was at a farmer's field in Kanjipatti village, Kalaiyarkoil block, Sivagangai district, Tamil Nadu (*rabi* 2023) and Location II was at the Central Farm of the Agricultural College and Research Institute, Madurai district, Tamil Nadu (*summer* 2024). Field trials were laid out in a split -plot design with three replications. The treatments comprised three drip irrigation methods in the main plots, namely; conventional drip irrigation (M_1), time-based automated drip irrigation (M_2) and sensor-based automated drip irrigation (M_3) and five drip fertigation methods in the subplots, viz., drip fertigation of 75% RDF (F_1), drip fertigation of 100% RDF (F_2), STCR-based drip fertigation (F_3), sensor-based fertigation at 75% NPK level (F_4) and sensor-based fertigation at 100% NPK level (F_5). The results revealed that pod yield, total NPK uptake, pod uptake, haulm uptake, microbial population and enzyme activities were significantly higher with the combination of sensor-based automated drip irrigation and sensor-based fertigation at 100% NPK level (M_3F_5). The M_3F_5 treatment increased crop yield by 44-45%, dehydrogenase activity by 44-64% and phosphatase activity by 57-65% across both seasons compared to M_1F_1. However, the post-harvest available nutrient status was recorded higher with conventional drip irrigation combined with drip fertigation of 100% RDF (M_1F_2). Based on the experimental results, it can be concluded that sensor-based automated drip irrigation combined with sensor-based fertigation at 100% NPK level (M_3F_5) enhanced groundnut yield, nutrient uptake, microbial population and enzyme activities.

Keywords

enzyme activities; groundnut; microbial population; nutrient uptake; sensors; smart fertigation; yield

Introduction

Groundnut (*Arachis hypogaea* L.), commonly referred to as the "King of oilseeds," is an annual legume crop primarily grown for its edible seeds.

Native to Brazil, groundnut belongs to the Leguminosae family and is an important crop in tropical and semiarid regions worldwide. It holds the position as the 13th most important food crop and the 4th most important oilseed crop globally. India is a leading country in groundnut cultivation, holding the top position in terms of area under cultivation and ranking second in production, following China. In India, groundnut is cultivated over an area of 6.02 million hectares, producing 10.2 million tonnes annually with an average productivity of 1703 kg/ha (1). A significant 82% of India's groundnut production is concentrated in five states. Gujarat leads with 34.8% of the total production, followed by Rajasthan (15.5%), Tamil Nadu (13%), Andhra Pradesh (11.8%) and Karnataka (7.1%). In Tamil Nadu, groundnut is cultivated over an area of 0.409 million hectares, producing 1.023 million tonnes annually with a higher average productivity of 2500 kg/ha (1).

Groundnut is the fourth most important source of edible oil and the third most important source of vegetable protein (2). Nutritionally, groundnut is a rich source of essential nutrients, containing approximately 50% oil, 25-30% protein, 20% carbohydrates and 5% fiber and ash (3). It also provides important vitamins and minerals such as copper, magnesium, potassium, biotin, niacin, folate, thiamine and the antioxidant vitamin E (4). Globally, around 50% of groundnut production is used for oil extraction, 37% for confectionery and 12% for seed purposes (5).

Optimizing the application of irrigation water and fertilizers is critical for efficient irrigation system design, water conservation, energy and cost savings and minimizing environmental hazards (6). Traditional irrigation and nutrient management practices face several challenges that hinder efficiency and sustainability. These systems often lead to uneven water distribution, water wastage and nutrient losses, reducing overall crop productivity. Over-irrigation can result in soil erosion and leaching, stripping the soil of essential nutrients. Similarly, conventional fertilizer application methods tend to be imprecise, causing excessive use, low nutrient uptake efficiency and environmental issues such as runoff and groundwater contamination. These practices are also labor-intensive and fail to account for real-time field conditions, leading to inconsistent crop growth and higher input costs. Such limitations highlight the need for more efficient and sustainable approaches in agriculture. Drip irrigation is the most effective way to supply water and nutrients to the plant, which not only saves water but also increases crop yield and increases water use efficiency (7). Drip irrigation supplies water directly to the root zone, significantly reducing water wastage. Currently, many farmers in India irrigate their fields through manual control, which can lead to inefficient water use. These issues can be effectively addressed through automated drip irrigation systems, where irrigation occurs only when there is a critical need for water.

Automation in drip irrigation minimizes the need for manual intervention, providing several benefits, including greater precision, more efficient water usage and reduced labor. Automated systems also enable high-frequency, low-volume irrigation and optimizing water distribution (8). These systems often incorporate sensors installed in the root zone to measure soil moisture. The soil moisture sensors are connected to controllers that regulate the irrigation valves, ensuring that water is applied only when necessary. This approach saves time, eliminates human error in adjusting soil moisture and maximizes yields while reducing water consumption (9, 10).

In addition to water, fertilizers play a crucial role in crop growth and their efficient management, alongside irrigation, is vital for enhancing crop production (6). When integrated with fertigation, drip irrigation offers a more effective method of nutrient delivery, significantly improving crop yield (11). Fertigation presents an efficient solution by delivering the optimal combination of water and nutrients directly to the plant's root zone, effectively meeting its water and nutrient needs (12). This method ensures precise and uniform nutrient application to the wetted area, where most active roots are concentrated, allowing for the right quantities and concentrations of nutrients throughout the growing season. The application of a high dose of fertilizers not only causes economic loss but also leads to chemical changes in the soil and reduces the yield (13). Conventional automated fertigation systems are typically controlled using preset timers (14) that turn fertilizer injectors and irrigation pumps on and off. These systems regulate the frequency and duration of nutrient supply based on predictive algorithms or historical data, which may not always accurately reflect current conditions (15). In contrast, sensor-based automated fertigation offers a more advanced approach by continuously adjusting irrigation and nutrient supply according to real-time data (16). These systems utilize inputs from moisture and nutrient sensors to manage the fertigation process effectively. By ensuring that the fertigation system delivers the correct amount of water and nutrients at the appropriate times, sensor-based fertigation minimizes water and nutrient waste while maximizing crop productivity.

This study addresses the gap in integrating sensor-based automation with drip irrigation and fertigation systems for groundnut cultivation, compared to conventional drip irrigation and fertigation practices. It explores the potential of a low-cost, indigenous smart fertigation system to optimize water and nutrient use, enhancing crop yield and soil health. By evaluating the performance of this system, the study aims to improve groundnut yield, nutrient content and microbial activities, offering a novel solution to the limitations of conventional practices.

Materials and Methods

Experimental field locations and soil characteristics

Field experiments were conducted at two different locations. Location I: farmer's field in Kanjipatti village, Kalaiyarkoil block, Sivagangai district, Tamil Nadu (*rabi* 2023). This experimental site is situated in the southern agro -climatic zone of Tamil Nadu, at 9° 48' 35'' N latitude and 78° 36' 26'' E longitude with an altitude of 77 m above mean sea level. Location II: Central Farm, Agricultural College and Research Institute in Madurai district, Tamil Nadu (*summer*

2024), located at 9° 57' 50'' N latitude and 78° 12' 19'' E longitude with an altitude of 115 m above mean sea level, also within the southern agro-climatic zone of Tamil Nadu. The locations of the experimental sites are shown in Fig. 1 & 2. The soil texture of the experimental field in Kanjipatti village, Kalaiyarkoil block, Sivagangai district, is classified as red sandy clay loam. In contrast, the soil texture of the experimental field at the College and Research Institute, Madurai district, is sandy clay loam. Before conducting the field trial, composite soil samples were collected from each experimental field and analyzed for their mechanical, chemical, physical and biological properties. Mechanical properties, including textural composition, were determined by using the international pipette method. Chemical properties were assessed for pH and EC (using a 1:2.5 soil:water suspension method), organic carbon (using the chromic acid wet digestion method), available nitrogen (using the alkaline permanganate method), available phosphorus (using the Olsen method) and available potassium (using the neutral normal ammonium acetate method). Physical properties, including field capacity, permanent wilting point (using the pressure plate apparatus) and bulk density (using the core method), were also measured. Biological properties were assessed for bacteria (using nutrient agar medium), fungi (using rose bengal agar medium), actinomycetes (using Ken Knight's agar Medium), phosphatase activity (using the p-Nitrophenyl Phosphate (PNP) Method) and dehydrogenase activity (using the triphenyl tetrazolium chloride method). The estimated values for these parameters are shown in Table 1. Soil samples were randomly taken at a depth of 20 cm below the surface, pooled and then a subsample was separated for analytical purposes using a compartmentation procedure.

