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RESEARCH ARTICLE

Performance of drip irrigation and fertigation levels on productivity and water requirement of aerobic rice (*Oryza sativa* L.) under rice-chia cropping system

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Abstract

Improving crop development and output requires efficient nutrient management, mainly when growing rice in an aerobic system using drip. Conventional rice farming and incorrect fertilizer delivery frequently result in a number of losses, including water loss, denitrification and volatilization. Split application of soluble fertilizers under drip irrigation techniques has become viable, increasing production while reducing water consumption. To address the problem, the trial was planned to find the optimum level of drip irrigation and fertigation for maximum productivity and water-use efficacy of aerobic rice. A study was conducted in the summer of 2022 and 2023 wetland farm Tamil Nadu Agricultural University, Coimbatore. The trial was operationalized using a randomized complete block design comprising 13 treatments, each duplicated thrice. Supplement of drip fertigation at the rate of 100% pan evaporation till 30 days after sowing (DAS), 150% pan evaporation till 60 DAS, 200% pan evaporation till 90 DAS with 125% recommended dose of fertilizer (25% as normal fertilizers + 75% as water-soluble fertilizers) exhibited notably greater number of productive tillers (416 and 434 m^{-2}) and increased panicle weight (2.07 and 2.08 g) respectively in summer 2022 and 2023 as related to other treatments. The similar treatment demonstrated enhanced water-use efficacy (5.12 and 5.17 kg $ha\text{-}mm^{-1}$), higher grain (4316 and 4446 kg/ha) and biological yield (9844 and 10221 kg/ha). Thus, it managed to conserve 25% and 24% of irrigation water compared to surface irrigation during both the years of the experimentations. Hence, adopting rice under the drip method in areas where water is scarce benefits the farmers.

Keywords

fertigation; grain yield; pan evaporation; tillers; water-use efficacy

Introduction

Rice (*Oryza sativa* L.) holds significant global importance as Asia's predominant staple food crop, meeting the dietary wants of over half of the world's residents (1). Since 90% of the world's rice consumption occurs in Asia, where more than 138 million ha of rice yield 677 million metric tons of rough rice annually, ensuring rice productivity is crucial for regional food security (2). However, irrigation water resources are a significant challenge that has impacted rice farming's competitiveness and productivity (3, 4). In India, rice cultivation spans a vast area of nearly 47.83 million ha, making it the largest rice-producing nation through a production output of 135.7 million tons and a normal productivity of 2.84 tons/ha. These figures highlight rice's indispensable role in sustaining livelihoods and nourishing populations worldwide (5). As of today, 83.3% of the total water consumed is considered available for agriculture and by 2025, that percentage is expected to drop to 71.6%. By 2050, it will drop to 64.6% (6). There are serious worries regarding rice agriculture due to the declining amount of water available per person, especially under water-intensive flooded irrigation techniques and mulch in some crops (7). The traditional or conventional irrigation approach requires a significant amount of water and severely depletes the ecosystem of water and nutrients when it is anaerobic, decreasing fertilizer usage efficiency (8).

Irrigated lowlands covering 79 million ha provide more than 75% of the world's rice production. By 2025, there may be "physical water scarcity" in more than 17 million ha of irrigated rice fields in Asia and "economic water scarcity" in 22 million ha (9). Redirecting the water saved from rice cultivation to regions with high water shortages can have a significant social and environmental impact. 10% less water would be used for rice irrigation, saving 150000 million m^3, or over 25% of the world's freshwater for non-agricultural uses (10). Soil flooding is a contributing factor to ongoing methane releases (11). Lowland rice is the primary agricultural source of methane, contributing to 9-11% of agricultural greenhouse gas emissions (12) and 22% of global anthropogenic agricultural emissions (13). Paddy field nitrogen losses lead to poor water quality, such as nitrate contamination of groundwater and eutrophication of surface water, as well as agricultural nonpoint source pollution (14, 15).

Sustainable rice farming depends on better efficient water management. Given the growing demand for rice production and the acute water scarcity, improved water-saving rice cultivation technologies are required to lower water usage and boost rice yield. Several technologies are being investigated to lessen the volume of water needed for rice production. These include switching to aerobic rice farming, introducing the system of rice intensification (SRI) and employing techniques like alternate wetting and drying (16). An aerobic rice system maintains the crop in regions cultivated in an unsaturated environment with adequate inputs and, if precipitation is insufficient, supplemental irrigation (17). Drip fertigation maximizes nutrient uptake and makes sure that water and fertilizers are delivered in harmony with the crop-specific demands by providing a precise and targeted technique of delivering water and nutrients straight to the crop's active root zone since nutrients are only supplied to a small area of soil, leads to enhanced fertilizer use efficacy (18). A new water-saving method has surfaced in response to the urgent need to raise rice output to fulfill the demands of an expanding population against the backdrop of declining water resources: fertilizer-infused drip irrigation (19).

The drip fertigation maximizes the use of available resources, boosts the effectiveness of fertilizers and improves crop output and quality while enabling sustainable and water-efficient practices. On the other hand, leaching, percolation and volatilization during traditional fertilization may cause significant nutrient losses (20). Therefore, clarifying the evidence now accessible on the use of drip irrigation to rice for future initiatives is imperative. How nutrients interact with water impacts plant characteristics and, ultimately, crop growth, likely dictating plants' physiological processes of nutrient absorption (21). To develop efficient and long-lasting techniques for rice farming in the future, it is crucial to learn about and understand drip irrigation. One possible method for conserving irrigation water is drip irrigation. However, there are still a lot of unanswered questions regarding this irrigation system's suitability for growing rice in terms of yield potential. Considering these things, an experiment assessed how different fertigation regimes affect aerobic rice's yield determinants, yield and water needs under drip irrigation.

