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RESEARCH ARTICLE

Response of indigenous low-cost smart fertigation system on yield and quality of groundnut (*Arachis hypogaea* L.)

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Abstract

The precise application of nutrients and water in groundnuts ensures optimal plant growth, enhances yield and quality and minimizes resource wastage. This approach promotes sustainable farming by enhancing nutrient use efficiency and conserving water. Field experiments were conducted in two locations to evaluate the effectiveness of automated drip irrigation and a low-cost smart drip fertigation system on groundnut growth, yield and quality. The study was conducted at two locations: (i) a farmer's field in Kanjipatti village, Kalaiyarkoil block, Sivagangai district during the *rabi* 2023 season and (ii) the central farm at the Agricultural College and Research Institute, Madurai district, during summer 2024 in Tamil Nadu. Field trials were conducted using a split-plot design with three replications. The main plot treatments consisted 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), whereas five drip fertigation treatments, viz., fertigation of 75 % RDF (F_1), 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) were imposed in the subplot. Significantly higher yield attributes, yield and quality parameters were recorded in the treatment with sensor-based automated drip irrigation combined with sensor-based fertigation at 100 % NPK Level (M_3F_5). Implementing sensor-based automated drip fertigation to groundnut cultivation enhanced yield and reduced water and fertilizer inputs while improving groundnut quality.

Keywords: groundnut; quality parameters; sensors; smart fertigation; yield attributes; yield

Introduction

Groundnut (*Arachis hypogaea* L.) is a vital legume crop widely cultivated in tropical and semi-arid regions worldwide, valued for its economic, nutritional and industrial importance. Based on production volume and economic value, it ranks as the 13th most important food crop and the 4th most significant oilseed crop globally. India is one of the largest groundnut-producing countries, ranking first in cultivated area and second in total production after China (Give here Year and source). In India, groundnut is cultivated across 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).

Optimizing irrigation water and fertilizer application is crucial in efficient irrigation system design, water conservation, cost and energy savings and reducing environmental hazards (2). Adopting more efficient irrigation technologies is essential to address challenges such as water scarcity and climate variability. Drip irrigation is a highly efficient method for supplying water and nutrients to plants, significantly improving water conservation, crop yield and water-use efficiency. Drip irrigation is particularly suitable for groundnut cultivation due to its efficient water management, which enhances water-use efficiency and crop yield. The system delivers water directly to the root zone, significantly reducing water wastage, improves nutrient uptake and helps control weed growth (3-5).

Currently, a significant proportion of farmers in India irrigate their fields manually, which can lead to inefficient water use. Excess water is sometimes applied, while water reaches the crops too late at other times, causing them to dry out. These practices contribute to water wastage and deficiencies, adversely affecting plant growth and yield. Automated drip irrigation systems can mitigate these issues by supplying water on real-time crop and soil moisture requirements. The system uses valves that turn on or off automatically, ensuring optimal water delivery (6). Automation in drip irrigation reduces manual intervention, offering several benefits, including greater precision, more efficient water use and reduced labour. Automated systems facilitate high-frequency, low-volume irrigation, enhancing water distribution and improving soil moisture consistency, benefiting crops like groundnut (7). These systems often incorporate sensors installed in the root zone to measure soil moisture. When integrated with fertigation, drip irrigation enhances nutrient delivery efficiency compared to traditional broadcasting methods, significantly boosting crop yields (8).

As an energy-rich crop, groundnut requires adequate nutrition to achieve higher yields (8). Fertigation provides an efficient solution by directly delivering the optimal combination of water and nutrients to the plant's root zone, effectively meeting its water and nutrient needs (9). This method ensures precise and uniform nutrient application to the root-active zone, where most active roots are concentrated, allowing optimal nutrient quantities and concentrations throughout the growing season.

Despite these potential advantages, research on fertigation in groundnut remains limited, particularly in sensor-based automation. Conventional automated fertigation systems are typically controlled using pre-set timers 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 (10). In contrast, sensor-based automated fertigation provides a dynamic approach by continuously adjusting irrigation and nutrient supply according to real-time soil and crop data. Sensor-based fertigation minimizes water and nutrient waste while maximizing crop growth efficiency by delivering the correct amount of water and nutrients appropriately. Advanced fertigation systems with multi-feed injection and automated controls are often expensive. However, a locally designed system with comparable capabilities is available at a significantly lower cost. This indigenous system reduces initial costs by approximately 50 % compared to existing systems, offering significant financial benefits to end users. Based on these factors, this study evaluates the performance of an indigenous low-cost smart fertigation system in groundnut cultivation.

Materials and Methods

Experimental field locations and soil characteristics

Field experiments were conducted at two locations. Location I was a farmer's field in Kanjipatti village, Kalaiyar Koil block, Sivagangai district, Tamil Nadu, where the experiment was conducted during the *rabi* 2023 season. This site lies 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 was field number C-38 of the research block at Agricultural College and Research Institute, Madurai district, Tamil Nadu, where the experiment was conducted during summer 2024. This site lies at 9° 57' 50'' N latitude and 78° 12' 19'' E longitude with an altitude, with an altitude of 115 m above mean sea level, 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, Sivagangai district (Location I), is red sandy clay loam. It is medium in available nitrogen (373 kg/ha), phosphorus (20.5 kg/ha) and potassium (275 kg/ha). In contrast, the soil texture of the experimental field at the Agricultural College and Research Institute, Madurai district (Location II), is sandy clay loam. It is low in available nitrogen (222 kg/ha) but medium in phosphorus (18.2 kg/ha) and potassium (190 kg/ha).

Weather and climate

At Location I, data temperature, relative humidity, pan evaporation, wind speed, rainfall and solar radiation were obtained from the Agro Climatic Research Centre, Coimbatore, Tamil Nadu. For Location II, data were collected from 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. At Location II, temperatures ranged from 35°C to 41°C (maximum) and 21°C to 27°C (minimum). 120.5 mm and 337.2 mm of rainfall 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 hrs and 38 % to 66 % at 14:14 hrs. 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 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. Fig. 3-4 provide the weather factors that prevailed during the crop growth.