Weather and climate

For Location I, data on maximum and minimum temperatures, relative humidity, pan evaporation, wind speed, rainfall and solar radiation were collected from the Agro Climatic Research Centre in Coimbatore, Tamil Nadu. For Location II, measurements were taken at the Agro Meteorological Observatory, Agricultural College and Research Institute, Madurai district, Tamil Nadu.

Maximum and minimum temperatures during the cropping period at Location I ranged from 28°C to 35°C and 21°C to 26°C, respectively. Location II prevailed temperatures ranging from 35°C to 41°C and 21°C to 27°C, respectively. Total rainfall of 120.5 mm and 337.2 mm was recorded with 9 and 15 rainy days in seasons I and II, respectively. For relative humidity, Location I recorded values between 70% and 92%, while Location II ranged from 61% to 90% at 7:14 h and 38% to 66% at 14:14 h. The weekly mean pan evaporation was 4.7 mm at Location I and 4.8 mm at Location II. The weekly mean wind speed was 7.4 km h^{-1} at Location I and 4.2 km h^{-1} at Location II. Location I recorded a weekly mean solar radiation of 370.2 Cal cm^{-2} day^{-1}, while Location II recorded 6.3 h day^{-1} of weekly mean sunshine hours. The weather conditions during the crop growth period are depicted in Fig. 3 & 4.

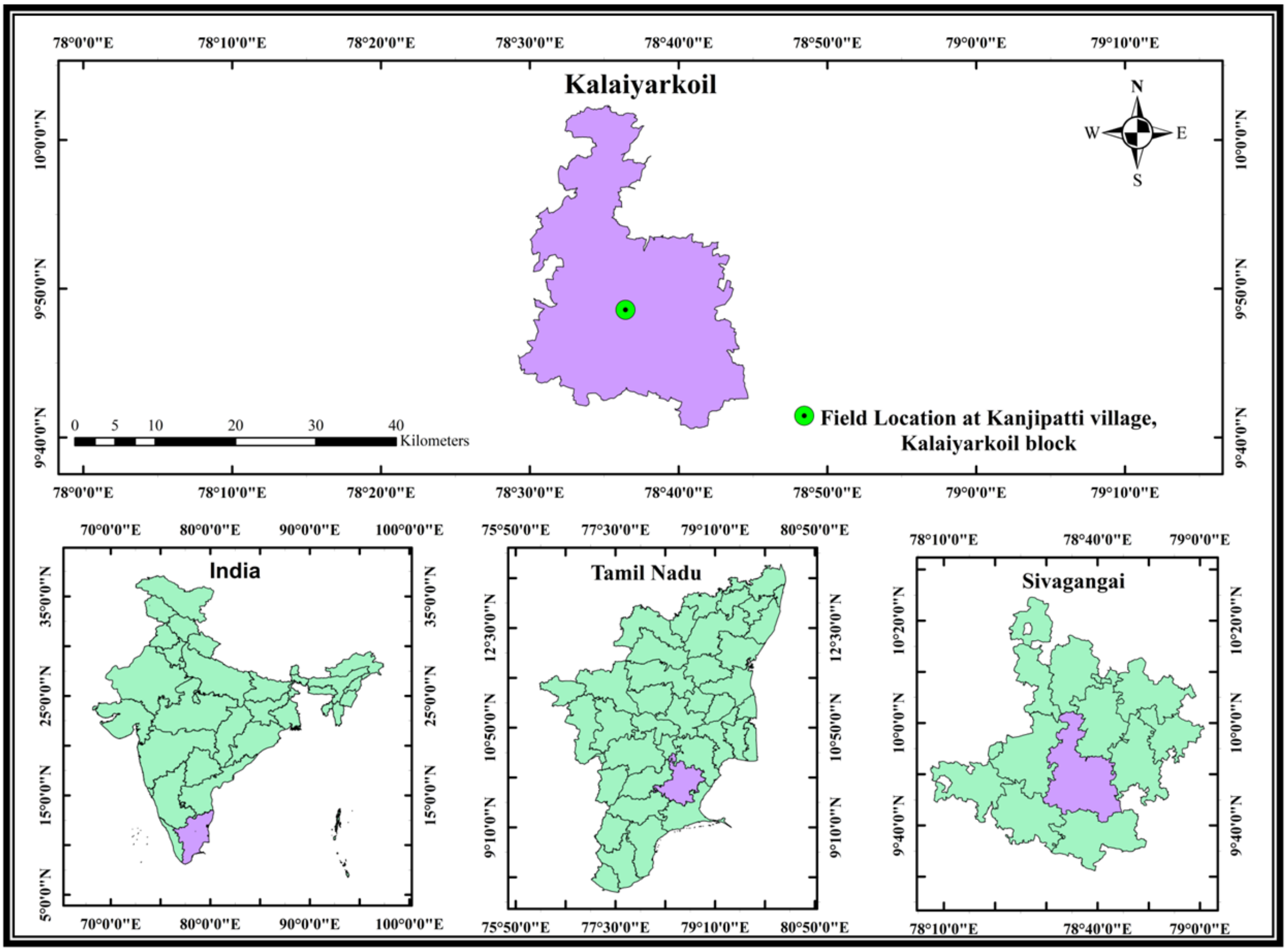

Fig. 1. Location of the experimental farm (Location I).

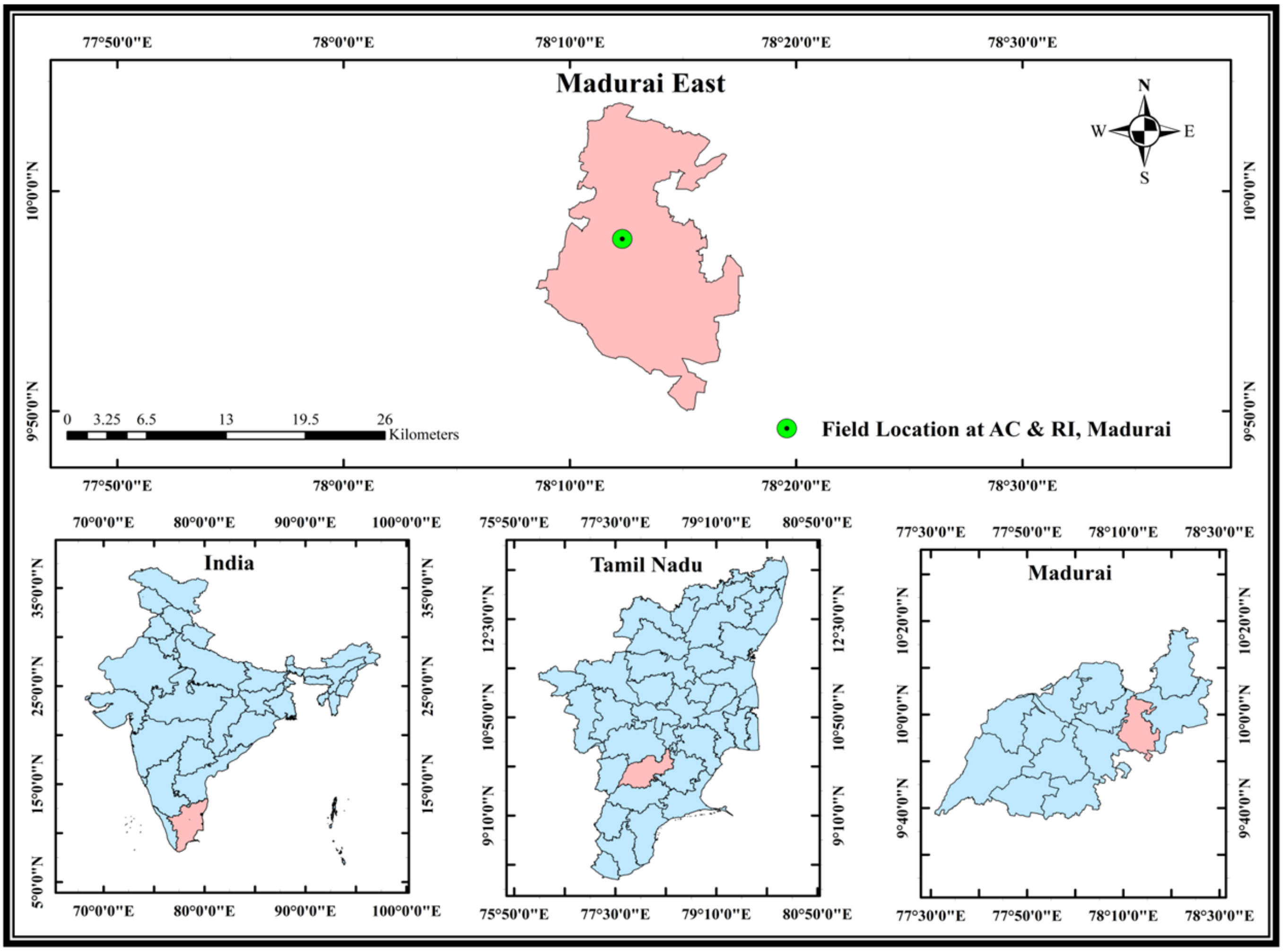

Fig. 2. Location of the experimental farm (Location II).