Materials and Methods

Experimental area

The trial was undertaken in the Tamil Nadu Agricultural University (TNAU), Coimbatore farm unit, during the summer of 2022 and 2023. The experimental site (11° N, 77° E) was 426.70 m above mean sea level and had clay-loam soil (27.18% sand, 12.56% silt and 42.53% clay). The research site had a somewhat alkaline pH (8.2), organic carbon (0.65%), diminished levels of accessible nitrogen (225 kg/ha), moderate levels of phosphorus (18.0 kg/ha) and elevated levels of accessible potassium (595 kg/ha). In 2022 and 2023, there were 146.4 mm and 47.5 mm of rainfall on 19.8 and 5 rainy days (87.84 and 28.5 mm of effective rainfall) respectively, received. The average superior (33 °C and 32.7 °C) and lowest temperatures (23.8 °C and 21.0 °C) were noticed in summer 2022 and 2023 respectively, with the average daily pan evaporation of 6.1 and 6.2 mm day^{-1} in both years (Fig. 1 and Fig. 2).

Experimental details

The field plot consisted of 13 treatments, spread out in a randomized complete block design, each replicated thrice. The treatments were T_1: Drip fertigation at the rate of 50% pan evaporation till 30 DAS, 100% pan evaporation till 60 DAS, 150% pan evaporation till 90 DAS with 75% recommended dose of fertilizer (75% as normal fertilizer + 25% as water soluble fertilizer); T_2: Drip fertigation at the rate of 75% pan evaporation till 30 DAS, 125% pan evaporation till 60 DAS, 175% pan evaporation till 90 DAS with 75% recommended dose of fertilizer (RDF) [50% as NF + 50% as water soluble fertilizers (WSF)]; T_3: Drip fertigation at the rate of 100% pan evaporation till 30 DAS, 150% pan evaporation till 60 DAS, 200% pan evaporation till 90 DAS with 75% RDF (25% as NF + 75% as WSF); T_4: Drip fertigation at the rate of 50% pan evaporation till 30 DAS, 100% pan evaporation till 60 DAS, 150% pan evaporation till 90 DAS with 100% RDF (75% as NF + 25% as WSF); T_5: Drip fertigation at the rate of 75% pan evaporation till 30 DAS, 125% pan evaporation till 60 DAS, 175% pan evaporation till 90 DAS with 100% RDF (50% as