Treatment details

Field experiments were laid out in split-plot design, having 3 drip irrigation methods, *viz.,* 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 (F3), sensor-based fertigation at 75 % NPK Level

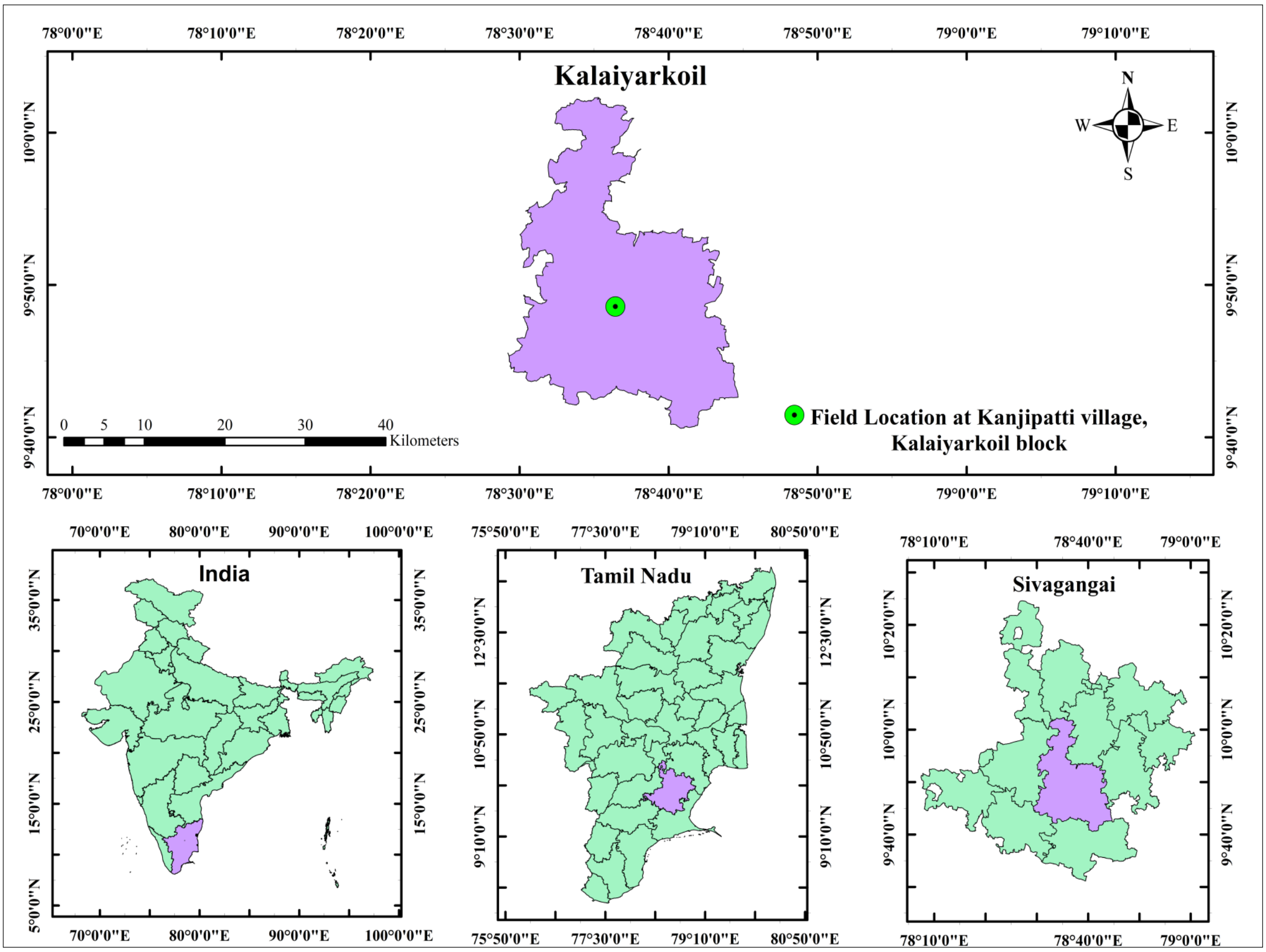

Fig. 1. Location of experimental farm (Location I).