Table 1. Initial soil physico-chemical properties of the experimental field

Sl. No	Constituents	Estimated analytical values – Location I	Estimated analytical values – Location II	Methods / Medium employed	Author(s)
		Mechanical analysis			
1	Clay (%)	26.3	28.2	International pipette method	(47)
2	Silt (%)	11.8	16.3		
3	Sand (%)	61.8	55.5		
4	Texture	Sandy clay loam	Sandy clay loam		
		Chemical analysis			
1	Ph	8.08	7.83	1:2.5 soil: water Suspension	(48)
2	EC (dSm^{-1})	0.02	0.23		
3	Organic carbon (%)	0.35	0.51	Chromic acid wet digestion method	(49)
4	Available N ($kg\ ha^{-1}$)	373	222	Alkaline permanganate method	(50)
5	Available P ($kg\ ha^{-1}$)	20.5	18.2	Olsen method	(51)
6	Available K ($kg\ ha^{-1}$)	275	190	Neutral normal ammonium acetate method	(52)
		Physical properties			
1	Field capacity (%)	9.2	12.1	Pressure plate apparatus	(53)
2	Permanent wilting point (%)	15.7	23.2		
3	Bulk density ($g\ cc^{-1}$)	1.48	1.53	Core method	(54)
		Biological properties			
1	Bacteria (10^{-6} CFU g $soil^{-1}$)	15.3	18.6	Nutrient agar medium	(18)
2	Fungi (10^{-4} CFU g $soil^{-1}$)	5.11	6.19	Rose bengal agar medium	
3	Actinomycetes (10^{-3} CFU g $soil^{-1}$)	6.24	4.98	Ken knight's agar medium	
4	Phosphatase (µg of PNP g^{-1} soil day^{-1})	1.53	1.41	p-Nitrophenyl Phosphate (PNP) Method	(19)
5	Dehydrogenase (µg of TPF g^{-1} soil day^{-1})	10.77	9.83	Triphenyl Tetrazolium Chloride method	(20)

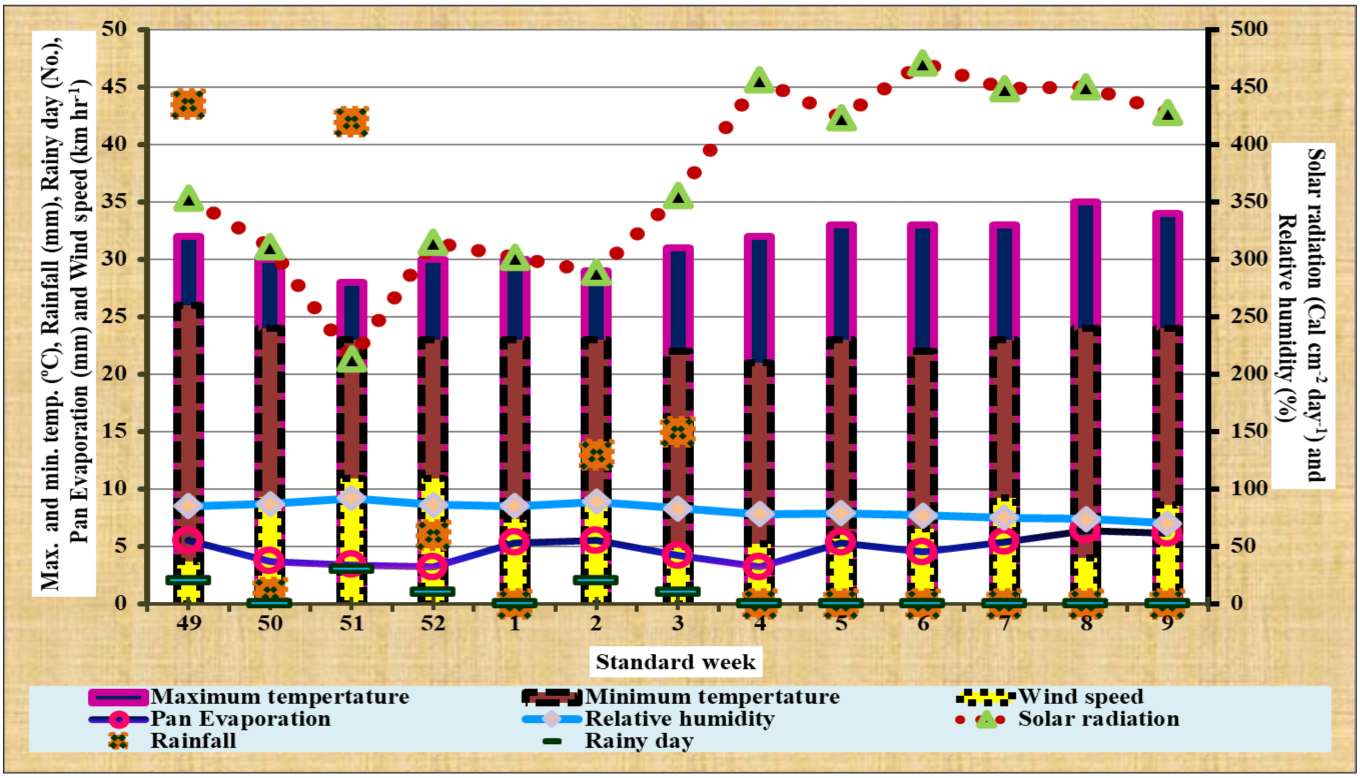

Fig. 3. Weekly weather parameters prevailed during the cropping period (*Rabi,* 2023).