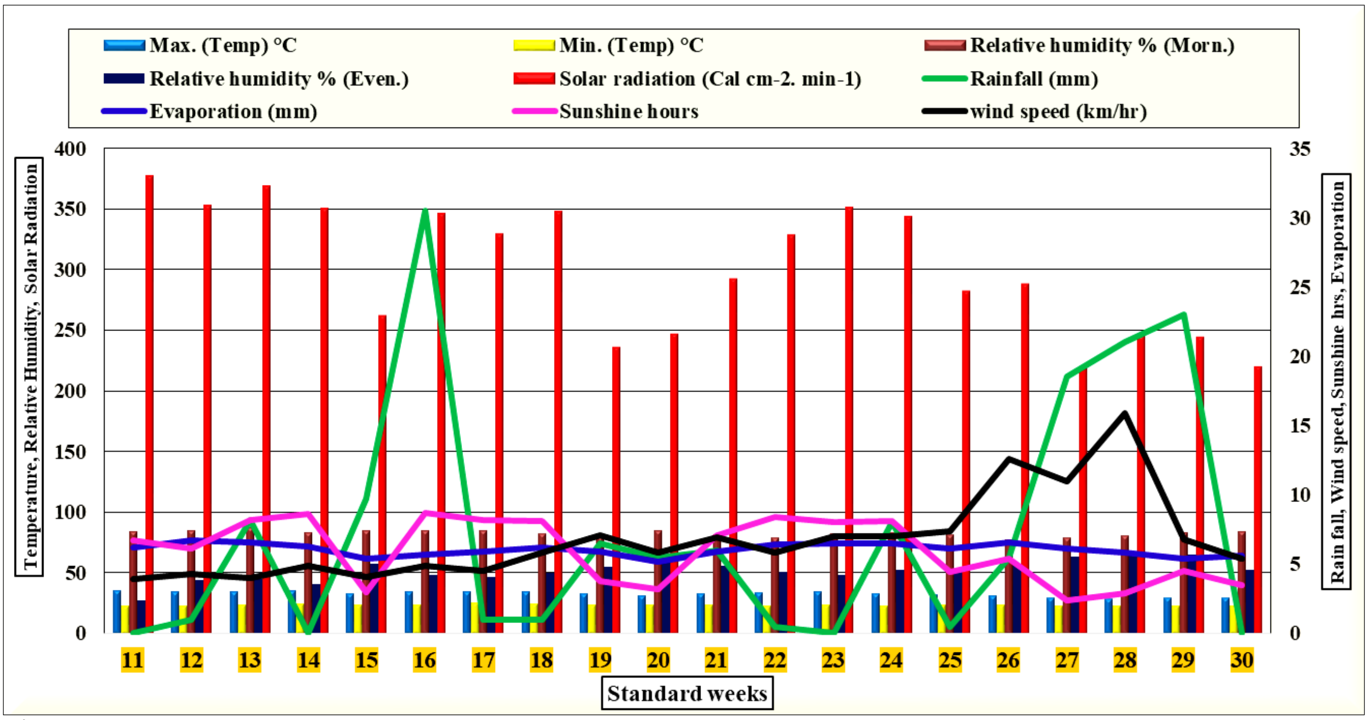

Fig. 1. Weather parameters prevailed during the cropping period of aerobic rice in the summer of 2022. The number of standard week depicted on horizontal x-axis and temperature, relative humidity and solar radiation on primary y-axis while rainfall, windspeed, sunshine hours evaporation on the secondary y-axis vertically in summer 2022.

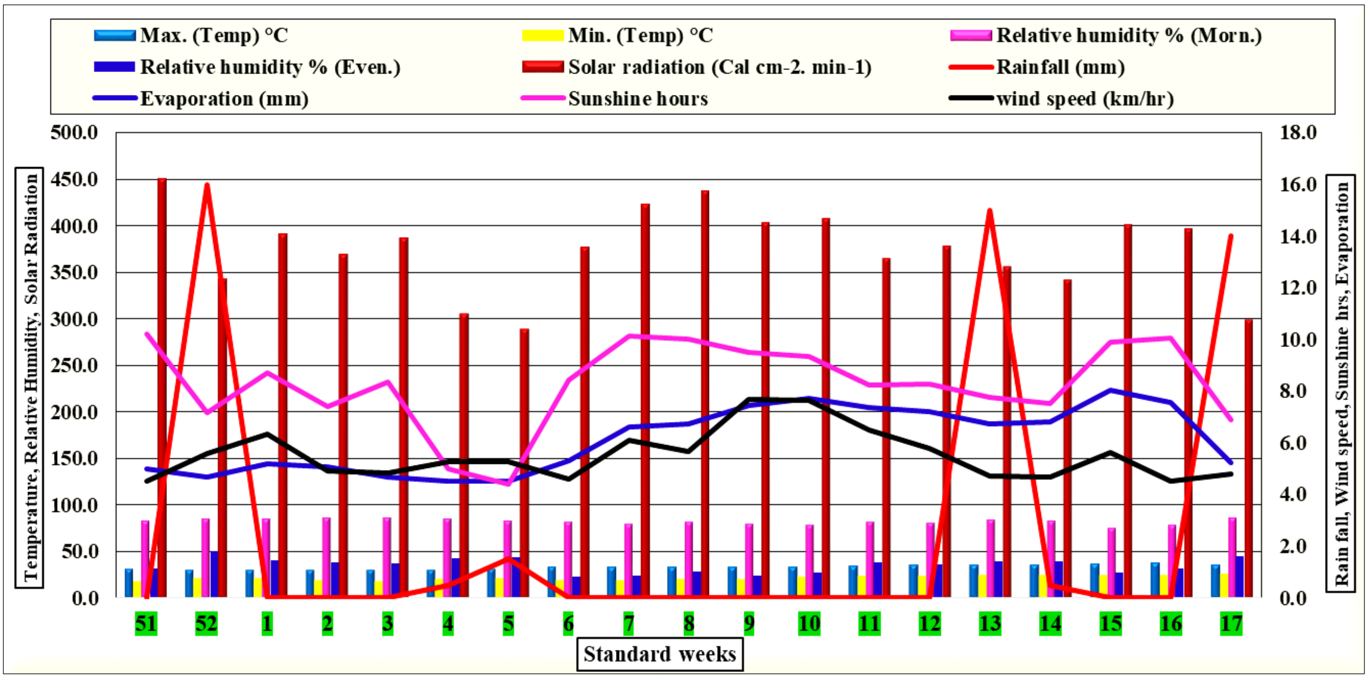

Fig. 2. Weather parameters prevailed during the cropping period of aerobic rice summer 2023. The number of standard week depicted on horizontal x-axis and temperature, relative humidity and solar radiation on the primary y-axis whereas rainfall, windspeed, sunshine hours evaporation on the secondary y-axis vertically in summer 2023.

NF + 50% as WSF); T_6: Drip fertigation at the rate of 100% pan evaporation till 30 DAS, 150% pan evaporation till 60 DAS, 200% pan evaporation till 90 DAS with 100% RDF (25% as NF + 75% as WSF); T_7: Drip fertigation at the rate of 50% pan evaporation till 30 DAS, 100% pan evaporation till 60 DAS, 150% pan evaporation till 90 DAS with 125% RDF (75% as NF + 25% as WSF); T_8: Drip fertigation at the rate of 75% pan evaporation till 30 DAS, 125% pan evaporation till 60 DAS, 175% pan evaporation till 90 DAS with 125% RDF (50% as NF + 50% as WSF); T_9: Drip fertigation at the rate of 100% pan evaporation till 30 DAS, 150% pan evaporation till 60 DAS, 200% pan evaporation till 90 DAS with 125% RDF (25% as NF + 75% as WSF); T_{10}: Drip irrigation at the rate of 50% pan evaporation till 30 DAS, 100% pan evaporation till 60 DAS, 150% pan evaporation till 90 DAS with 100% RDF as soil application of NF; T_{11}: Drip irrigation at the rate of 75% pan evaporation till 30 DAS, 125% pan evaporation till 60 DAS, 175% pan evaporation till 90 DAS with 100% RDF as soil application of NF; T_{12}: Drip irrigation at the rate of 100% pan evaporation till 30 DAS, 150% pan evaporation till 60 DAS, 200% pan evaporation till 90 DAS with 100% RDF as soil application of regular fertilizer and T_{13}: Surface flood watering with soil application of 100% RDF (IW/CPE ratio 1.2).

