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RESEARCH ARTICLE

Performance of wheat (*Triticum aestivum* L.) as influenced by phosphorus levels and drip irrigation regimes

Shrikant Reddy Patil[1], Santosh Korav[1*], Sujatha H T[2] & Vikas Sharma[3]

[1]Department of Agronomy, School of Agriculture, Lovely Professional University, Jalandhar 144 411, Punjab, India
[2]Department of Agronomy, Keladi Shivappa Nayaka University of Agricultural and Horticultural Sciences, Shivamogga 577 412, Karnataka, India
[3]Department of Soil Science, School of Agriculture, Lovely Professional University, Jalandhar 144 411, Punjab, India

*Correspondence email - santoshkorav@gmail.com

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Abstract

The strategic integration of phosphorus (P) fertilization with drip irrigation regimes is critical for mitigating water stress, enhancing wheat growth, yield and improving water productivity. This study aimed to evaluate the interactive effects of deficit drip irrigation and P application on wheat performance. A field experiment was conducted during the *Rabi* season of 2023-24 at the experimental farm of Lovely Professional University, Punjab, in a split-plot design with 3 replications. The main plot treatments comprised 3 irrigation regimes based on crop evapotranspiration (ETc): 1.0, 0.85 and 0.70 ETc. The subplot treatments included 4 P levels: 0, 45, 60 and 75 kg ha^{-1}. Drip irrigation at 1.0 ETc combined with 75 kg ha^{-1} P recorded the maximum growth attributes, including plant height (95.63 cm), tillers (393.84 m^{-2}) and dry matter (965.60 g), which were 10.06 %, 3.67 % and 1.71 % higher respectively, than at 0.70 ETc. Similarly, P application at 75 kg ha^{-1} enhanced plant height (93.85 cm), tillers (391.39 m^{-2}) and dry matter (962.94 g) compared to the control. Chlorophyll index increased by 6.7 % and 29.7 % under 1.0 ETc with 75 kg ha^{-1} P compared to 0.85 and 0.70 ETc respectively. Grain and straw yields under 1.0 ETc with 75 kg ha^{-1} P improved by 17.5 % and 13.4 % over 0.70 ETc, while yields under 0.85 ETc with 75 kg ha^{-1} P were statistically comparable to full irrigation. Optimizing P at 75 kg ha^{-1} in combination with deficit drip irrigation at 0.85 ETc effectively improves root architecture, enhances growth, yield and increases water productivity in wheat.

Keywords: chlorophyll index; drip irrigation; dry matter content; grain yield; water productivity

Introduction

The rice-wheat cropping system (RWCS) is one of the largest and most important agricultural systems in the world, covering approximately 26 million hectares across China and South Asia. It provides staple food supplies to more than 20 % of the global population. In South Asia, over 85 % of RWCS is concentrated in the Indo-Gangetic Plains (IGP), with India alone accounting for about 10 million hectares of its geographical area (1). In India, rice and wheat are prioritized over all other crops and form the backbone of the nation's food security. The RWCS is particularly significant in the states of Punjab, Haryana and Uttar Pradesh, which form part of the IGP. This system plays a critical role in ensuring food security, contributing more than 50 % of the total food grain production in the region (2). Wheat is the second most important cereal crop in India after rice and serves as a staple food rich in carbohydrates (71 %), protein (8 %–15 %), fat (1.5 %) and essential micronutrients such as iron (Fe), zinc (Zn), magnesium (Mg) and phosphorus (P) (3, 4). It forms a key component of the Indian diet and is also fed to animals due to its high nutritional value. Although significant yield improvements have been achieved since the Green Revolution, challenges such as water scarcity and climate change now threaten the sustainability of wheat production in India. This has increased the demand for drought-tolerant strategies.

Recent advancements, such as drought-resistant wheat varieties, microbial inoculation, deficit irrigation and genetic engineering, have emerged as promising solutions to enhance wheat resilience under water-limited conditions and secure future food production. Drip irrigation has emerged as a water-saving and highly efficient method, widely adopted for crops such as vegetables, orchards, flowers and plantations. However, limited research has been conducted on its application to field crops like wheat. Drip irrigation can conserve more than 20 % of irrigation water and significantly improve yield and yield attributes compared to traditional irrigation methods. It also enhances water productivity while reducing water use per unit of production (5, 6). Estimates suggest that by adopting drip irrigation in wheat cultivation, India could conserve nearly 18976 million cubic meters of water annually. Despite these benefits, only a few studies have examined the suitability of drip irrigation systems for intensive field crop conditions (7).