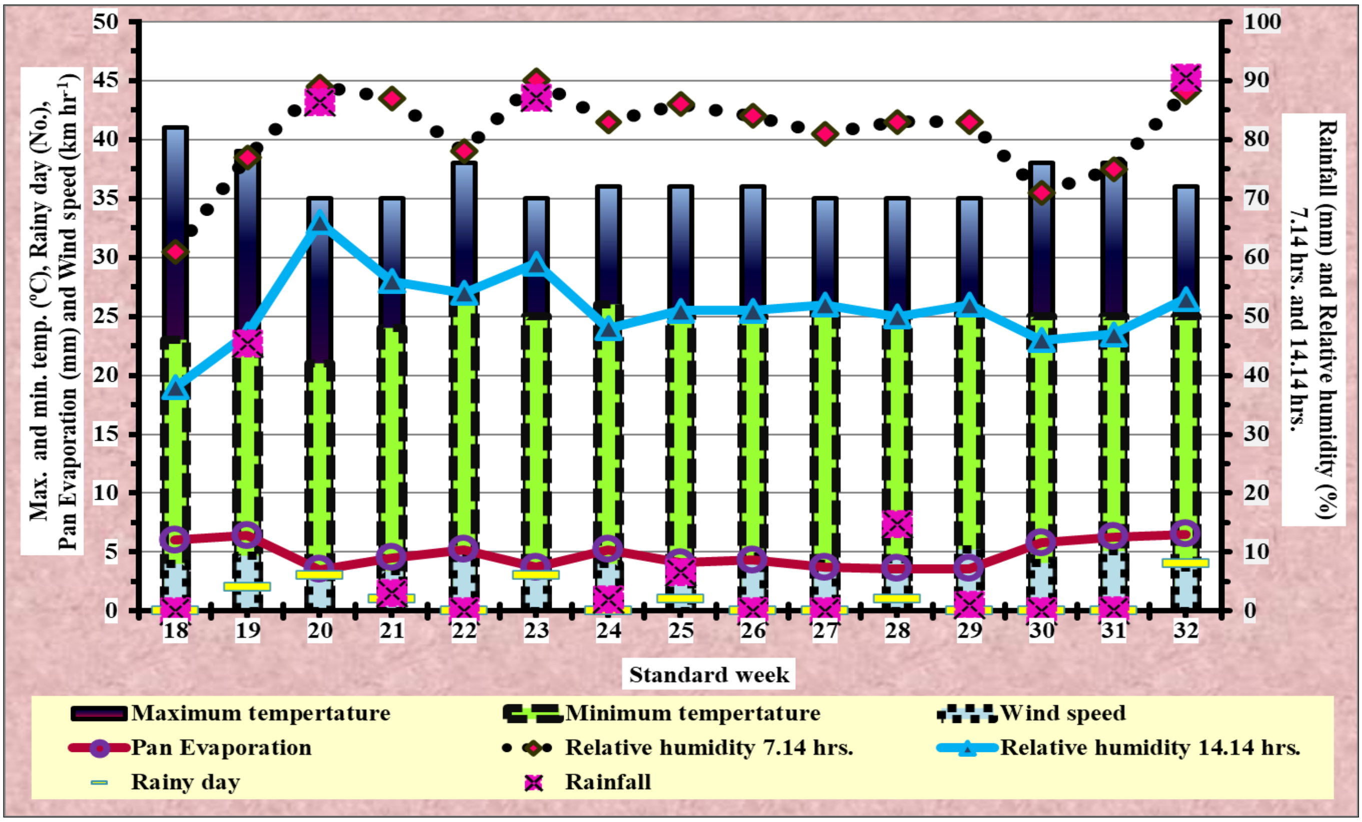

Fig. 4. Weekly weather parameters prevailed during the cropping period (*Summer,* 2024).

Treatment details

Field experiments were laid out in a split-plot design with three replications. This design was selected for this study due to its suitability for experiments involving multiple factors, especially when some factors are difficult to apply uniformly across the entire experimental area. Drip irrigation (main plot) requires large areas for uniform application, making it appropriate for the main plot. Fertigation methods (subplot) can be more easily controlled on smaller subplots, allowing for better management and reliability in irrigation and fertigation trials by effectively minimizing variability. The treatments consisted of a combination of three drip irrigation methods namely; conventional drip irrigation (M_1), time-based automated drip irrigation (M_2) and sensor-based automated drip irrigation (M_3) in the main plot and 5 drip fertigation methods, *viz.,* drip fertigation of 75% RDF (F_1), drip fertigation of 100% RDF (F_2), STCR based drip fertigation (F_3), sensor-based fertigation at 75% NPK level (F_4) and sensor-based fertigation at 100% NPK level (F_5) in sub plot.

M_1- Water is supplied through a drip irrigation system manually, without automation. The irrigation timing and quantity are based on crop evapotranspiration (ETc), M_2- Water is supplied through an automated drip irrigation system on a pre-set schedule. The system turns on and off at predetermined times, ensuring consistent water application based on fixed time intervals. M_3- Irrigation is controlled using soil moisture sensors. Water is applied only when sensors detect that the soil moisture has dropped below a certain threshold. This system ensures efficient water use, applying water only when needed based on real-time soil conditions. F_1- Fertilizer is applied through drip irrigation at 75% of the Recommended Dose of Fertilizers (RDF), as per (17), reducing fertilizer input by 25%, F_2 - Fertilizer is applied through drip irrigation at the full 100% RDF, ensuring that crop nutrient requirements are fully met throughout the growing season, F_3 - Fertilizer application is based on Soil Test Crop Response recommendations, with dosages adjusted according to soil test results. This approach optimizes fertilizer use according to the specific nutrient status of the soil and crop needs, F4 - Water Soluble Fertilizers (WSF's) are applied when sensors detect that soil nutrient levels have fallen below the 75% NPK level threshold, automatically initiating fertigation to maintain the nutrient level at 75% NPK level. This approach ensures fertigation is conducted based on real-time soil nutrient levels and F5 - WSF's are applied when sensors detect that soil nutrient levels have fallen below the 100% NPK level threshold, automatically initiating fertigation to maintain the nutrient level at 100% NPK level. This ensures precise and adequate fertilization based on real-time nutrient needs.

Calibration and maintenance of soil moisture and nutrient sensors

The soil moisture and nutrient sensors were calibrated at the start of the experiment using standard solutions and field soil samples with known moisture and nutrient content. To ensure ongoing accuracy, recalibration was performed monthly. The sensors were periodically cleaned to prevent blockages and their performance was continuously monitored using dedicated software. This allowed for early detection of any inconsistencies and adjustments were made as needed to maintain precise readings throughout the experiment.

Crop management practices

Groundnut variety VRI 10 with a duration of 90-95 days was used as the test crop in both seasons. Seeds were sown at a spacing of 30 cm × 10 cm. The seed rate was calculated at 125 kg per hectare, which is the recommended rate for irrigated groundnut. Gap filling was done 15 days after sowing (DAS) to maintain the optimum plant population across all plots. The spraying of pre-emergence herbicide Pendimethalin @ 2.5 L ha^{-1} was done at 3 DAS. Subsequently, one-hand weeding was employed at 30 DAS.

The first crop was raised during *rabi* 2023 - 24 (Ayppasi pattam). The sowing was taken up on 03.12.2023 and harvesting was completed on 27.02.2024. Subsequently, the second crop was raised during *summer* 2024 (Chithirai pattam). Sowing was taken up on 06.05.2024 and harvesting was done on 13.08.2024.

Pod yield

The harvested pods from the net plot were standardized to have a moisture content of 14 % and expressed in kg ha^{-1}.

Plant analysis

The groundnut plant sample was taken separately at the harvest stage, ground into a fine powder using a Willey mill and used for chemical analysis of nutrient content. The methods used for the analysis of the plant nutrients are listed in Table 2.

Table 2. Methods employed in plant analysis

Sl. No.	Particulars	Method	Reference
1.	Total Nitrogen	Micro kjeldhal's method	(55)
2.	Total Phosphorus	Triple acid digestion with colorimetric estimation	(45)
3.	Total Potassium	Triple acid digestion with flame photometric method	(52)

Soil analysis

From the experimental plot, soil samples were collected randomly after the harvest of crops and composite samples were made by the quartering method. The samples are then passed through a 2 mm sieve and used for analysis of N, P and K. The analysis was carried out based on the standard procedures as described in Table 1.

Soil microbial analysis (CFU g^{-1})

The microbial population in the collected soil samples was determined as described by (18). Soil microbial analysis was observed in the initial soil sample (taken before sowing) and post-harvest soil sample (after the harvest).

Enumeration of total bacterial population

Collected soil samples were weighed to one gram and serially diluted up to 10^{-7}. From 10^{-7} dilution 0.1 mL of aliquots were spread over the Nutrient agar medium in pertiplates and incubated at 35±1°C for 2 days. Then the bacterial colonies were counted and the population was estimated on the soil dry weight basis and expressed in CFU g^{-1} of dry soil.

Enumeration of total fungal population

From 10^{-4} dilution 0.1 mL aliquots were taken and spread over Martins Rose Bengal agar plates and incubated at 25±1° C for 3 days. The fungal population was calculated and expressed in CFU g^{-1} of dry soil.

Enumeration of total actinomycetes population

From 10^{-3} dilutions, 0.1 mL of aliquots were taken and spread over the Kenknights agar medium. The plates were incubated at 37±1°C for 7 days. The actinomycetes population was assessed and expressed in CFU g^{-1} of dry soil.

Enzymatic analysis

Soil enzyme analysis was observed in the initial soil sample (taken before sowing) and post-harvest soil sample (after the harvest).

Phosphatase

Weighed 1 g of soil and transferred it to boiling tubes containing 3 mL of para-nitrophenol phosphate with 3.5 mL of 0.1 M phosphate buffer. Incubated it for about 4 h.

Added 1 mL of 0.5 M calcium chloride along with 4 mL of 0.5 M sodium hydroxide. After the development of yellow colour the intensity was measured by a spectrophotometer at 420 nm. The values were expressed in µg of pNP g^{-1} soil h^{-1} (19).