Installation and crop management

A drip system with 1 main line (63 mm) and 3 sub-main lines (50 mm) was installed, 80 cm apart drip laterals with an outside diameter (OD) of 16 mm (250-micron wall thickness) that are placed in the sub mains. Laterals had 4 L/h of discharge rate, emitting points 30 cm apart. Drip irrigations were scheduled at 3 days intervals using evaporation values of the previous 3 days (USWB Class A) to 90 DAS in accordance with the treatments while deducting the real rainfall during this phase (T_1 to T_{12}). Effective rainfall (ERF) is part of total rainfall and it is 60% of total rainfall. Because the experiment site had clay loam in structure and the intensity of rainfall was lower, the infiltration in clay soil was higher than that in other sandy soils. In contrast, surface flood irrigation (T_{13}) was scheduled at 1.2 IW/CPE with an irrigation depth of 5 cm during both years. Of the recommended 150:50:50 kg NPK ha^{-1} of fertilizer, 50% N and the full doses of P_2O_5 and K_2O should be applied as basal. For soil-applied treatments (T_{10} to T_{13}) having standard fertilizers, the remaining 50% of N was treated in 2 equal splits at 30 and 60 DAS.

On the other hand, fertilizers were applied via fertigation in equivalent splits at intervals of 3 days in accordance with the treatment until 90 DAS for T_1 through T_9. Mono-ammonium phosphate, calcium ammonium nitrate and potassium nitrate were utilized as water soluble fertilizers for fertigation to supply NPK. Whereas, urea, di-ammonium phosphate and muriate of potash were applied to the soil as standard fertilizers. Seeds of rice cultivar (Co-51) mature in 105 to 110 days. Seeds were sown at a geometry of 0.2 × 0.1 m^2. All the treatments received 2 consistent irrigations immediately after seeding to ensure adequate crop germination and establishment. Five plants were randomly labeled in each net plot for non-destructive yield parameter observations, *viz.* no. of effective tillers m^{-2}, panicle weight (g), panicle length (cm) and test weight (g). Observations were recorded at the harvest stage per the guidelines from the International Rice Testing Programme (22).

Test weight

An arbitrary sample of 1000 dried seeds from independent treatments were taken and their weight was calculated and counted in grams.

Crop yield

Following the harvest of the net plots and a few days of sun drying in the field, the total biomass yield was calculated. The yield of the cleaned and dried seed was noted after threshing. Straw yield was subtracted from total biomass production to determine seed yield. The unit of yield was kg/ha.

Harvest index

The harvesting index (HI) was intended by the following formula (23)

$$HI = \frac{\text{Grain yield (kg/ha)}}{\text{Biological yield (kg/ha) (Grain + straw)}} \quad \text{....(Eqn 1.)}$$

Drip irrigation

Drip irrigations were scheduled once in three days based on the daily pan evaporation values (USWB Class A open pan evaporimeter). The irrigation was given as per the treatments for both rice during both years of 2022 and 2023.

$$\text{Water requirement (mm/irrigation)} = \frac{\text{PE x Kp x Kc}}{\text{IE}} \text{ X 100} \quad \text{.........(Eqn 2.)}$$

$$\text{Water requirement (L/unit area/irrigation)} = \frac{\text{PE x Kp x Kc x A}}{\text{IE}} \text{ X 100} \quad \text{.........(Eqn 3.)}$$

Where, PE= Pan evaporation (mm), K_p= Pan co-efficient (0.8), K_c= Crop coefficient (1.05, 1.20 and 0.90), IE = Irrigation efficiency (80%) for drip, Area (A) = 25.6 m^2 (8.0 x 3.2 m^2).

The equation was employed to estimate the drip system operating time to provide the necessary volume of water per plot.

$$\text{Time of application (min)} = \frac{\text{Volume of water required (L per plot) x 60}}{\text{Emitter discharge (L/hr) x Number of emitters/plot}} \quad \text{.........(Eqn 4.)}$$

Surface irrigation (T_{13})

Irrigation was given to the experimental field by surface flooding method with an IW/CPE ratio of 1.2 with 5.0 cm depth for rice. During the crop time, repeated watering applied in accordance with the pan evaporation values derived from the USWB Class A open pan evaporimeter.

Water use efficiency

The rice yield and the water volume utilized throughout the cropping season were used to calculate the Water Use Efficiency (WUE) (kg ha-mm^{-1}) (24).

$$\text{WUE (kg/ha-mm} = \frac{\text{Grain yield (kg/ha)}}{\text{Total water used (mm)}} \quad \text{.....(Eqn 5.)}$$

$$\text{Total water used (mm)} = \text{Total irrigation water applied (IW) + Effective rainfall (ERF)} \quad \text{.........(Eqn 6.)}$$

Economics

Cost of cultivation: The cost of input that prevailed at their use was considered to work out the cost of cultivation. The cost of cultivation was worked out considering the material input cost, such as the seed, manure, fertilizer, plant protection chemicals, etc. and labor for all the operations. Treatment the cost of cultivation was worked out and expressed as rupees (₹) ha^{-1}. The annualized cost of the drip system was computed based on the system's life span (7 years) and drip maintenance cost.