P is another critical factor influencing plant growth and development, particularly under stressful environmental conditions. It plays a key role in stomatal regulation, stress responses and root development (8). However, much of the applied P in soil becomes fixed and unavailable for plant uptake, creating a barrier to growth. Adequate P availability improves plant tolerance to drought, enhances root density and supports higher rates of photosynthesis (9). Given these considerations, drip irrigation has gained prominence as a technique that optimizes water delivery directly to the root zone, thereby increasing water productivity and reducing losses from evaporation and runoff (10). Research on the combined effects of deficit irrigation and variable phosphorus levels on wheat under sandy loam soils is limited, particularly regarding yield response and water productivity in North-Western India. The combined application of drip irrigation and P fertilization offers a promising strategy for improving wheat growth, yield and water productivity, particularly in the face of climate change and growing resource limitations. Therefore, the present study was undertaken to evaluate how different phosphorus levels and drip irrigation regimes influence the growth, yield and water productivity of wheat.

Materials and Methods

Description of the experimental site

The experiment was conducted during the *Rabi* season of 2023-24 at the experimental farm of Lovely Professional University, Punjab. The soil at the site was classified as sandy loam. A split-plot design with 3 replications was employed. The main plot treatments include 3 irrigation levels: 1.0 ETc (I_1), 0.85 ETc (I_2) and 0.7 ETc (I_3). The subplot treatment was 4 sub plot P levels: 0 kg ha^{-1} (P_1), 60 kg ha^{-1} (P_2), 75 kg ha^{-1} (P_3) and 45 kg ha^{-1} (P_4). The use of recommended dose of fertilizer (120:40 kg ha^{-1} NK) was applied through urea and Morat of potash (MOP) respectively, while P was applied through single super phosphate (SSP). All other crop management practices were followed with the package and practices given by Punjab Agricultural University, Ludhiana.

Soil properties

Composite soil samples were collected from the experimental site at a depth of 0-30 cm before sowing. The soil was classified as sandy loam, with a slightly alkaline reaction (pH 7.32-7.37) and low electrical conductivity (0.23–0.26 dS m^{-1}), indicating non-saline conditions. The organic carbon content ranged from 0.52 % to 0.57 %. The nutrient status revealed available nitrogen of 172.48 kg ha^{-1} (Kjeldahl method) (11), available P of 21.28 kg ha^{-1} (Olsen's method) (12) and available potassium (13) of 284.48 kg ha^{-1} (flame photometry), reflecting a medium fertility status suitable for wheat cultivation. Soil physicochemical properties, including pH, EC and organic carbon, remained uniform across irrigation and P treatments, with no significant interaction effects observed.

Crop variety and sowing

The wheat cultivar employed in this study was PBW 550, a high-yielding variety widely cultivated in the Punjab region. PBW 550 is recognized for its adaptability to local agro-climatic conditions, tolerance to rust diseases and suitability for late sowing. The recommended seed rate for this cultivar is 100 kg ha^{-1}, with a row spacing of 22.5 cm.

Sowing and crop establishment

To maintain uniform seed germination and crop establishment, 3 initial irrigations were applied at intervals of 3-4 days. This pre-sowing irrigation helped maintain consistent soil moisture necessary for seedling emergence. Wheat seeds of PBW 550 were sown at the recommended rate of 100 kg ha^{-1} with a spacing of 22.5 cm between rows. Seeds were placed at an optimal depth (4-5 cm) to ensure rapid germination and early seedling vigor. Post-sowing, standard field management practices, including weed control and timely fertilizer application, were followed to support healthy crop growth and establishment.