Dehydrogenase

The assay method was used for the estimation of dehydrogenase enzyme activity. The method described is based on extraction with methanol and calorimetric determination of the TPF produced from the reduction of TTC in soils.

Weighed 20 g of sieved dry soil in a 50 mL beaker and transferred 0.2 g of $CaCo_3$, which was stirred well and added 6 g of this mixture in every three test tubes. 3% solution of TTC and 25 mL of distilled water were added to each tube one by one. After mixing the contents, a tiny quantity of free liquid seemed to be on the soil surface. The contents of every test tube were thoroughly mixed with the help of glass rod, stoppered the tube and incubated at 37°C.

After one day, the stopper was removed. 10 mL of methanol was poured into each test tubes and stoppered the tube and then shaken for 1 min. After shaking of test tubes, the suspension was filtered through a glass funnel plugged with absorbent cotton into a 100 mL volumetric flask. The test tubes were washed with methanol and transferred the soil to the funnel, methanol was added constantly in 10 mL quantities till the disappearance of red colour from the cotton plug. Then the intensity of reddish colour was dignified by using a spectrophotometer at a wavelength of 485 nm. Determined the amount of TPF produced by reference to a calibration graph arranged from TPF standards (20).

Statistical analysis

Collected plant samples and computed data were subjected to statistical analysis as per the procedures described by (21). The data were analyzed using AGRES software packages using the critical difference (C.D.) test at a five percent probability level. Non-significant treatment differences were denoted as 'NS'. The correlation was analyzed using Grapes version 1.1.0 software (22) to evaluate the relationship between total NPK uptake and pod yield in groundnut.

Results and Discussion

Pod yield

Drip irrigation and fertigation methods had a significant impact on the pod yield of groundnut in both seasons (Table 3, Fig. 5). Sensor-based automated drip irrigation (M_3) recorded significantly higher pod yield of 2709 and 2519 kg ha^{-1} in the *rabi* (2023) *and summer* (2024) seasons, respectively. The higher yield under tensiometer-based drip irrigation might be due to the application of the required amount of water to the crop at the required time. Similar results were reported by (23).

Among the drip fertigation methods, sensor-based fertigation at 100% NPK level (F_5) recorded the maximum pod yield of 2774 and 2585 kg ha^{-1} in both seasons, respectively. This was followed by sensor-based fertigation

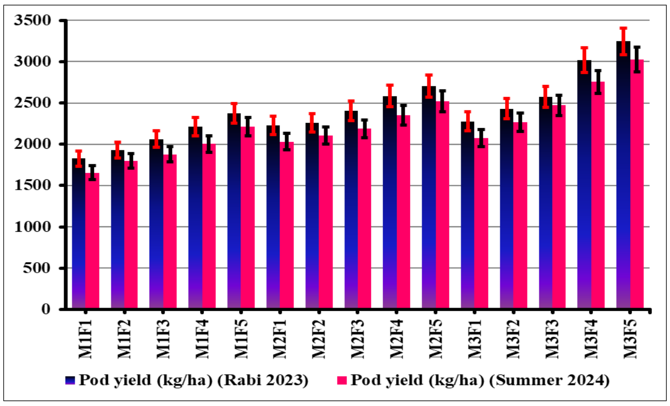

Fig. 5. Effect of drip irrigation and fertigation methods on pod yield of groundnut during *rabi* (2023) and *summer* (2024) seasons.

at 75% NPK level (F_4). The increased responses are mainly attributed to the higher solubility percentage of water-soluble fertilizers, which led to increased nutrient uptake which was ultimately reflected in the yield. Similar results were obtained by (24).

Pod yield was significantly influenced by a combination of various drip irrigation and fertigation methods. The combination of sensor-based automated drip irrigation and sensor-based fertigation at 100% NPK level (M_3F_5) recorded a higher pod yield of 3246 and 3025 kg ha^{-1} in both seasons, respectively. The M_3F_5 treatment ensured higher soil water potential and a steady nutrient supply, which facilitated optimal nutrient uptake and supported microbial activity. Adequate water availability enhanced the translocation of photosynthates and carbohydrate synthesis, maintaining plant water balance and improving physiological functions such as protein synthesis, cell wall development and cell enlargement. Simultaneously, the consistent nutrient supply created a favorable rhizosphere environment, promoting microbial proliferation and activity. This synergistic effect improved soil fertility, nutrient availability and overall plant productivity, demonstrating the efficiency of the M_3F_5 combination in optimizing resource utilization. Higher nutrient uptake might have been aided by the solubility and availability of sufficient quantities of nutrients with optimum soil moisture across the entire crop growth cycle. This helped to absorb more photosynthetically active radiation accompanied with increased yield attributes. The higher rate of photosynthate translocation from source to sink might have resulted in higher pod yield in peanut. Many reports indicated that fertigation with water soluble fertilizer can increase the yield of many crops besides saving 25% of the fertilizer (25). The M_3F_5 treatment significantly enhanced groundnut yield, nutrient uptake and microbial activity in our study. Comparable results were documented by (26), where sensor-based irrigation and fertigation in capsicum achieved improved nutrient availability with a 25% nutrient saving. Our study uniquely demonstrates the efficacy of an indigenous low-cost system, addressing the needs of resource-limited farmers. These findings emphasize the role of precision agriculture in promoting sustainable farming practices, especially in regions with limited water resources.

Nutrient uptake

Nutrient uptake is linked to plant metabolic activities as well as the concentration and distribution of ions in the external

Table 3. Effect of drip irrigation and fertigation methods on pod yield and NPK uptake of groundnut

Treatments	Pod yield (kg ha^{-1})		N uptake (kg ha^{-1})		P uptake (kg ha^{-1})		K uptake (kg ha^{-1})	
	Rabi 2023	*Summer* 2024	*Rabi* 2023	*Summer* 2024	*Rabi* 2023	*Summer* 2024	*Rabi* 2023	*Summer* 2024
Main plot (M) (Drip irrigation methods)								
M_1	2079	1909	84.57	77.41	14.42	14.90	82.01	69.21
M_2	2436	2239	99.52	89.26	17.66	17.35	94.91	79.83
M_3	2709	2519	108.83	97.55	19.60	19.37	103.50	88.08
S.Ed	29.1	27.4	0.87	0.89	0.05	0.19	0.46	0.78
CD (P=0.05)	80.8	76.0	2.43	4.96	0.13	0.53	1.27	2.17
Sub plot (F) (Drip fertigation methods)								
F_1	2110	1922	85.73	78.41	14.95	15.31	81.70	69.49
F_2	2205	2058	89.66	80.93	15.74	15.80	85.78	72.11
F_3	2347	2178	95.53	85.28	16.90	16.67	91.08	76.40
F_4	2605	2369	105.14	94.79	18.67	18.54	100.62	85.41
F_5	2774	2585	112.14	100.96	19.87	19.71	108.19	91.77
S.Ed	34.5	35.0	1.66	1.44	0.29	0.23	1.69	1.27
CD (P=0.05)	71.1	72.1	3.42	3.92	0.59	0.48	3.48	2.62
Interaction (M × F) (Drip irrigation methods × Drip fertigation methods)								
M_1F_1	1826	1656	74.30	69.21	12.52	13.42	71.66	61.29
M_1F_2	1926	1799	78.18	71.74	13.36	13.92	75.98	64.17
M_1F_3	2063	1878	84.09	75.33	14.27	14.45	81.01	66.92
M_1F_4	2211	2002	89.89	82.43	15.44	15.81	87.28	73.90
M_1F_5	2371	2210	96.37	88.34	16.51	16.91	94.11	79.75
M_2F_1	2227	2032	90.39	82.99	15.62	16.01	85.93	72.92
M_2F_2	2258	2107	92.88	84.33	16.18	16.20	88.43	74.14
M_2F_3	2404	2187	98.37	85.65	17.71	16.77	93.62	77.05
M_2F_4	2584	2350	105.14	94.24	18.92	18.44	100.30	85.11
M_2F_5	2705	2521	110.83	99.08	19.86	19.30	106.27	89.92
M_3F_1	2277	2078	92.49	83.04	16.70	16.49	87.51	74.25
M_3F_2	2431	2268	97.91	86.71	17.69	17.29	92.93	78.03
M_3F_3	2574	2470	104.13	94.87	18.72	18.80	98.63	85.25
M_3F_4	3019	2754	120.40	107.70	21.65	21.36	114.26	97.22
M_3F_5	3246	3025	129.23	115.45	23.24	22.90	124.18	105.63
S.Ed	60.8	60.6	2.71	2.40	0.45	0.41	2.65	2.12
CD (P=0.05)	135.4	134.0	5.80	5.18	0.93	0.91	5.54	4.57