Gross return : Gross monetary returns were calculated by multiplying the grain and straw yield with the prevailing market price at the experimental study and expressed as ₹ ha^{-1}.

Gross return (₹ ha^{-1}) =

Economic yield (kg ha^{-1}) x Market value of the produce (₹ kg^{-1}) ....(Eqn.7)

Net return: Net returns were obtained by subtracting the cost of cultivation from gross returns for each treatment.

Net returns (₹ ha^{-1}) =

Gross return (₹ ha^{-1}) - Cost of cultivation (₹ ha^{-1}) ...(Eqn.8)

Benefit-cost ratio: The benefit-cost ratio (B: C) was worked out using the formula Palaniappan suggested (25).

$$\text{B : C ratio} = \frac{\text{Gross return (₹ ha}^{-1})}{\text{Total cost of cultivation(₹ ha}^{-1})} \quad .....(\text{Eqn.9})$$

Statistical examination of the investigational data using (26) method of analysis of variance (ANOVA) in the SPSS software (Statistical Package for the Social Sciences), the findings are shown at a 5% level of significance (p=0.05).

Results and Discussion

Yield attributes

The treatment, drip fertigation at the rate of 100% pan evaporation till 30 DAS, 150% pan evaporation till 60 DAS, 200% pan evaporation till 90 DAS with 125% RDF (25% as NF + 75% as WSF) (T_9) produced notably more fruitful tillers (416 and 434 per m^2) and panicle weight (2.07 and 2.08 g) in summer 2022 and 2023 respectively (Table 1) and was comparable to T_6 and T_8 in both years. In contrast, drip fertigation at the rate of 50% pan evaporation till 30 DAS, 100% pan evaporation till 60 DAS, 150% pan evaporation till 90 DAS with 75% RDF (75% as NF + 25% as WSF) (T_1) had the lowest number of productive tillers m^{-2} (251 and 264) and the lowest panicle weight (1.42 and 1.41 g) in both years.

Ensuring adequate moisture and nutrient supply tailored to meet the crop's requirements likely enhanced the crop's structural and functional aspects, leading to an increased number of productive tillers and higher panicle weights (27). When irrigation is applied at lower PE rates, rice yield parameters typically decrease. Even slight water stress on rice plants results in tiller death and spikelet sterility, which lowers the number of productive tillers m^{-2} and filled grains panicle^{-1} (16). The limited soil moisture results in less growth and dry matter production and leaf area index produce less productive tillers (28). Further, there were significant differences in panicle length and test weight as they are genetic characters; no significant differences were found during both years (Table 1).

Yield

A positive relationship between the number of productive tillers m^{-2} of aerobic rice and grain yield was evidenced in the past (28). The treatment T_9 resulted in notably higher grain yield (4316 and 4446 kg ha^{-1}) and biological yield (9844 and 10221 kg ha^{-1}) in 2022 and 2023 respectively, but on par with T_6, followed by T_8 (Table 2). Nevertheless, the treatment drip fertigation at the rate of 50% pan evaporation till 30 DAS, 100% PE till 60 DAS, 150% PE till 90 DAS with 75% RDF (75% as NF + 25% as WSF) (T_1) had lowest grain (2301 and 2365 kg ha^{-1}) and biological yield (5713 and 5768 kg ha^{-1}) in summer 2022 and 2023 respectively (Table 2).

Table 1. Yield attributes of aerobic rice as influenced by drip irrigation and fertigation levels during summer 2022 and 2023