Irrigation application and crop ETc calculations

Following seedling establishment, drip irrigation was applied using 16 mm laterals fitted with inline emitters discharging 4 L h^{-1}. The laterals were placed between crop rows and water flow was regulated through control valves. Irrigation was scheduled at weekly intervals as per the treatment plan, based on calculated ETc, to optimize water use efficiency during the crop growth period. Estimation of ETc was performed in sequential steps. Initially, reference ETo was calculated using accumulated pan evaporation data from a Class-A pan evaporimeter installed at the Lovely Professional University agrometeorological observatory, applying equation (i). Thereafter, ETc for wheat was derived using equation (ii), incorporating the crop coefficient (Kc) as recommended in standard procedures (14, 15). The total volume of irrigation water required for the treatment receiving full irrigation (I_1: 1.0 ETc) was estimated using equation (iii). The corresponding irrigation duration (min) was determined by dividing the total irrigation water requirement by the combined discharge of the emitters installed in the respective plot. For deficit irrigation treatments (I_2: 0.85 ETc and I_3: 0.70 ETc), water was applied for 85 % and 70 % of the irrigation duration calculated for I_1 respectively. The total water depth supplied to the crop was computed by summing the net irrigation water applied per hectare with the effective rainfall, the latter estimated using equation (iv).

$$ETo = Epan \times Kpan \ldots\ldots (i)$$

Where,

Epan- Accumulated pan evaporation (mm week^{-1})

Kpan- Pan coefficient (0.7)

$$ETc = ET_0 \times K_c \ldots\ldots\ldots (ii)$$

$$\text{Irrigation water requirement (L/plot)} = ETc \times W_P \times A \ldots\ldots\ldots (iii)$$

Where,

ETc: Crop evaporation (mm week^{-1})

K_c: crop coefficient of wheat (as per Table 1)

W_P: Wetting area percentage (taken as 1)

A: Plot/bed area (m^2)

According to FAO, effective rainfall was calculated by multiplying daily rainfall exceeding 5 mm by a factor of 0.75 (16), as expressed by the following equation;

$$\text{Effective rainfall (mm)} = (\text{Rainfall} - 5) \times 0.75 \ldots\ldots (iv)$$

Table 1. Kc data followed during the wheat growth period

S. No.	Crop growth period	Duration (days)	Kc
1	Initial stage	20	0.30
2	Crop developmental stage	35	0.70
3	Reproductive stage	40	1.05
4	Late-season stage	30	0.65

Measurement of physiological and yield parameters

All growth and yield parameters reported in this study were measured at the physiological maturity (harvest) stage. Plant height was recorded by measuring the average height of 5 randomly selected plants per plot from ground level to the tip of the spike, excluding awns. The number of tillers m^{-2} was counted manually in selected quadrats of 0.5 m^2 area within each experimental plot at harvest. This count reflects the crop's tillering capacity and final stand density, which are key determinants of yield potential. Dry matter content was measured by harvesting all above-ground plant material within the same quadrats at harvest. Samples were oven dried at 65 °C until a constant weight was achieved and dry biomass was expressed in g m^{-2}. This measurement provides an estimate of total vegetative growth accumulated throughout the crop cycle. Chlorophyll index was measured at 120 days after sowing (DAS) of wheat using a soil plant analysis development (SPAD) chlorophyll meter on fully expanded flag leaves. The SPAD readings provide an estimate of leaf chlorophyll content, reflecting photosynthetic efficiency and overall plant health. Measurements were taken on 5 randomly selected plants per plot, avoiding the leaf midrib area to ensure representative data. Yield attributes, including spike number per square meter, grains per spike and test weight (1000 grain weight) were carefully recorded on harvested samples. Grain and straw yield were determined by harvesting the net plot area, threshing manually and weighing using a digital balance. Yields were then expressed in quintals per hectare (q ha^{-1}).

Statistical analysis

Statistical analysis was conducted using the least significant difference (LSD) method at a significance level of $p < 0.05$, employing the statistical software Statistix 10.0 and OPSTAT (17, 18).

Results and Discussion

Response of drip irrigation regimes on growth and productivity of wheat

During the 2023-24 period, different drip irrigation regimes and P application levels significantly influenced wheat growth and yield parameters (Table 2, Fig. 1, 2). The significantly maximum plant height (95.63 cm) at maturity was found in DI at 1.0 ETc, which was comparable to the height of 92.47 cm seen with DI at 0.85 ETc. Conversely, the lowest plant height of 86.89 cm was observed in DI at 0.7 ETc. Higher growth observed at 1.0 ETc was attributed to optimal soil moisture, which promotes cell division, cell expansion and stem elongation, contributing to increased plant height (19). Decreased growth and reduced plant height under deficit irrigation treatments, such as water deficit, could be attributed to disruptions in basic cellular processes. Limited water availability alters cell turgor pressure, which is essential for maintaining cell rigidity and promoting expansion. A reduction in turgor pressure negatively affects cell division, enlargement and differentiation (20).