Treatment details are given under Materials and Methods

medium. Nitrogen, Phosphorus and potassium uptake by pod, haulm and total uptake differed significantly as influenced by drip irrigation and fertigation methods in groundnut and presented in Table 3, 4 & 5. Sensor-based automated drip irrigation (M_3) resulted in significantly higher uptake of N (108.83 and 97.55 kg/ha), P (19.60 and 19.37 kg/ha), K (103.50 and 88.08 kg/ha), pod NPK content (63.08:11.48:52.93 and 52.53:12.06:50.60 NPK kg/ha) and haulm NPK content (45.75:8.12:50.58 and 45.03:7.31:37.48 NPK kg/ha) in the *rabi* (2023) *and summer* (2024) seasons, respectively. The higher availability of soil moisture resulted in enhanced uptake of both moisture and nutrients. Similarly, frequent irrigation applications, based on soil moisture depletion and matching crop demand, which in turn increased uptake and efficiency of added nutrients. The results are in accordance with (27, 28). However, under deficit water conditions, nutrient uptake was reduced due to inhibition of growth rate as well as impaired nutrient transport to the plant roots (27, 29). Among the drip fertigation methods, sensor-based fertigation at 100% NPK level (F_5) application resulted in significantly higher uptake of N (112.14 and 100.96 kg/ha), P (19.87 and 19.71 kg/ha), K (108.19 and 91.77 kg/ha), pod NPK content (64.46:11.55:54.19 and 53.94:12.07:51.48 NPK kg/ha) and haulm NPK content (47.68:8.32:53.99 and 47.02:7.63:40.29 NPK kg/ha) in the *rabi* (2023) *and summer* (2024) seasons, respectively. Frequent fertigation of water-soluble fertilizers through drip improved the uptake of nutrients by continuous replenishment of nutrients in the depletion zone at the vicinity of the root interface. On the other hand, the optimum moisture availability in the root zone enhanced the transport of dissolved nutrients by mass flow (30). Similar results were also reported by (27, 31-33). In combination, sensor-based automated drip irrigation combined with sensor-based fertigation at 100% NPK level registered significantly higher uptake of N (129.23 and 115.45 kg/ha), P (23.24 and 22.90 kg/ha), K (124.18 and 105.63 kg/ha), pod NPK content (75.60:13.75:63.49 and 62.53:14.36:60.24 NPK kg/ha) and haulm NPK content (53.63:9.49:60.69 and 52.92:8.55:45.39 NPK kg/ha) in the *rabi* (2023) *and summer* (2024) seasons, respectively. Higher nutrient uptake might have been aided by the solubility and availability of sufficient quantities of nutrients with optimum soil moisture, combined with improvements in soil characteristics across the entire crop growth cycle. The results in this present investigation are in line with the findings of previous workers (13, 26, 34-38).

Available nutrients

Initial soil N, P and K statuses are shown in Table 1. Data (Table 6) on soil nutrient status after the harvest of groundnut indicates that drip irrigation and fertigation methods caused a significant variation in soil available N, P and K, indicating their buildup in treated soil. Conventional drip irrigation (M_1) resulted in significantly higher post-harvest soil available N (291.3 and 150.4 kg/ha), P (37.91 and 38.04 kg/ha) and K (228.2 and 159.0 kg/ha) in the *rabi* (2023) *and summer* (2024) seasons, respectively. Among the drip fertigation methods, drip fertigation of 100% RDF (F_2) application resulted in

Table 4. Effect of drip irrigation and fertigation methods on NPK content (kg ha^{-1}) of pod in groundnut

Treatments	N content (kg ha^{-1})		P content (kg ha^{-1})		K content (kg ha^{-1})	
	Rabi 2023	*Summer* 2024	*Rabi* 2023	*Summer* 2024	*Rabi* 2023	*Summer* 2024
Main plot (M) (Drip irrigation methods)						
M_1	47.51	40.74	8.13	8.83	40.53	38.43
M_2	56.62	47.38	10.20	10.54	47.53	45.03
M_3	63.08	52.53	11.48	12.06	52.93	50.60
S.Ed	0.30	0.85	0.06	0.09	0.30	0.42
CD (P=0.05)	0.84	2.36	0.17	0.26	0.83	1.17
Sub plot (F) (Drip fertigation methods)						
F_1	48.56	41.34	8.54	9.20	41.13	39.25
F_2	50.76	43.13	9.05	9.60	43.01	40.96
F_3	54.46	45.40	9.70	10.17	45.80	43.37
F_4	60.45	50.61	10.84	11.34	50.86	48.36
F_5	64.46	53.94	11.55	12.07	54.19	51.48
S.Ed	0.88	0.40	0.17	0.15	0.84	0.73
CD (P=0.05)	1.82	0.82	0.35	0.30	1.73	1.50
Interaction (M × F) (Drip irrigation methods × Drip fertigation methods)						
M_1F_1	41.05	35.40	6.94	7.81	35.52	33.93
M_1F_2	43.36	37.34	7.49	8.23	37.52	35.77
M_1F_3	47.47	39.93	8.02	8.59	40.24	37.39
M_1F_4	50.88	43.84	8.79	9.43	43.13	41.05
M_1F_5	54.78	47.17	9.43	10.11	46.26	43.99
M_2F_1	51.62	44.62	9.04	9.70	43.44	41.45
M_2F_2	52.34	45.17	9.36	9.82	44.04	41.96
M_2F_3	55.97	45.19	10.18	10.19	46.91	43.54
M_2F_4	60.18	49.81	10.95	11.23	50.45	47.99
M_2F_5	63.01	52.12	11.46	11.75	52.82	50.21
M_3F_1	53.00	43.98	9.64	10.10	44.44	42.37
M_3F_2	56.58	46.88	10.29	10.76	47.45	45.16
M_3F_3	59.92	51.07	10.90	11.73	50.26	49.20
M_3F_4	70.30	58.17	12.79	13.36	59.00	56.04
M_3F_5	75.60	62.53	13.75	14.36	63.49	60.24
S.Ed	1.40	1.05	0.27	0.25	1.33	1.20
CD (P=0.05)	2.94	2.66	0.57	0.53	2.79	2.59

Treatment details are given under Materials and Methods

Table 5. Effect of drip irrigation and fertigation methods on NPK content (kg ha^{-1}) of haulm in groundnut

Treatments	N content (kg ha^{-1})		P content (kg ha^{-1})		K content (kg ha^{-1})	
	Rabi 2023	*Summer* 2024	*Rabi* 2023	*Summer* 2024	*Rabi* 2023	*Summer* 2024
Main plot (M) (Drip irrigation methods)						
M_1	37.06	36.68	6.29	6.07	41.47	30.78
M_2	42.90	41.88	7.46	6.81	47.38	34.80
M_3	45.75	45.03	8.12	7.31	50.58	37.48
S.Ed	0.27	0.48	0.06	0.03	0.29	0.33
CD (P=0.05)	0.76	1.34	0.17	0.09	0.80	0.92
Sub plot (F) (Drip fertigation methods)						
F_1	37.17	37.08	6.41	6.10	40.57	30.23
F_2	38.90	37.80	6.69	6.20	42.77	31.15
F_3	41.08	39.89	7.20	6.50	45.28	33.03
F_4	44.69	44.19	7.83	7.20	49.76	37.06
F_5	47.68	47.02	8.32	7.63	53.99	40.29
S.Ed	0.64	0.60	0.11	0.09	0.70	0.46
CD (P=0.05)	1.31	1.24	0.24	0.18	1.44	0.95
Interaction (M × F) (Drip irrigation methods × Drip fertigation methods)						
M_1F_1	33.25	33.81	5.59	5.61	36.14	27.36
M_1F_2	34.82	34.39	5.87	5.70	38.46	28.40
M_1F_3	36.62	35.41	6.25	5.86	40.77	29.53
M_1F_4	39.01	38.60	6.65	6.38	44.15	32.86
M_1F_5	41.59	41.17	7.08	6.80	47.85	35.75
M_2F_1	38.77	38.37	6.57	6.31	42.49	31.46
M_2F_2	40.54	39.16	6.82	6.38	44.39	32.17
M_2F_3	42.40	40.46	7.53	6.58	46.70	33.50
M_2F_4	44.96	44.43	7.97	7.21	49.86	37.13
M_2F_5	47.82	46.96	8.40	7.55	53.44	39.71
M_3F_1	39.49	39.05	7.06	6.39	43.07	31.88
M_3F_2	41.34	39.83	7.39	6.52	45.48	32.87
M_3F_3	44.21	43.80	7.82	7.08	48.36	36.05
M_3F_4	50.10	49.53	8.86	8.00	55.27	41.19
M_3F_5	53.63	52.92	9.49	8.55	60.69	45.39
S.Ed	1.02	1.05	0.19	0.14	1.17	0.79
CD (P=0.05)	2.16	2.32	0.40	0.29	2.36	1.72