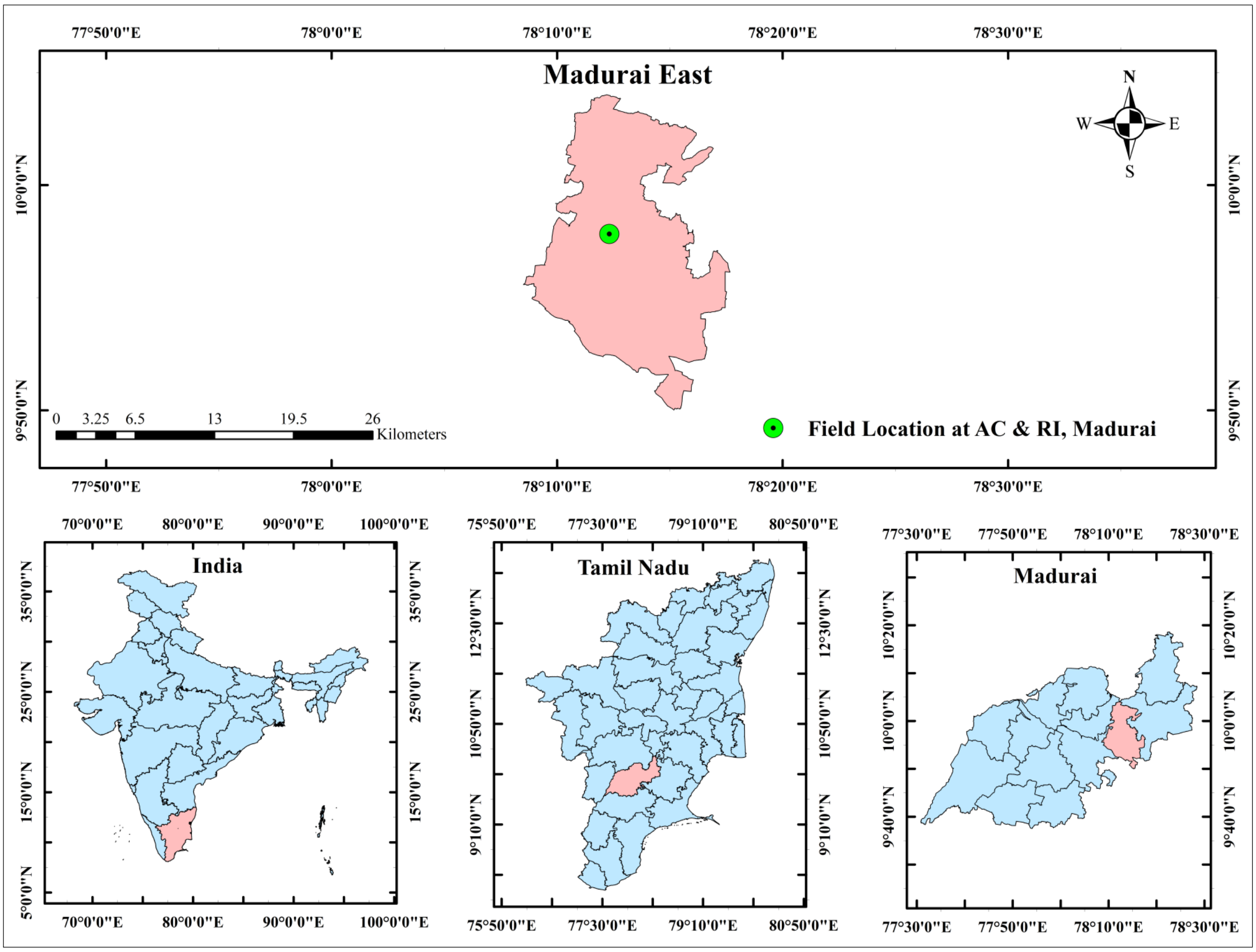

Fig. 2. Location of experimental farm (Location II).

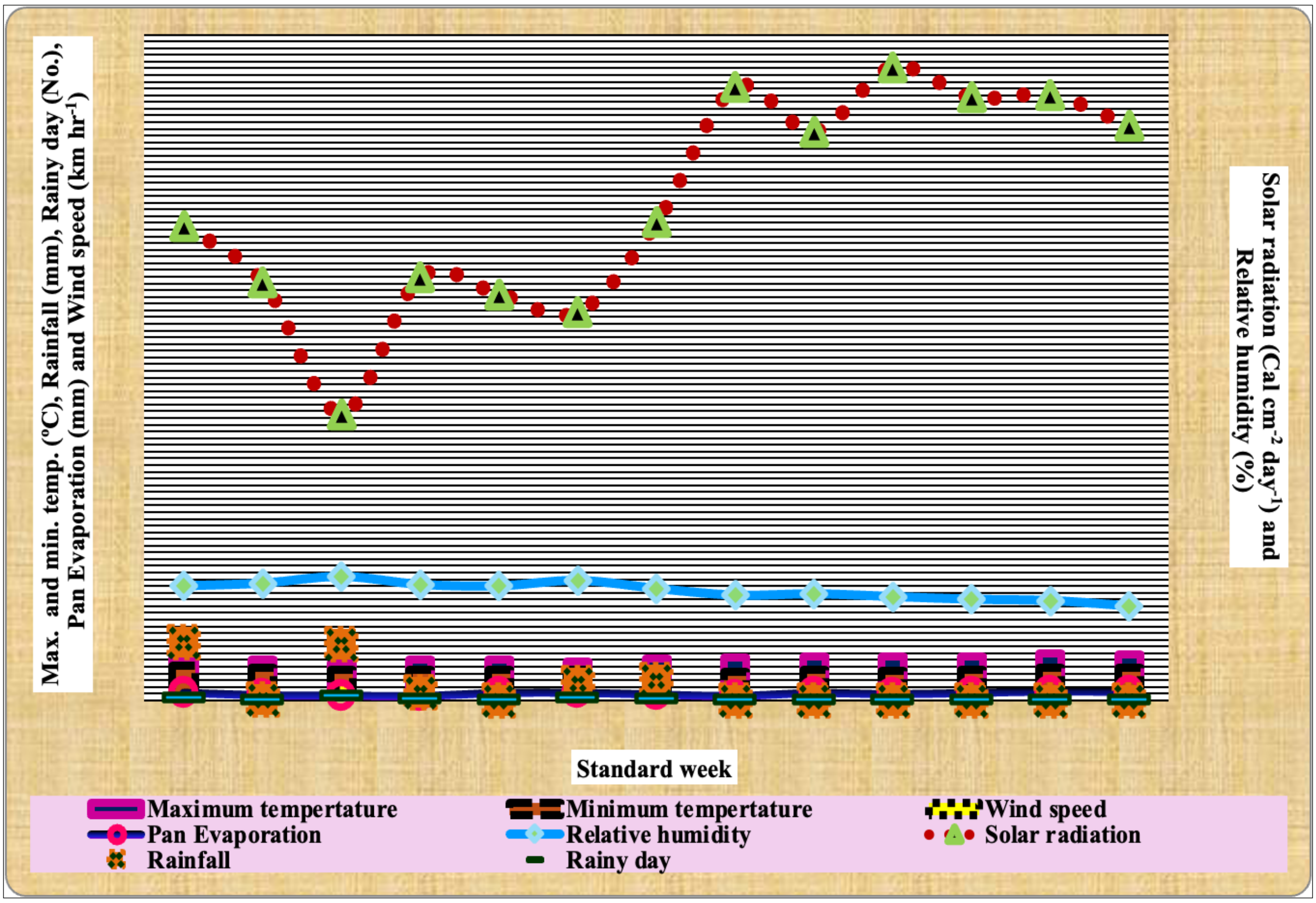

Fig. 3. Weekly weather parameters prevailed during the cropping period (*Rabi,* 2023).