Treatments	Number of productive tillers m^{-2}		Panicle weight per panicle (g)		Panicle length per panicle (cm)		Test weight (1000 seeds) (g)	
	2022	2023	2022	2023	2022	2023	2022	2023
T_1	251.43 ± 12.78	264.19 ± 13.95	1.42 ± 0.03	1.42 ± 0.07	17.3 ± 0.13	17.43 ± 0.96	15.57 ± 0.31	15.54 ± 0.33
T_2	262.56 ± 13.04	275.92 ± 21.12	1.47 ± 0.04	1.52 ± 0.03	18 ± 1.23	17.92 ± 1.5	15.76 ± 0.38	15.9 ± 0.39
T_3	352.2 ± 13.31	357.98 ± 8.95	1.75 ± 0.04	1.80 ± 0.09	20.79 ± 0.65	20.83 ± 0.55	17.2 ± 0.35	17.31 ± 0.25
T_4	285.98 ± 47.31	304.66 ± 46.22	1.54 ± 0.13	1.56 ± 0.06	18.83 ± 0.73	19.08 ± 1	15.9 ± 0.85	15.6 ± 0.9
T_5	342.66 ± 12.02	348.91 ± 19.06	1.72 ± 0.06	1.79 ± 0.07	20.74 ± 0.43	20.61 ± 1.27	17.11 ± 0.53	17.21 ± 0.61
T_6	384.69 ± 18.48	395.06 ± 15.24	1.93 ± 0.07	1.98 ± 0.08	22.21 ± 2.27	21.24 ± 1.23	17.47 ± 0.17	17.79 ± 0.39
T_7	301.98 ± 23.32	315.24 ± 22.93	1.60 ± 0.08	1.57 ± 0.21	19.41 ± 0.58	19.38 ± 0.94	16.3 ± 0.58	16.26 ± 0.66
T_8	373.64 ± 26.25	382.23 ± 26.17	1.86 ± 0.05	1.88 ± 0.08	21.02 ± 0.47	21.13 ± 0.53	17.4 ± 0.59	17.44 ± 0.67
T_9	416.12 ± 7.39	434.14 ± 7.22	2.07 ± 0.12	2.08 ± 0.03	23.1 ± 0.21	22.93 ± 1.93	17.53 ± 0.38	17.65 ± 0.35
T_{10}	274.76 ± 31.04	286.78 ± 26.51	1.53 ± 0.12	1.57 ± 0.14	18.88 ± 0.1	19.05 ± 1.34	16.1 ± 0.66	16.24 ± 0.89
T_{11}	334.66 ± 11.01	346.89 ± 10.55	1.68 ± 0.03	1.77 ± 0.06	20.22 ± 0.69	20.25 ± 0.2	16.9 ± 0.41	16.57 ± 0.49
T_{12}	361.01 ± 14.65	374.58 ± 6	1.80 ± 0.11	1.86 ± 0.05	20.92 ± 0.7	20.96 ± 0.71	17.31 ± 0.26	17.22 ± 0.35
T_{13}	318.23 ± 17.49	337.39 ± 15.85	1.67 ± 0.05	1.69 ± 0.07	19.61 ± 2.39	19.6 ± 1.65	16.63 ± 0.7	16.67 ± 0.46
S.Em (±)	17.38	18.71	0.08	0.09	1.12	1.19	0.49	0.50
CD (P=0.05)	50.74	54.60	0.28	0.26	NS	NS	NS	NS

Treatment details are given under Materials and Methods; ***S**- Significant; **NS**- Non significant. The values represent the averages (±SE) of independent replicates, significantly different at p ≤ 0.05, according to Duncan's Multiple Range test.

Table 2. The yield of aerobic rice as influenced by drip irrigation and fertigation levels during summer 2022 and 2023

Treatments	Grain yield (kg ha^{-1})		Biological yield (kg ha^{-1})		Harvest index	
	2022	2023	2022	2023	2022	2023
T_1	2301 ± 132.3	2364.8 ± 127.1	5712.8 ± 318	5768.1 ± 218.8	0.4 ± 0.01	0.41 ± 0.02
T_2	2625.1 ± 58.5	2714.8 ± 255.6	6295.1 ± 218	6373.7 ± 195.6	0.42 ± 0.01	0.43 ± 0.03
T_3	3523.4 ± 182	3606 ± 73	8152.6 ± 497.4	8452.4 ± 312.7	0.43 ± 0.01	0.43 ± 0.01
T_4	2784.6 ± 151.4	2921.2 ± 127.8	6694.3 ± 409.4	6976.8 ± 501.6	0.42 ± 0	0.42 ± 0.01
T_5	3189.7 ± 486.9	3294.9 ± 213.6	7397.2 ± 746.5	7610.7 ± 487.3	0.43 ± 0.02	0.43 ± 0.01
T_6	3984.7 ± 305.5	4117.9 ± 271.9	9000.4 ± 572.1	9300.9 ± 486.5	0.44 ± 0.01	0.44 ± 0.01
T_7	2917.9 ± 68.7	3041.7 ± 53.8	6912.2 ± 162.2	7229.8 ± 231.1	0.42 ± 0	0.42 ± 0
T_8	3711.4 ± 202.8	3804.5 ± 270	8674 ± 401	8867.5 ± 495.5	0.43 ± 0	0.43 ± 0.03
T_9	4315.9 ± 155	4446.1 ± 153.3	9843.5 ± 207.5	10221.1 ± 438.7	0.44 ± 0.01	0.44 ± 0.01
T_{10}	2680 ± 197.1	2728.5 ± 316.7	6455.9 ± 393.5	6510 ± 289.1	0.41 ± 0.01	0.42 ± 0.04
T_{11}	3102.3 ± 336.5	3198 ± 466.5	7320.3 ± 558.8	7516.9 ± 845.5	0.42 ± 0.02	0.42 ± 0.01
T_{12}	3662.2 ± 87.9	3735 ± 272.2	8391.9 ± 128.2	8760 ± 228.6	0.44 ± 0.01	0.43 ± 0.03
T_{13}	3001.8 ± 153.9	3122.7 ± 135.7	7126 ± 485.7	7227.6 ± 333.5	0.42 ± 0.01	0.43 ± 0
S.Em (±)	311	316	422	429	0.01	0.03
CD (P=0.05)	642	652	1234	1253	NS	NS

Treatment details are given under Materials and Methods; ***S***- Significant; **NS**- Non significant. The values represent the averages (±SE) of independent replicates, significantly different at P ≤ 0.05, according to Duncan's Multiple Range test.