Treatment details are given under Materials and Methods

Table 6. Effect of drip irrigation and fertigation methods on post-harvest soil available NPK (kg ha^{-1}) of groundnut

Treatments	N (kg ha^{-1})		P (kg ha^{-1})		K (kg ha^{-1})	
	Rabi 2023	*Summer* 2024	*Rabi* 2023	*Summer* 2024	*Rabi* 2023	*Summer* 2024
Main plot (M) (Drip irrigation methods)						
M_1	291.3	150.4	37.91	38.04	228.2	159.0
M_2	276.3	138.6	34.68	35.60	215.3	148.4
M_3	267.0	130.3	32.73	33.58	206.9	140.1
S.Ed	3.07	1.79	0.42	0.43	2.26	1.68
CD (P=0.05)	8.52	4.96	1.18	1.18	6.28	4.68
Sub plot (F) (Drip fertigation methods)						
F_1	291.0	150.3	38.14	38.39	231.6	161.8
F_2	292.8	153.6	49.35	49.90	246.1	177.4
F_3	274.0	136.2	41.69	42.53	210.9	143.6
F_4	267.1	129.5	21.59	22.33	198.2	131.4
F_5	266.0	129.1	24.77	25.54	197.3	131.7
S.Ed	3.53	1.90	0.48	0.43	2.89	1.87
CD (P=0.05)	7.28	3.92	0.99	0.89	5.97	3.86
Interaction (M × F) (Drip irrigation methods × Drip fertigation methods)						
M_1F_1	302.4	159.5	40.57	40.28	241.6	170.0
M_1F_2	304.3	162.8	51.73	51.78	255.5	185.3
M_1F_3	285.4	146.2	44.32	44.75	221.0	153.1
M_1F_4	282.4	141.8	24.82	25.06	211.5	142.9
M_1F_5	281.7	141.8	28.13	28.34	211.4	143.8
M_2F_1	286.4	145.8	37.47	37.69	227.3	158.3
M_2F_2	289.6	150.2	48.91	49.50	243.1	175.4
M_2F_3	271.1	135.8	40.88	42.43	208.4	143.0
M_2F_4	267.1	130.0	21.34	22.43	198.5	131.7
M_2F_5	267.3	131.0	24.78	25.95	199.2	133.6
M_3F_1	284.3	145.7	36.39	37.21	225.7	157.0
M_3F_2	284.6	147.8	47.40	48.41	239.6	171.5
M_3F_3	265.4	126.6	39.87	40.40	203.4	134.8
M_3F_4	251.9	116.6	18.61	19.51	184.5	119.6
M_3F_5	248.9	114.6	21.40	22.35	181.3	117.9
S.Ed	6.27	3.44	0.85	0.79	5.02	3.35
CD (P=0.05)	14.01	7.76	1.91	1.80	11.08	7.52

Treatment details are given under Materials and Methods

significantly higher post-harvest soil available N (292.8 and 153.6 kg/ha), P (49.35 and 49.90 kg/ha) and K (246.1 and 177.4 kg/ha) in the *rabi* (2023) *and summer* (2024) seasons, respectively. In combination, conventional drip irrigation combined with drip fertigation of 100% RDF (M_1F_2) registered significantly higher post-harvest soil available N (304.3 and 162.8 kg/ha), P (51.73 and 51.78 kg/ha), K (255.5 and 183.5 kg/ha) in the *rabi* (2023) *and summer* (2024) seasons, respectively. This maximum gain in soil available nutrients (NPK) might be attributed to lesser plant growth, nutrient uptake and yield of peanut which utilized lesser amount of nutrients as compared to other treatments. Also, the amount of nutrients added was relatively higher than 75% of WSF's treatment (11, 13, 39, 40).

Microbial population

Soil microbial population, the active fraction of soil serves as an index of soil fertility. Initial soil microbial populations are shown in Table 1. Soil microbial populations were significantly influenced by drip irrigation and fertigation methods in both seasons (Table 7). Sensor-based automated drip irrigation (M_3) recorded a higher soil microbial population of bacteria (41.02 and 50.60 × 10^7 CFU g soil^{-1}), fungi (20.40 and 29.80 × 10^4 CFU g soil^{-1}) and actinomycetes (15.40 and 21.40 × 10^3 CFU g soil^{-1}) in the *rabi* (2023) *and summer* (2024) seasons, respectively. The optimum moisture condition favoured higher microbial load in the soil. Similar results were also reported (26). Among the drip fertigation methods, sensor-based fertigation at 100% NPK level (F_5) recorded higher soil microbial population of bacteria (46.00 and 48.33 × 10^7 CFU g soil^{-1}), fungi (23.66 and 30.33 × 10^4 CFU g soil^{-1}) and actinomycetes (18.00 and 23.00 × 10^3 CFU g soil^{-1}) in the *rabi* (2023) *and summer* (2024) seasons, respectively. On interaction, the combination of sensor-based automated drip irrigation and sensor-based fertigation at 100% NPK level (M_3F_5) recorded a higher soil microbial population of bacteria (53.00 and 59.00 × 10^7 CFU g soil^{-1}), fungi (28.00 and 37.00 × 10^4 CFU g soil^{-1}) and actinomycetes (22.00 and 29.00 × 10^3 CFU g soil^{-1}) in both seasons, respectively. The lower soil microbial population observed with the combination of conventional drip irrigation and drip fertigation of 100% RDF (M_1F_1) (bacteria (53.00 and 59.00 × 10^7 CFU g soil^{-1}), fungi (28.00 and 37.00 × 10^4 CFU g soil^{-1}) and actinomycetes (22.00 and 29.00 × 10^3 CFU g soil^{-1}) in both seasons, respectively). The lower microbial load might be due to moisture deficiency, which causes stress and death of microbes in the soil. Similar results were also reported by many researchers (17, 23, 41-45).

Soil enzyme activities

Initial soil enzyme activities are presented in Table 1. Soil enzyme activities were significantly influenced by drip irrigation and fertigation methods in both seasons (Table 8). Sensor-based automated drip irrigation (M_3) recorded significantly higher dehydrogenase activity of 6.298 and 5.859 µg of TPF g soil^{-1} day^{-1} in the *rabi* (2023) *and summer* (2024) seasons, respectively. The optimum moisture conditions favored higher microbial load as well as enzymatic activity, which led to higher nutrient uptake and higher yield. Similar results were also reported by (23). Among the drip fertigation methods, sensor-based fertigation at 100% NPK level (F_5) recorded the maximum dehydrogenase activity of 6.692 and

Table 7. Effect of drip irrigation and fertigation methods on soil microbial population