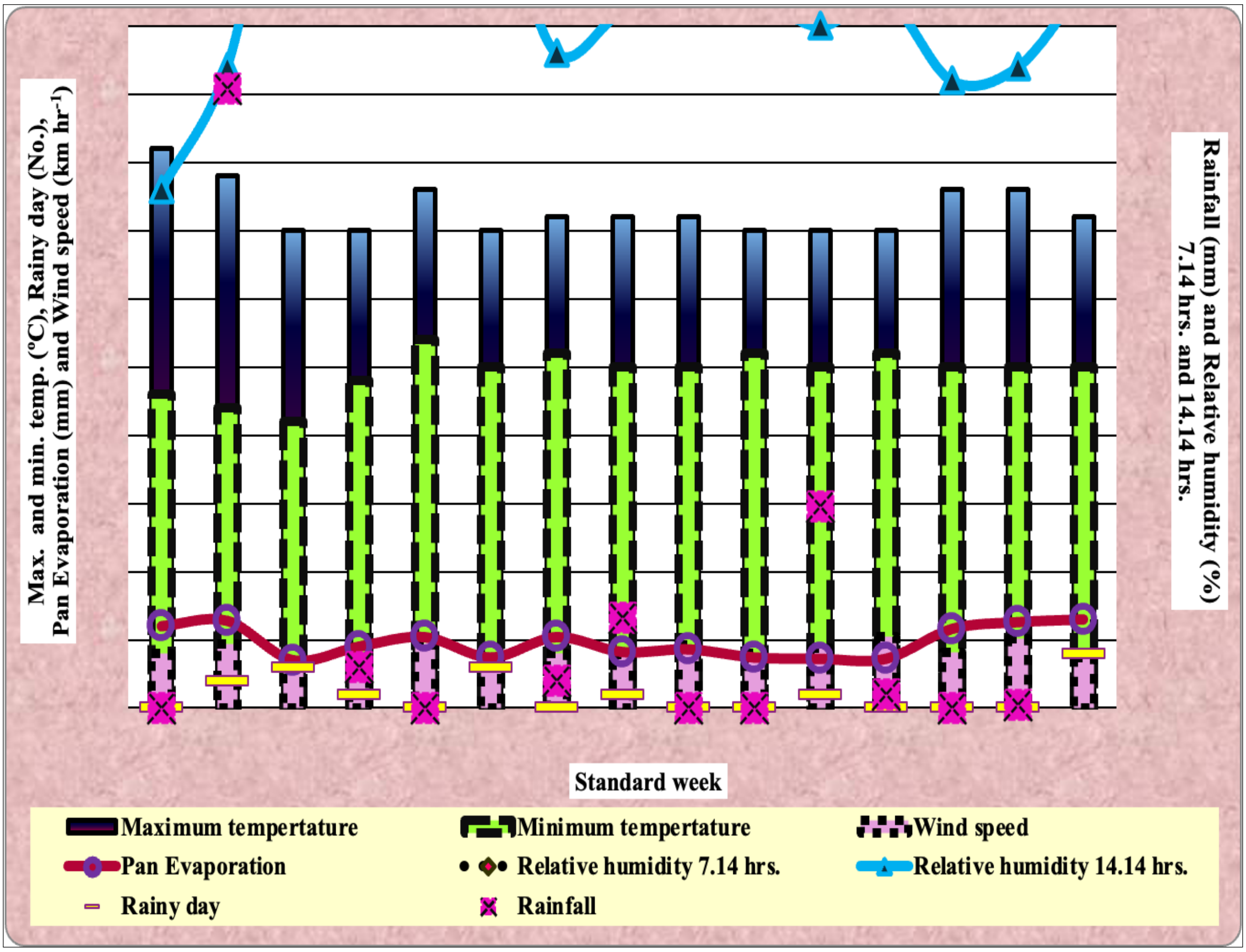

Fig. 4. Weekly weather parameters prevailed during the cropping period (Summer, 2023).

(F_4) and sensor-based fertigation at 100 % NPK Level (F5) in subplot, replicated thrice. M_1 - Without automation, water is supplied manually through a drip irrigation system. The irrigation timing and quantity are based on crop evapotranspiration (ETc). M2 - Water is provided 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 (11), reducing fertilizer input by 25 %. F_2 - Fertilizer is applied through drip irrigation at the complete 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, F_4 – Water Soluble Fertilizers (WSFs) 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. This approach ensures fertigation is conducted based on real-time soil nutrient levels and F_5 – WSF 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. This ensures precise and adequate fertilization based on real-time nutrient needs.

Crop management practices

Groundnut variety VRI 10, with a duration of 90-95 days, was used as a test crop during both seasons. Seeds were sown at a spacing of 30 cm × 10 cm. The seed rate was calculated at 125 kg per hectare, the recommended rate for irrigated groundnuts. Gap filling was done on 15 DAS to maintain the optimum plant population across all plots. The spraying of pre-emergence herbicide Pendimethalin @ 2.5 L/ha was done at 3 DAS. Subsequently, one-hand weeding was employed at 30 DAS. The first crop was raised during *rabi* 2023 (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 the *summer* of 2024 (Chithirai Pattam). Sowing was taken up on 06.05.2024 and harvesting was done on 13.08.2024.

Biometric observations

Yield attributes and yield

The yield attributes of groundnut were recorded from the selected plants in each plot at harvest time.

Total number of pods/plant

The total number of pods plant^{-1} was recorded at harvest from five tagged plants in each plot and the average was computed.

Number of single-seeded pods/plant

Five tagged plants yielded a total of single-seeded pods during harvest. The average was determined and given as single-seeded pods/plants.

Number of double-seeded pods/plant

Five tagged plants yielded a total of two seeded pods during harvest. The average was determined and given as double-seeded pods/plant.

Hundred pod weight

The dry weight of 100 randomly chosen pods was measured and expressed in gram (g) from each treatment.

Hundred kernel weight

The dry weight of one hundred randomly picked kernels from every plot was noted and expressed in gram (g).

Shelling percentage

The kernels' weight as a percentage of the pods (100 g) from which the kernels were shelled out was used to compute the shelling rate. The formula that was used in the study is given below.

$$\text{Shelling percentage} = \frac{\text{Kernal weight}}{\text{Pod weight}} \times 100 \qquad \text{(Eqn.1)}$$

Yield

Pod yield

The harvested pods from the net plot were standardized to have a moisture content of 14 % and expressed in kg/ha.

Haulm yield

After stripping off the pods, the haulms were sun-dried and their dry weight was recorded and expressed in kg/ha**.**

Harvest index

The Harvest index was determined by comparing the yield of the economically significant plant portions (economic yield) to the overall biological yields in dry matter.

$$\text{Harvest index} = \frac{\text{Economic yield}}{\text{Biological yield}} \times 100 \qquad \text{(Eqn.2)}$$

Quality parameters

Five plants were unsystematically harvested from every net plot at the harvest stage. Pods were stripped out and air dried under shade. After that, the sample kernels were used to evaluate quality characters.

Oil content

The kernel's oil content was estimated using Soxhlet's Ether Extraction Method, described and expressed in percentage (12).

Protein content

Using the Micro-Kjeldahl method, Kernels were analyzed for total nitrogen content and the protein content was obtained by multiplying the factor. 6.25 with the N fraction of protein and articulated as a percentage (13).

$$\text{Nitrogen \%} = \frac{\text{(Sample titre value – Blank titre value)} \times \text{Equivalent weight of N} \times \text{Normality of HCL} \times 100}{\text{Weight of the sample} \times 1000} \quad \text{(Eqn.3)}$$

Seed Protein content (%) =

$$\text{Nitrogen content in seed (\%)} \times 6.25 \quad \text{(Eqn.4)}$$

Statistical analysis

Collected plant samples and computed data were subjected to statistical analysis per the procedures (14). The data were analyzed using the AGRES software packages and treatment means were compared using the critical difference (CD) test at a 5 % probability level. Non-significant differences among treatments were denoted as 'NS' in the results.