The significantly maximum number of tillers m^{-2} was found in DI of 1.0 ETc (393.84 no.), which was at par with DI 0.85 ETc (390.28 no.) and the lowest was in DI 0.7 ETc (379.91 no.). The highest number of tillers per square meter of tillers at 1.0 ETc was related to the adequacy of the water supply for the tillering period, which in turn increased nutrient uptake (21). Dry matter content at 1.0 ETc drip irrigation was significantly higher (965.60 g) than 0.85 ETc (960.53 g) and the lowest was found in DI of 0.7 ETc. (949.33 g). The higher dry matter content at 1.0 ETc was due to optimal water availability, which enhances cell elongation, expansion and overall plant growth (22). Higher dry matter accumulation (DMA) observed under frequent irrigation regimes can be attributed to the positive influence of increased plant height and improved vegetative growth (23). The stunted growth properties were a result of a decrease in the flow of water from the xylem to the different cells, which is the process of cell division, elongation and the development of the cells.

Additionally, there was a decline in chlorophyll content and oxidative degradation of lipids in the cell membrane (24). Similarly, irrigation regimes significantly influenced on yield attributes of wheat. DI at 1.0 ETc produced the maximum number of grains $spike^{-1}$ (47.78 no.),

Table 2. Effect of irrigation regimes and phosphorus levels on growth attributes of wheat

Treatment	Plant height (cm)	No. of tillers (no. m^{-2})	Chlorophyl index	Dry matter content (g m^{-2})
Irrigation regimes				
I_1	95.63	393.84	43.07	965.60
I_2	92.47	390.28	40.33	960.53
I_3	86.89	379.91	33.20	949.33
SEm (±)	0.137	0.146	0.106	0.178
CD ($p = 0.05$)	0.538	0.574	0.417	0.698
Phosphorus levels				
P_1	88.51	381.99	35.34	951.20
P_2	92.94	390.46	40.33	962.10
P_3	93.85	391.39	40.82	962.94
P_4	91.34	388.21	38.96	957.70
SEm (±)	0.121	0.134	0.186	0.131
CD ($p = 0.05$)	0.360	0.398	0.554	0.390
Interaction (I×P)				
$I_1 P_1$	92.00	388.17	38.50	957.63
$I_1 P_2$	97.00	396.03	45.00	969.50
$I_1 P_3$	98.00	397.04	45.47	970.17
$I_1 P_4$	95.50	394.13	43.30	965.10
$I_2 P_1$	90.37	385.33	35.50	955.47
$I_2 P_2$	93.50	392.23	42.23	963.17
$I_2 P_3$	94.02	393.07	43.00	964.00
$I_2 P_4$	92.00	390.50	40.57	959.50
$I_3 P_1$	83.17	372.47	32.02	940.50
$I_3 P_2$	88.33	383.10	33.77	953.63
$I_3 P_3$	89.53	384.07	34.00	954.67
$I_3 P_4$	86.53	380.00	33.00	948.50
Factor (B) at the same level of A				
SEm (±)	0.210	0.232	0.323	0.227
CD ($p = 0.05$)	0.623	0.689	0.959	0.675
Factor (A) at the same level of B				
SEm (±)	0.228	0.248	0.299	0.265
CD ($p = 0.05$)	0.676	0.738	0.888	0.788

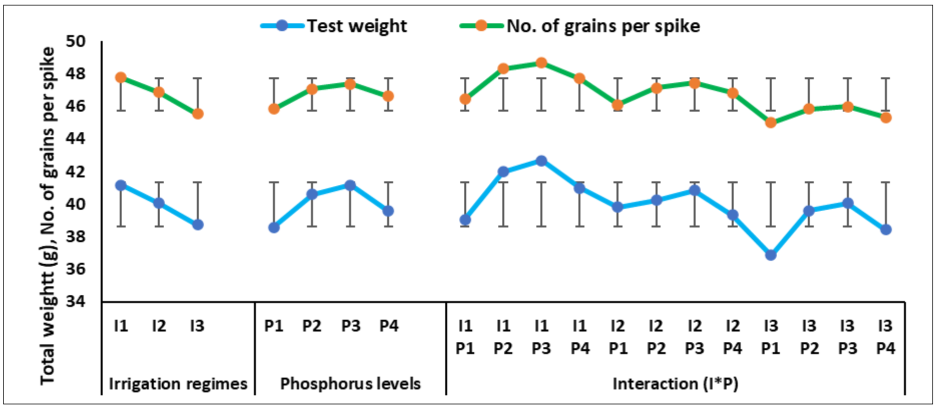

Fig. 1. Test weight and number of grains per spike of wheat as influenced by irrigation regimes and phosphorus levels.