Treatments	Bacteria (10^7 CFU g soil^{-1})		Fungi (10^4 CFU g soil^{-1})		Actinomycetes (10^3 CFU g soil^{-1})	
	Rabi 2023	*Summer* 2024	*Rabi* 2023	*Summer* 2024	*Rabi* 2023	*Summer* 2024
Main plot (M) (Drip irrigation methods)						
M_1	27.80	31.80	11.60	19.40	11.00	13.00
M_2	35.00	41.40	19.60	24.20	11.60	15.20
M_3	41.20	50.60	20.40	29.80	15.40	21.40
S.Ed	0.49	0.38	0.09	0.18	0.12	0.15
CD (P=0.05)	1.35	1.05	0.26	0.51	0.32	0.42
Sub plot (F) (Drip fertigation methods)						
F_1	23.33	33.33	12.00	17.00	7.66	11.33
F_2	32.00	37.66	12.00	21.66	10.00	14.00
F_3	33.33	41.66	18.00	25.33	13.00	16.00
F_4	38.66	45.33	20.33	28.00	14.66	18.33
F_5	46.00	48.33	23.66	30.33	18.00	23.00
S.Ed	0.42	0.65	0.27	0.38	0.18	0.25
CD (P=0.05)	0.87	1.34	0.55	0.79	0.38	0.53
Interaction (M × F) (Drip irrigation methods × Drip fertigation methods)						
M_1F_1	18.00	22.00	5.00	12.00	6.00	8.00
M_1F_2	25.00	26.00	9.00	17.00	10.00	11.00
M_1F_3	28.00	32.00	11.00	20.00	12.00	13.00
M_1F_4	30.00	39.00	15.00	23.00	12.00	15.00
M_1F_5	38.00	40.00	18.00	25.00	15.00	18.00
M_2F_1	21.00	35.00	15.00	18.00	7.00	10.00
M_2F_2	34.00	39.00	15.00	22.00	8.00	13.00
M_2F_3	33.00	43.00	21.00	25.00	12.00	14.00
M_2F_4	40.00	44.00	22.00	27.00	14.00	17.00
M_2F_5	47.00	46.00	25.00	29.00	17.00	22.00
M_3F_1	30.00	43.00	16.00	21.00	10.00	16.00
M_3F_2	38.00	48.00	12.00	26.00	12.00	18.00
M_3F_3	39.00	50.00	22.00	31.00	15.00	21.00
M_3F_4	46.00	53.00	24.00	34.00	18.00	23.00
M_3F_5	53.00	59.00	28.00	37.00	22.00	29.00
S.Ed	0.81	1.07	0.42	0.62	0.31	0.42
CD (P=0.05)	1.89	2.31	0.89	1.32	0.67	0.91

Treatment details are given under Materials and Methods

Table 8. Effect of drip irrigation and fertigation methods on soil enzyme activities

Treatments	Dehydrogenase activity (µg of TPF g soil^{-1} day^{-1})		Phosphotase activity (µg of PNP g soil^{-1} day^{-1})	
	Rabi 2023	*Summer* 2024	*Rabi* 2023	*Summer* 2024
Main plot (M) (Drip irrigation methods)				
M_1	4.502	4.006	30.13	21.48
M_2	5.985	5.171	33.88	29.58
M_3	6.298	5.859	39.57	35.38
S.Ed	0.06	0.05	0.51	0.40
CD (P=0.05)	0.17	0.15	1.41	1.11
Sub plot (F) (Drip fertigation methods)				
F_1	5.050	3.880	27.31	22.60
F_2	4.894	4.448	32.21	24.77
F_3	5.484	4.975	34.63	29.17
F_4	5.856	5.512	37.45	31.49
F_5	6.692	6.248	41.02	36.05
S.Ed	0.09	0.07	0.43	0.38
CD (P=0.05)	0.19	0.15	0.89	0.79
Interaction (M × F) (Drip irrigation methods × Drip fertigation methods)				
M_1F_1	4.232	2.643	20.13	14.40
M_1F_2	3.716	3.465	30.17	19.33
M_1F_3	4.479	4.227	31.68	22.32
M_1F_4	4.754	4.598	33.42	22.45
M_1F_5	5.332	5.101	35.26	28.91
M_2F_1	5.376	4.254	28.23	21.79
M_2F_2	5.232	4.320	30.76	22.42
M_2F_3	5.698	5.365	33.29	31.47
M_2F_4	6.387	5.521	35.72	33.74
M_2F_5	7.232	6.398	41.41	38.52
M_3F_1	5.543	4.743	33.59	31.61
M_3F_2	5.734	5.559	35.70	32.56
M_3F_3	6.276	5.332	38.94	33.73
M_3F_4	6.427	6.418	43.23	38.29
M_3F_5	7.511	7.244	46.41	40.74
S.Ed	0.15	0.13	0.84	0.72
CD (P=0.05)	0.34	0.28	1.96	1.64

Treatment details are given under Materials and Methods.

6.248 μg of TPF g soil^{-1} day^{-1} in the *rabi* (2023) *and summer* (2024) seasons, respectively. On interaction, the combination with sensor-based automated drip irrigation and sensor-based fertigation at 100% NPK level (M_3F_5) recorded significantly higher dehydrogenase activity of 7.511 and 7.244 μg of TPF g soil^{-1} day^{-1} in both seasons, respectively. The significantly higher activity of dehydrogenase might be attributable to frequent changes in soil redox potential. Soil water content and temperature influence dehydrogenase activity indirectly by affecting the soil redox status (13, 46).

Regarding phosphotase activity, increased phosphotase activity was recorded with sensor-based automated drip irrigation (M_3) (39.57 and 35.38 μg of PNP g soil^{-1} day^{-1}) in the *rabi* (2023) *and summer* (2024) seasons, respectively. The optimum moisture condition favored higher enzymatic activity (21). Among the drip fertigation methods, sensor-based fertigation at 100% NPK level (F_5) recorded significantly higher phosphatase activity of 41.02 and 36.05 μg of PNP g soil^{-1} day^{-1} in the *rabi* (2023) *and summer* (2024) seasons, respectively. On interaction, Combination with sensor-based automated drip irrigation and sensor-based fertigation at 100% NPK level (M_3F_5) recorded significantly higher phosphatase activity of 46.41 and 40.74 μg of PNP g soil^{-1} day^{-1} in both seasons, respectively.

Correlation analysis

Correlation analysis was carried out to evaluate the relationship between total NPK uptake and pod yield in groundnut. The findings revealed that pod yield exhibited a strong positive correlation with N uptake (0.99), P uptake (1.00) and K uptake (0.99) (Fig. 6).

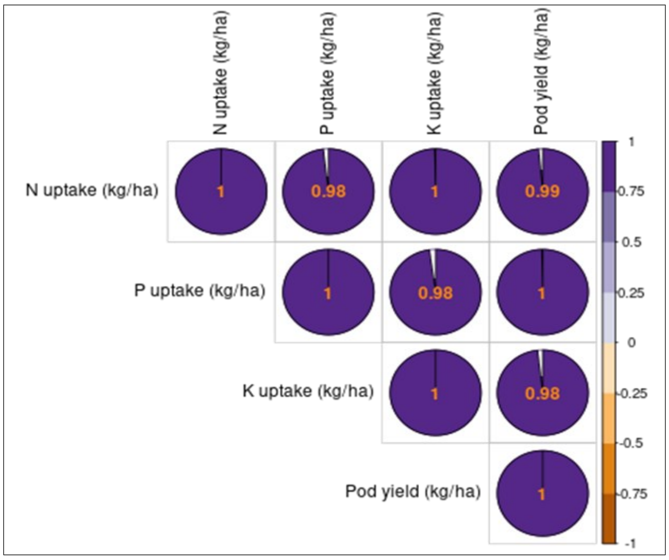

Fig. 6. Correlation between total NPK uptake and pod yield (Pooled data).

Conclusion

Based on the experimental results, it can be concluded that sensor-based automated drip irrigation combined with sensor-based fertigation at 100% NPK level (M_3F_5) enhanced nutrient uptake, microbial population and enzyme activities resulting in higher pod yield of groundnut. Future research should focus on long-term soil health studies, economic assessments and nutrient cycling under sensor-based fertigation systems. Additionally, exploring crop-specific responses, climate resilience and integration with other smart farming technologies will enhance system efficiency. Sustainability evaluations will ensure resource conservation and improved yield. These areas will optimize sensor-based fertigation for sustainable agriculture. This approach enhances water use efficiency, vital for arid and semi-arid regions with limited water resources. The findings support policies promoting advanced irrigation systems and water management guidelines to ensure sustainable farming practices.

Scaling up sensor-based fertigation requires financial support for farmers, training on system operation and affordable solutions, with government policies incentivizing adoption. Over time, the system's efficiency and long-term savings will encourage farmers to adopt and increase wider use.

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Authors' contributions

CA wrote the first draft of the paper. AG conceptualized, reviewed and edited the research paper holistically. ES, GH, KK, BABS and KS reviewed the paper and shared their inputs for upscaling. All authors have read and approved the final manuscript.

Compliance with ethical standards

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

Ethical issues: None

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