Results and Discussion

Yield attributes

Yield attributes were significantly influenced by drip irrigation and fertigation methods in both seasons (Tables 1-2). Sensor-based automated drip irrigation (M_3) recorded higher values of yield attributes, namely, total number of pods per plant (21.09 and 19.38), number of single-seeded pods per plant (3.65 and 3.30), number of double-seeded pods per plant (17.45 and 16.08), hundred pod weight (126.7 g and 124.0 g), hundred kernel weight (49.93 g and 48.31 g) and shelling percentage (69.55 % and 69.51 %) in the the *rabi* (2023) and summer (2024) seasons, respectively. This outcome was attributed to using tensiometer-based sensor drip irrigation, which enables real-time monitoring and control (15).

Concerning drip fertigation methods, sensor-based fertigation at 100 % NPK Level (F_5) recorded higher yield attributes, namely, total number of pods per plant (22.03 and 20.06), number of single-seeded pods per plant (3.65 and 3.41), number of double seeded pods per plant (18.38 and 16.65), hundred pod weight (128.7 g and 125.9 g), hundred kernel weight (50.28 g and 48.86 g) and shelling percentage (69.11 % and 69.14 %) in both seasons, respectively. The increased responses are mainly attributed to enhanced water and nutrient availability through these systems, as the limited wetted area receives water at regular intervals. The higher solubility percentage of water-soluble fertilizers improves nutrient uptake, ultimately enhancing yield parameters. These results are inconsistent with the findings of previous research (16).

Sensor-based automated drip irrigation combined with sensor-based fertigation at 100 % NPK level (M_3F_5) recorded maximum yield attributes, namely, total number of pods per plant (25.24 and 22.97), number of single-seeded pods per plant (4.57 and 4.42), number of double seeded pods per plant (20.67 and 18.55), hundred pod weight (132.1 g and 130.2 g), hundred kernel weight (53.20 g and 51.33 g) and shelling percentage (71.71 % and 71.32 %) in both seasons, respectively. Higher availability of nutrients through fertigation with optimum moisture distribution in the rhizosphere resulted in uniform availability of the required quantity of nutrients throughout crop growth, which might enhance the yield attributes (17).

Table 1. Effect of drip irrigation and fertigation methods on yield attributes of groundnut

Treatments	Single-seeded pods/plant		Double-seeded pods/plant		Total number of pods/plant	
	Rabi 2023	*Summer* 2024	*Rabi* 2023	*Summer* 2024	*Rabi* 2023	*Summer* 2024
Main plot (M) (Drip irrigation methods)						
M_1	2.45	2.23	14.33	13.09	16.78	15.32
M_2	3.01	2.75	16.50	15.07	19.50	17.81
M_3	3.65	3.30	17.45	16.08	21.09	19.38
S.Ed	0.02	0.03	0.22	0.13	0.27	0.19
CD (P=0.05)	0.07	0.09	0.61	0.36	0.74	0.52
Sub plot (F) (Drip fertigation methods)						
F_1	2.54	2.30	14.48	13.33	17.03	15.63
F_2	2.63	2.43	14.79	13.68	17.42	16.11
F_3	2.99	2.61	15.46	14.24	18.45	16.86
F_4	3.35	3.04	17.35	15.83	20.69	18.87
F_5	3.65	3.41	18.38	16.65	22.03	20.06
S.Ed	0.04	0.05	0.23	0.20	0.25	0.25
CD (P=0.05)	0..09	0..10	0.48	0.42	0.52	0.51
Interaction (M × F) (Drip irrigation methods × Drip fertigation methods)						
M_1F_1	2.06	1.89	12.81	11.74	14.87	13.63
M_1F_2	2.22	2.03	13.43	12.29	15.65	14.32
M_1F_3	2.35	2.15	13.99	12.78	16.34	14.93
M_1F_4	2.68	2.44	15.20	13.86	17.88	16.30
M_1F_5	2.92	2.66	16.22	14.77	19.14	17.43
M_2F_1	2.70	2.47	15.26	13.98	17.96	16.45
M_2F_2	2.74	2.51	15.45	14.14	18.19	16.65
M_2F_3	2.87	2.63	16.01	14.62	18.88	17.25
M_2F_4	3.26	2.97	17.51	15.97	20.76	18.94
M_2F_5	3.46	3.15	18.25	16.62	21.72	19.77
M_3F_1	2.87	2.54	15.38	14.26	18.25	16.80
M_3F_2	2.93	2.75	15.49	14.61	18.42	17.36
M_3F_3	3.75	3.07	16.38	15.32	20.13	18.39
M_3F_4	4.11	3.70	19.33	17.67	23.44	21.38
M_3F_5	4.57	4.42	20.67	18.55	25.24	22.97
S.Ed	0.07	0.07	0.42	0.34	0.47	0.43
CD (P=0.05)	0.15	0.17	0.96	0.74	1.08	0.94

Treatment details are given under Materials and Methods

Table 2. Effect of drip irrigation and fertigation methods on yield attributes of groundnut

Treatments	Hundred pod weight (g)		Hundred kernel weight (g)		Shelling percentage (%)	
	Rabi 2023	*Summer* 2024	*Rabi* 2023	*Summer* 2024	*Rabi* 2023	*Summer* 2024
			Main plot (M) (Drip irrigation methods)			
M_1	118.7	116.7	44.34	44.88	63.21	65.03
M_2	123.6	122.0	47.83	47.20	66.43	67.95
M_3	126.7	124.0	49.93	48.31	69.55	69.51
S.Ed	1.83	1.43	0.55	0.43	0.64	0.77
CD (P=0.05)	5.09	3.97	1..53	1.19	1.78	2.13
			Sub plot (F) (Drip fertigation methods)			
F_1	118.6	116.9	45.10	45.30	63.75	66.08
F_2	120.6	118.0	45.93	45.57	64.73	66.53
F_3	121.7	120.4	46.78	46.28	66.66	67.16
F_4	125.3	123.3	48.74	47.99	67.74	68.60
F_5	128.7	125.9	50.28	48.86	69.11	69.14
S.Ed	1.46	1.53	0.69	0.71	0.88	0.96
CD (P=0.05)	3.01	3.17	1.42	1.46	1.82	1.99
			Interaction (M × F) (Drip irrigation methods × Drip fertigation methods)			
M_1F_1	114.6	113.8	42.10	43.53	60.59	63.98
M_1F_2	116.1	114.1	42.23	43.54	61.37	64.02
M_1F_3	117.3	115.8	43.17	43.91	63.64	64.46
M_1F_4	120.5	118.2	46.31	46.48	64.65	66.09
M_1F_5	124.9	121.4	47.86	46.96	65.82	66.62
M_2F_1	117.6	117.7	45.62	46.08	63.19	66.53
M_2F_2	120.9	119.6	46.98	46.86	64.79	67.35
M_2F_3	123.5	122.2	48.04	47.06	66.90	67.61
M_2F_4	126.6	124.6	48.72	47.72	67.49	68.83
M_2F_5	129.3	126.0	49.78	48.30	69.79	69.46
M_3F_1	123.8	119.2	47.56	46.28	67.46	67.73
M_3F_2	124.6	120.3	48.58	46.32	68.03	68.21
M_3F_3	124.4	123.2	49.14	47.86	69.45	69.41
M_3F_4	128.7	127.2	51.18	49.77	71.09	70.87
M_3F_5	132.1	130.2	53.20	51.33	71.71	71.32
S.Ed	2.91	2.77	1.20	1.78	1.51	1.68
CD (P=0.05)	6.82	6.25	2.65	2.54	3.31	3.71