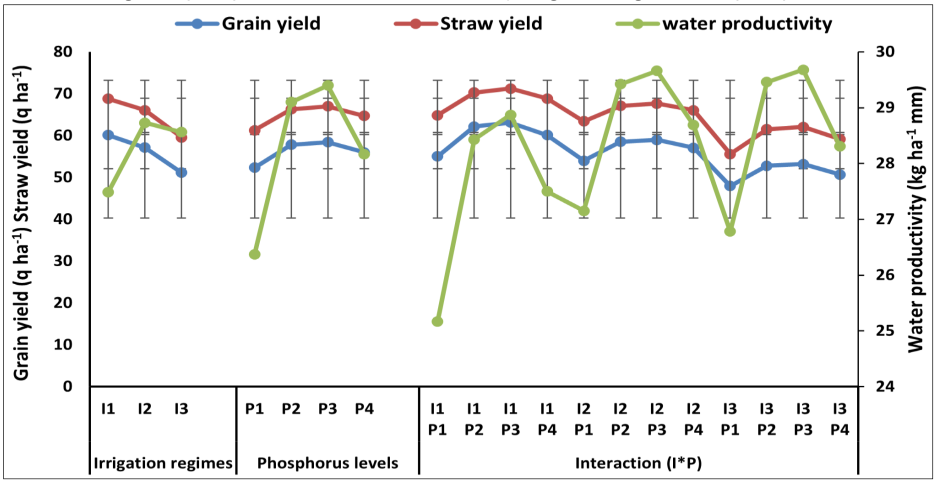

Fig. 2. Grain yield, straw yield and water productivity of wheat as influenced by irrigation regimes and phosphorus levels.

test weight (41.18 g), grain yield (60.11 q ha^{-1}) and straw yield (68.81 q ha^{-1}). Higher yield attributes, grain yield and straw yield were induced due to timely and sufficient water supply during the crop growth and development stages. This facilitated optimal crop growth and profuse tillering continued with a rising rate at harvest (25). Higher grain yield was due to proper maintenance of adequate protoplasmic hydration, which could have lowered viscosity and increased water and nutrient permeability. The uniform and adequate availability of water creates a conducive rhizosphere for nutrient uptake, which boosts growth and yield attributes. This process facilitates the allocation of photosynthates towards the sink, enhancing yield attributes such as the number of spikes per square meter, grains per spike and overall grain and straw yields (26).

Consistent wetting of the root zone due to proper irrigation also promotes nutrient release from the soil, further supporting plant growth and development. The higher straw yield was due to maintenance of a well-balanced soil moisture status in the plant's root zone, ultimately leading to greater biomass production (18). A higher test weight was the result of enough moisture during grain filling, which stimulated the grain by supplying the assimilates of dry matter to the seed (27). In the same measure of proportionality, the yield deficit was accompanied by the decrease in the yield attributing factors such as the number of grains spike^{-1}, test weight and grain yield were the consequence of loss of soil moisture content, a vapour gap formed around roots due to their turgor pressure in water stress and unfavourable weather conditions for cell division and expansion, which led to the decrease of net photosynthesis and diminished effective photosynthetically active radiations (28, 29).

Response of P levels on growth and productivity of wheat

Application of higher P levels significantly influenced growth and yield attributes and yield of wheat during 2023-24 (Table 2, Fig. 1, 2). The significantly highest plant height (93.85 cm), number of tillers (391.39 no.), dry matter content (962.94 g) was found in P3 (75 kg ha^{-1} P) followed by P_2 which was considered to be moderate level of P. Significantly lowest plant height (88.51 cm), number of tillers (381.99 no.), dry matter content (951.20 g) was found in absolute control. Higher plant height and no of tillers were due to ideal balanced and nutrient availability that support vigorous growth without causing nutrient imbalance and it also promotes healthy root development and plant growth (30). This improvement, in turn enhances the capacity of the plant to absorb water and nutrients. Besides, high level of P not only cause plants to undergo several metabolic reactions like photosynthesis and cellular energy transfer (31). Reduced the plant height due to insufficient P can prolong the duration of the phyllochron, the interval between the emergence of successive leaves thereby slowing down the overall development and leading to shorter plant height and also reported that reduced number of tillers was due to lower P availability directly affects tiller emergence by reducing leaf growth on main stem and lowering the maximum tiller emergence rate (32-34).