The grain yield in any crop depends upon the photosynthetic source it can build up. Production and partitioning of dry matter are vital for the determination of the overall yield of the crop (29, 30). The grain production of any crop hinges on its ability to accumulate photosynthetic resources. Enhanced grain and biological output might be attributed to its superior capacity to produce more productive tillers, longer panicles, higher panicle weights and test weights compared to other treatments (20). This capacity is largely attributed to the consistent supply of water and nutrients, which facilitates increased nutrient uptake and subsequently, higher dry matter production under fertigation (28, 30). The improved grain yield was caused by the greater photosynthates that could be directed towards the reproductive sink due to the resource absorption efficiency (31, 32). Soil moisture was maintained at field capacity (33) due to a steady and constant delivery of moisture that met crop requirements in a timely manner (34). Additionally, at the effective root zone, WSF full solubility and increased nutrient availability resulted in improved nutrient uptake and a possible productivity boost in the STCR targeted yield strategy (35).

The reduced yield in T_1 could be due to reduced nutrient uptake, lower soil moisture at the crop root zone depth and barrier in translocating assimilates to the grains (36). A significant increase in moisture stress results in a higher percentage of sterility in grains and lower rates of photosynthetic translocations because of a lower leaf area index or direct suppression of the translocation system itself (37). It has been recorded that the harvest index was not constant with crop output but was often substantially associated with both grain yield and WUE. Nonetheless, no appreciable variation was observed in the harvest index among the various treatments.

Water use efficacy

Drip fertigation is likely to have higher water-use efficacy since the volume of water provided through the drip system nearly matches the amount of water that plants consume. The drip fertigation at the rate of 100% pan evaporation till 30 DAS, 150% pan evaporation till 60 DAS and 200% pan evaporation till 90 DAS with 125% RDF (25% as NF + 75% as WSF) (T_9) had considerably greater water use efficacy (5.12 and 5.17 kg ha-mm^{-1}). It saved 25 and 24% of water compared to surface irrigation (Table 3). The crop with surface irrigation and 100% RDF showed the lowest WUE (2.66 and 2.65 kg ha-mm^{-1} in summer 2022 and 2023 respectively). Total water used was highest with surface soil irrigation in 100% RDF (1130 and 1186 mm) than T_3, T_6, T_9 and T_{12} (843 and 893 mm), followed by T_2, T_5, T_8 and T_{11} (729 and 768 mm). The least total water used (615 and 643 mm) was with T_1, T_4, T_7 and T_{10} during summer 2022 and 2023 respectively. Providing water to soil closer to the plant with minimal water loss increases water-use efficacy.

The higher WUE in drip irrigated treatments than flood irrigation was mainly due to significant irrigation water savings, enhanced crop production and higher fertilizer use efficiency (36, 38, 39). Reduced nitrogen leaching and volatilization losses resulted from regular nutrient and water supply to the root zone, which increased crop production by increasing nutrient uptake (40). Greater water consumption efficiency was probably caused by the favorable effects of water and nutrients on crop growth and output under drip irrigation (20, 32).

Economics

The economic analysis revealed that the initial cost of cultivation was higher under drip fertigation treatments than surface irrigation with soil application of fertilizers due to the higher amount of fertilizers and drip cost. The lowest cost of cultivation incurred under surface irrigation with soil application of fertilizer was due to the lack of extra fertilizers and there is no cost of drip involved. Significantly, higher gross returns were reported under T_9 (₹ 102901 and ₹ 106247 ha^{-1}) and treatment T_1 found the least gross return of ₹ 56255 and 57505 ha^{-1} in summer 2022 and 2023, respectively. Likewise, T_{12} resulted in significantly the highest net return of ₹ 35789 and 37131 ha^{-1} B: C ratio with a tune of 1.69 and 1.73 during summer 2022 and 2023, respectively. However, the least Net returns and B: C were in T_1 (₹ 7234 and 6634 ha^{-1}; 1.15 and 1.13) during both years of study (Fig. 3 and Fig. 4).

Table 3. Total water used (mm) and water use efficiency (kg ha-mm^{-1}) of aerobic rice as influenced by drip irrigation and fertigation levels during summer 2022 and 2023

Treatments	Irrigation water applied (I_R) (mm)		Effective rainfall (E_R) (mm)		Total water used (I_R+E_R) (mm)		Water use efficiency (kg ha-mm^{-1})		Water saved over surface irrigation (%)	
	2022	2023	2022	2023	2022	2023	2022	2023	2022	2023
T_1	568	599	47.0	19.8	615	618	3.74 ± 0.22	3.82 ± 0.2	45.5	47.7
T_2	682	719	47.0	19.8	729	739	3.60 ± 0.08	3.67 ± 0.33	35.5	37.7
T_3	796	840	47.0	19.8	843	860	4.18 ± 0.22	4.19 ± 0.08	25.4	27.5
T_4	568	599	47.0	19.8	615	618	4.53 ± 0.25	4.72 ± 0.2	45.5	47.7
T_5	682	719	47.0	19.8	729	739	4.38 ± 0.67	4.46 ± 0.28	35.5	37.7
T_6	796	840	47.0	19.8	843	860	4.73 ± 0.36	4.79 ± 0.3	25.4	27.5
T_7	568	599	47.0	19.8	615	618	4.74 ± 0.11	4.92 ± 0.08	45.5	47.7
T_8	682	719	47.0	19.8	729	739	5.09 ± 0.28	5.15 ± 0.35	35.5	37.7
T_9	796	840	47.0	19.8	843	860	5.12 ± 0.18	5.17 ± 0.17	25.4	27.5
T_{10}	568	599	47.0	19.8	615	618	4.36 ± 0.32	4.41 ± 0.49	45.5	47.7
T_{11}	682	719	47.0	19.8	729	739	4.26 ± 0.46	4.33 ± 0.61	35.5	37.7
T_{12}	796	840	47.0	19.8	843	860	4.35 ± 0.1	4.34 ± 0.3	25.4	27.5
T_{13}	1083	1166	47.0	19.8	1130	1186	2.66 ± 0.14	2.63 ± 0.12	-	-
S.Em (±)	-	-	-	-	-	-	0.30	0.29	-	-
CD (P=0.05)	-	-		-	-	-	0.86	0.85	-	-