Treatment details are given under Materials and Methods

Yield

Drip irrigation and fertigation methods had a significant impact on pod and haulm yield of groundnut in both seasons (Table 3 and Fig. 5). Sensor-based automated drip irrigation (M_3) recorded significantly higher pod yield (2709 kg ha^{-1} and 2519 kg ha^{-1}) and haulm yield (5123 kg ha^{-1} and 4584 kg ha^{-1}) in the *rabi* (2023) and summer (2024) seasons, respectively. The higher yield under tensiometer-based drip irrigation might be due to applying the required amount of water to the crop at the time necessary. These results are consistent with the findings of previous research (15, 18).

Among the drip fertigation methods, sensor-based fertigation at 100 % NPK level (F_5) recorded the maximum pod yield (2774 kg ha^{-1} and 2585 kg ha^{-1}) and haulm yield (5339 kg ha^{-1} and 4810 kg ha^{-1}) in both seasons, respectively. This was followed by sensor-based fertigation at 75 % NPK level (F_4). The increased responses are mainly attributed to the higher solubility percentage of water-soluble fertilizers, which has led to increased nutrient uptake, which is ultimately reflected in the yield. These results are consistent with those reported by (16,19-22).

Various irrigation methods and nutrient management practices significantly influenced grain and straw yield. Combination with sensor-based automated drip irrigation and sensor-based fertigation at 100 % NPK level (M_3F_5) recorded higher yield (3246 kg/ha and 3025 kg/ha) and haulm yield (5970 kg/ha and 5385 kg/ha) in both seasons, respectively. Higher nutrient uptake might have

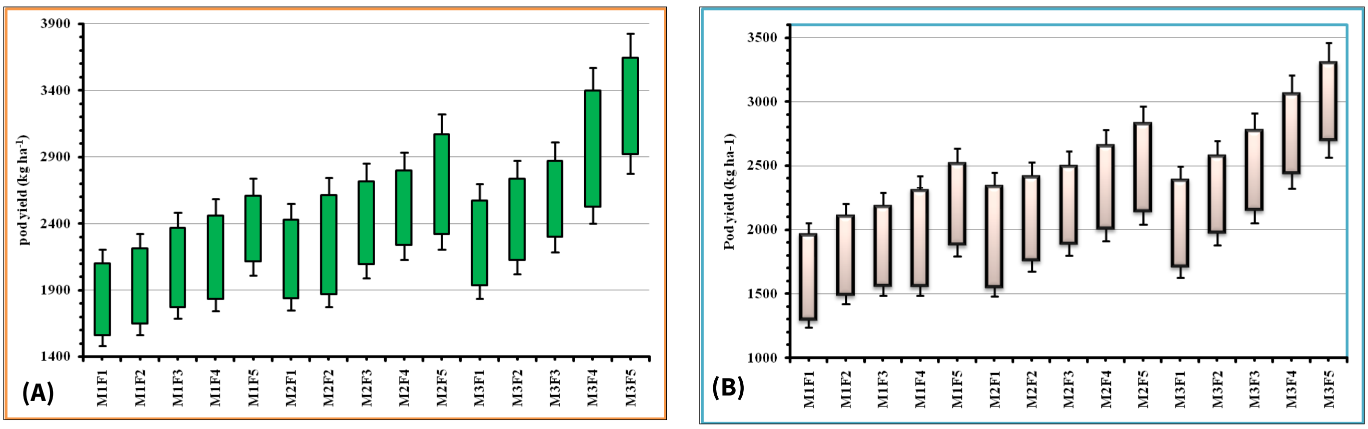

Fig. 5. Effect of drip irrigation and fertigation methods on pod yield of groundnut during rabi (2023) (A) and summer (2024) (B) seasons.

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

Treatments	Pod yield (kg/ha)		Haulm yield (kg/ha)		Harvest index*	
	Rabi 2023	*Summer* 2024	*Rabi* 2023	*Summer* 2024	*Rabi* 2023	*Summer* 2024
Main plot (M) (Drip irrigation methods)						
M_1	2079	1909	4239	3804	0.328	0.333
M_2	2436	2239	4812	4269	0.335	0.344
M_3	2709	2519	5123	4584	0.345	0.354
S.Ed	29.1	27.4	40.6	55.2	-	-
CD (P=0.05)	80.8	76.0	112.8	153.3	-	-
Sub plot (F) (Drip fertigation methods)						
F_1	2110	1922	4230	3847	0.332	0.332
F_2	2205	2058	4408	3907	0.333	0.344
F_3	2347	2178	4624	4098	0.336	0.346
F_4	2605	2369	5023	4435	0.336	0.347
F_5	2774	2585	5339	4810	0.341	0.349
S.Ed	34.5	35.0	77.9	58.2	-	-
CD (P=0.05)	71.1	72.1	160.7	120.1	-	-
Interaction (M × F) (Drip irrigation methods × Drip fertigation methods)						
M_1F_1	1826	1656	3816	3534	0.323	0.319
M_1F_2	1926	1799	3988	3589	0.326	0.334
M_1F_3	2063	1878	4189	3692	0.330	0.337
M_1F_4	2211	2002	4457	3921	0.326	0.337
M_1F_5	2371	2210	4746	4285	0.333	0.340
M_2F_1	2227	2032	4406	3976	0.336	0.337
M_2F_2	2258	2107	4562	4022	0.331	0.344
M_2F_3	2404	2187	4757	4144	0.336	0.345
M_2F_4	2584	2350	5033	4444	0.335	0.346
M_2F_5	2705	2521	5302	4760	0.338	0.346
M_3F_1	2277	2078	4467	4029	0.338	0.340
M_3F_2	2431	2268	4674	4109	0.342	0.356
M_3F_3	2574	2470	4926	4459	0.343	0.357
M_3F_4	3019	2754	5579	4940	0.347	0.358
M_3F_5	3246	3025	5970	5385	0.353	0.360
S.Ed	60.8	60.6	127.3	105.7	-	-
CD (P=0.05)	135.4	134.0	271.9	238.8	-	-