Water productivity

Drip irrigation regimes significantly influenced water productivity during 2023-24 (Fig. 2). The water productivity of wheat differed significantly with different levels of irrigation. Drip irrigation at 0.85 ETc recorded the highest water productivity (28.73 kg ha^{-1} mm^{-1}) compared to drip irrigation level at 0.7 ETc (28.56 kg ha^{-1} mm^{-1}). The lowest water productivity was found in the drip irrigation level at 1.0 ETc (27.49 kg ha^{-1} mm^{-1}). This is due to an increase in grain yield per unit consumption of water as compared to the higher level of irrigation. In response to stress conditions at reduced irrigation level, chemical signals generated in the roots might have changed the physiology of the plant. The partial opening of stomata, regulated leaf development and altered transpiration rate were among these modifications that led to a rise in water productivity (35, 36). Similarly, P levels significantly influenced water productivity. The maximum water productivity was found in P_3 (29.40 kg ha^{-1} mm^{-1}) followed by P2. The lowest WP was found in absolute control (26.37 kg ha^{-1} mm^{-1}), showing an improvement of 11.50 % over the control (P_1). These findings underscore the beneficial impact of optimized irrigation and P management in enhancing water productivity.

Interaction effect of irrigation regimes and P levels on growth, yield and water productivity of wheat

Interaction effects between irrigation levels and P levels (I × P) were significant for several wheat growth, physiological yield parameters and water productivity, but not universally across all (Table 2, Fig. 1, 2). The interaction significantly affected plant height, number of tillers, dry matter content and chlorophyll index at various growth stages, typically from 60 DAS onwards. At 30 DAS, most parameters showed non-significant interaction effects. Improved photosynthetic capacity leading to higher yields under optimal irrigation and phosphorus application.

To further justify statistical claims, interaction plots are provided illustrating the combined effects of irrigation and P levels on parameters such as plant height, chlorophyll index and grain yield (37). These plots show that the highest values generally occurred under full irrigation (1.0 ETc) combined with the recommended P dose (75 kg ha^{-1}) (38), whereas the lowest were under deficit irrigation (0.7 ETc) without P application. These comprehensive statistical analyses strengthen the evidence for the synergistic benefits of phosphorus fertilization and optimized drip irrigation (39). The maximum water productivity was found in I_3P_3, which was statistically similar to I_3P_2, I_2P_3 and I_2P_2. Due to less water utilization in I_3 and I_2 achieved maximum water productivity was achieved (5). Under deficit irrigation, higher doses of P performed well by altering their root architecture, leading to enhanced water absorption and utilization capacity.

Conclusion

This study shows that deficit drip irrigation at 0.85 ETc combined with P application at 75 kg ha^{-1} significantly enhances wheat growth, yield and water productivity under water-limited conditions. The synergistic interaction between irrigation and P improved key physiological traits, such as chlorophyll content and dry matter accumulation, leading to higher grain yield and water use efficiency. These findings underscore the importance of optimizing water and P supply according to crop requirements to achieve sustainable wheat production, particularly in water-scarce regions. The recommended irrigation regime with adequate P reduces water consumption while sustaining high productivity, offering a practical and resource-efficient strategy for wheat cultivation. Overall, applying 0.85 ETc irrigation in combination with 75 kg ha^{-1} fertilizer provides a scientifically supported approach to improve wheat performance in water-constrained environments. Long-term field validation and economic analyses are suggested to facilitate broader adoption of this water-nutrient management practice.

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Authors' contributions

SRP carried out conceptualization, methodology, investigation, data curation and writing-original draft. SK, SHT and VS carried out supervision, formal analysis, visualization, validation, writing original draft, editing and review. All authors read and approved the final manuscript.

Compliance with ethical standards

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

Ethical issues: None

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