Treatment details are given under Materials and Methods; ***S**- Significant; **NS**- Non significant. The values represent the averages (±SE) of independent replicates, significantly different at $p \le 0.05$, according to Duncan's Multiple Range test

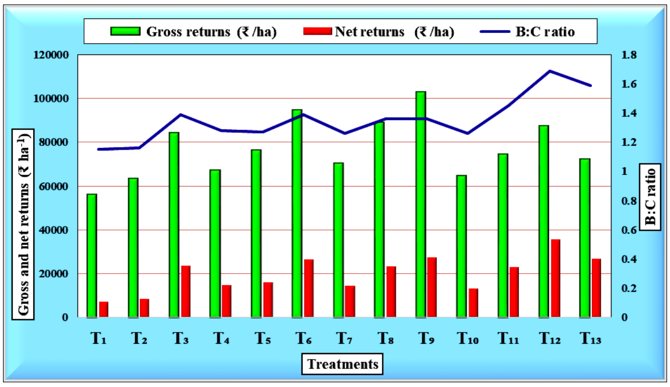

Fig. 3. Influence of drip fertigation on economics (₹ ha^{-1}) of aerobic rice in summer 2022. This graph showed the treatments on the horizontal x-axis gross and net returns (₹ ha^{-1}) on the primary y-axis and the B: C ratio on the secondary y-axis vertically in summer 2022.

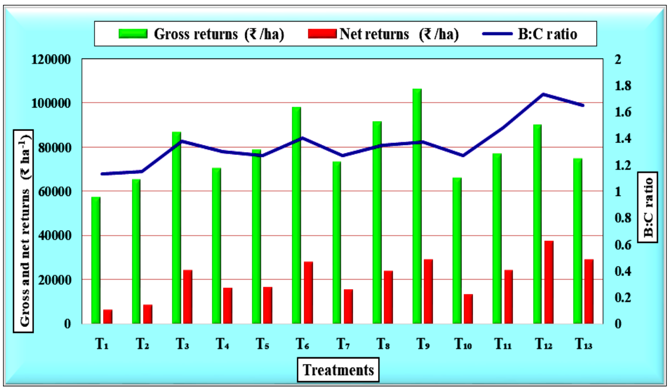

Fig. 4. Influence of drip fertigation on economics (₹ ha^{-1}) of aerobic rice in summer 2023. This graph showed the treatments on the horizontal x-axis gross and net returns (₹ ha^{-1}) on the primary y-axis and the B: C ratio on the secondary y-axis vertically in summer 2023.

During both years, cultivation's economic efficiency and viability are mainly the outcomes of crop yields with lesser management costs. The greater cost of water-soluble fertilizer was the primary reason for the poorer net returns and B: C ratio, even if the water-soluble fertilizer with drip fertigation recorded a better yield, leading to a higher gross. All drip fertigation treatments have been determined to be less profitable than drip irrigation. Compared to other treatments, the highest grain yield was achieved due to lower fertilizer costs. The primary causes of this are lower cultivation costs and higher grain and straw yields compared to alternative treatments (20, 36). Drip fertilized tomatoes require costly specialized fertilizers, the benefit-to -cost ratio was lower even though water-soluble plots yielded higher yields (41). Due to the faster uptake and higher nutrient consumption efficiency of costly fertilizers, which led to a very slight change in the B: C ratio, the fertigated plots produced a higher yield and gross income when compared to drip irrigation with 100% RDF soil application. Consequently, the higher income (35) found comparable results, with 80% of the soluble fertilizers producing higher yields with lower B: C ratios due to higher WSF pricing, thereby fairly offsetting the higher prices for the water-soluble fertilizers.

Conclusion

The two-year field experiments demonstrated that drip fertigation at the rate of 100% PE till 30 DAS, 150% pan evaporation till 60 DAS, 200% pan evaporation till 90 DAS with 125% recommended dose of fertilizer (25% as normal fertilizer + 75% as water soluble fertilizer) consistently had significantly higher yields to the tune of 43.8% and 42.4% over surface watering with soil-applied 100% RDF during both years of trial. It also produced higher yield characteristic values, including panicle length and fertile tiller numbers, while reducing the weed population. The highest water usage efficacy (5.12 and 5.17 kg/ha-mm) was reported above similar treatments in both years. On the contrary, the highest net returns and B: C ratio were found in drip irrigation with surface application of conventional nutrients. The research hypotheses tend to be confirmed and more research has to be conducted simultaneously at various locations this concept can make industrially and economically sustainable.

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Authors' contributions

NUS has done writing original draft, formal analysis, data curation, investigation, funding acquisition, software and validation. KV has done conceptualization and supervision. SP and YSS has shared funding acquisition and resources. SB and JP has done writing review and editing and funding. VV and HSL has provided funding. NJ and PAR shared resources.

Compliance with ethical standards

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

Ethical issues: None

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