Treatment details are given under Materials and Methods. * Harvest index - Not statistically analyzed

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 by increased yield attributes. The higher rate of photosynthate translocation from source to sink might have resulted in higher pod yield in peanuts. Many reports indicated that fertigation with water-soluble fertilizer can increase the yield of many crops and save 25 % of the fertilizer (23-31).

Regarding harvest index, sensor-based automated drip irrigation (M_3) recorded a higher harvest index (0.345 and 0.354) in both seasons. Among the drip fertigation methods, sensor-based fertigation at 100 % NPK level (F_5) recorded harvest index (0.341 and 0.349) in both seasons, respectively. On interaction, sensor-based automated drip irrigation combined with sensor-based fertigation at 100 % NPK level (M_3F_5) recorded a higher harvest index (0.345 and 0.354) in both seasons, respectively. None of the treatments had any perceptible variation in the harvest index of groundnut.

Quality parameters

Quality parameters of groundnut were significantly influenced by drip irrigation and fertigation methods in both seasons (Table 4 and Fig. 6). Sensor-based automated drip irrigation (M3) recorded higher oil content of 45.88 and 45.96 % in the rabi (2023) and summer (2024) seasons, respectively. This might be due to the precise amount of water provided throughout the growth period, enhancing the oil content. Among the drip fertigation methods, sensor -based fertigation at 100 % NPK Level (F5) recorded higher oil content of 48.14 and 46.17 % in both seasons, respectively. This might be due to increased nutrient availability through water-soluble fertilizers, which increases the oil content. Similar results were reported by (32). During the interaction, sensor-based automated drip irrigation combined with Sensor-based fertigation at 100 % NPK Level (M3F5) recorded higher oil content of 48.92 and 47.25 % in both seasons, respectively. The precise and continuous provision of water and nutrients using water-soluble fertilizers throughout the growth period may contribute to the enhanced oil content.

Regarding protein, sensor-based automated drip irrigation (M3) recorded higher protein levels of 24.62 and 22.29 % in the *rabi* (2023) and summer (2024) seasons, respectively. Enhanced protein content could be attributed to the accurate water supply during growth. Among the drip fertigation methods, sensor-based fertigation at 100 % NPK Level (F_5) recorded higher protein of 25.54 and 22.34 % in both seasons, respectively, which could be due to higher availability of nutrients at different crop growth stages resulting in enhancement of protein content of kernels, suggesting that hydrocarbons synthesized during photosynthetic processes are diverted to reproductive part and form more proteins. These results are consistent with previous research (33). Regarding interaction, sensor-based automated drip irrigation combined with Sensor-based fertigation at 100 % NPK Level (M_3F_5) recorded higher protein of 27.90 and 24.41 % in both seasons, respectively. The consistent and accurate delivery of water and nutrients through water-soluble fertilizers ensures that plants have access to the required resources throughout their growth

Table 4. Effect of drip irrigation and fertigation methods on quality parameters of groundnut

Treatments	Oil content (%)		Protein content (%)	
	Rabi 2023	*Summer* 2024	*Rabi* 2023	*Summer* 2024
Main plot (M) (Drip irrigation methods)				
M_1	43.62	43.79	21.38	19.26
M_2	44.59	45.52	23.12	21.01
M_3	45.88	45.96	24.62	22.29
S.Ed	0.55	0.58	0.28	0.22
CD (P=0.05)	1.53	1.60	0.78	0.60
Sub plot (F) (Drip fertigation methods)				
F_1	41.85	44.13	20.76	19.69
F_2	43.01	44.52	21.79	20.13
F_3	44.14	45.02	22.95	20.57
F_4	46.36	45.61	24.16	21.54
F_5	48.14	46.17	25.54	22.34
S.Ed	0.67	0.58	0.34	0.28
CD (P=0.05)	1.38	1.18	0.70	0.58
Interaction (M × F) (Drip irrigation methods × Drip fertigation methods)				
M_1F_1	40.59	43.14	19.06	18.12
M_1F_2	41.83	43.20	20.09	18.59
M_1F_3	42.91	43.48	21.65	18.99
M_1F_4	45.40	44.36	22.38	19.93
M_1F_5	47.40	44.79	23.69	20.68
M_2F_1	42.16	44.54	21.44	20.36
M_2F_2	42.51	45.25	22.15	20.49
M_2F_3	43.58	45.43	23.05	20.89
M_2F_4	46.60	45.94	23.96	21.36
M_2F_5	48.11	46.47	25.01	21.92
M_3F_1	42.79	44.72	21.78	20.59
M_3F_2	44.68	45.12	23.13	21.30
M_3F_3	45.92	46.16	24.14	21.83
M_3F_4	47.07	46.53	26.14	23.34
M_3F_5	48.92	47.25	27.90	24.41
S.Ed	1.17	1.06	0.59	0.49
CD (P=0.05)	2.60	2.42	1.32	1.08

Treatment details are given under Materials and Methods.

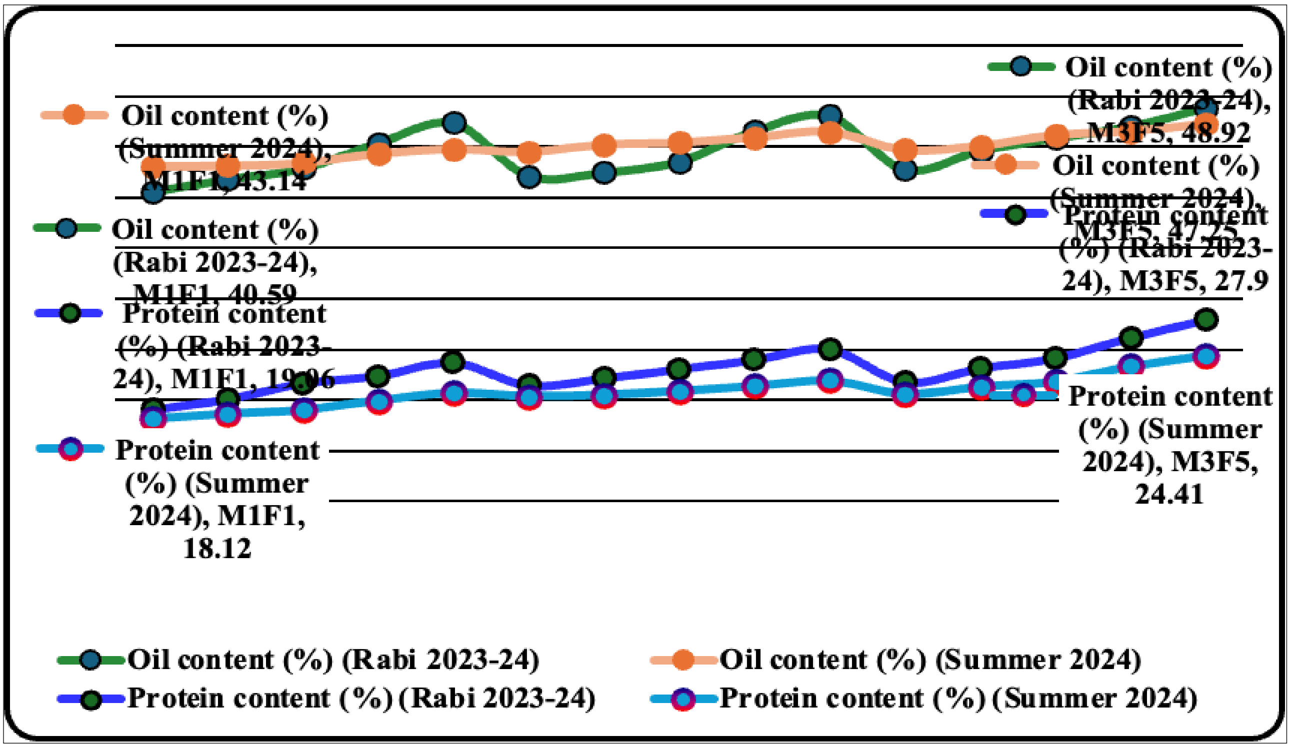

Fig. 6. Effect of drip irrigation and fertigation methods on quality parameters of groundnut during *rabi* (2023) and *summer* (2024) seasons.

period. This steady supply fosters ideal growth conditions crucial for protein synthesis. Consequently, the improved availability of water and nutrients leads to a higher protein content in the crops.

Correlation analysis

Correlation analysis was carried out to evaluate the relationship between yield attributes and pod yield in groundnut. The findings revealed that pod yield exhibited a strong positive correlation with total number of pods per plant (0.99), hundred pod weight (0.97), hundred kernel weight (0.97) and shelling percentage (0.96) (Fig. 7).

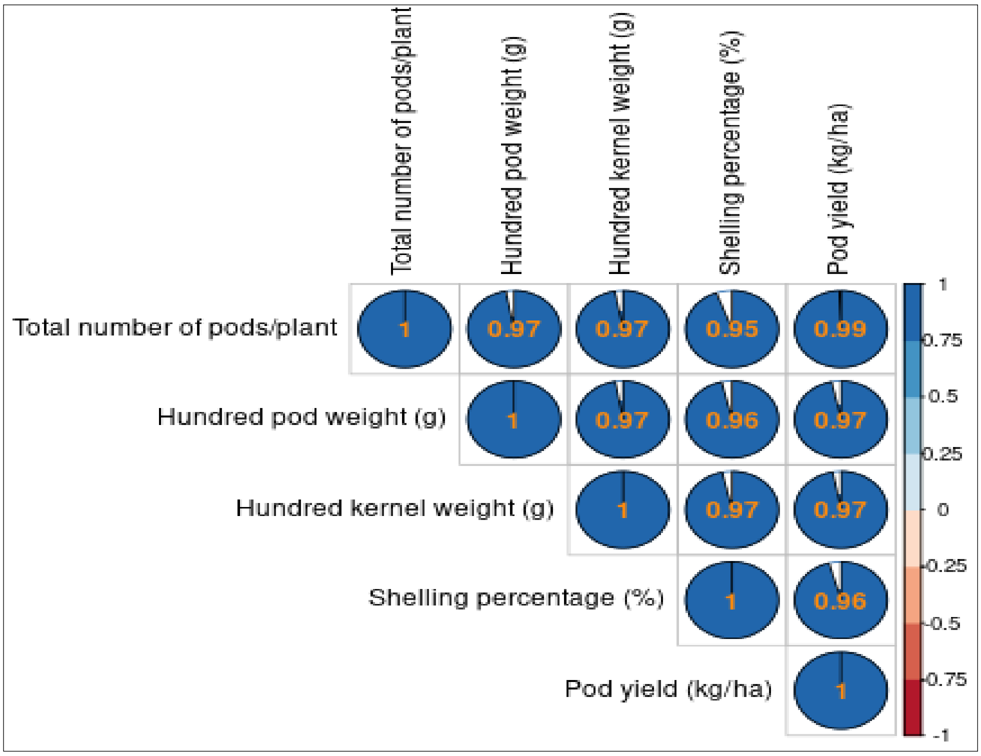

Fig. 7. Correlation between yield attributes and yield (Pooled data).

Conclusion

Based on the above results, it is concluded that sensor-based automated drip irrigation combined with sensor-based fertigation at 100 % NPK level (M3F5) resulted in higher yield attributes, yield and quality of groundnut. Practising sensor-based automated drip irrigation combined with sensor-based fertigation would also reduce water and fertilizer in groundnuts. Moreover, this approach enhances the quality of groundnuts by improving oil and protein content.

For farmers, adopting sensor-based drip irrigation and fertigation can optimize water and nutrient use, leading to higher yields, improved crop quality and better resource efficiency. Additionally, it reduces input wastage, lowers production costs and minimizes environmental impact. For policymakers, the findings emphasize the need to promote precision agriculture technologies through subsidies, training programs and research support. Encouraging the adoption of sensor-based irrigation can contribute to sustainable water management and enhanced agricultural productivity, especially in resource-constrained regions.

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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 input for upscaling.

Compliance with ethical standards

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

Ethical issues: None

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