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Impacts of Irrigation Regimes, Phosphorus and Potassium Fertilizer on the Root Development, Evapotranspiration and Grain Yield of Green Gram (*Vigna radiata* L.)

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ABSTRACT

Background: Efficient water management is utterly needed for sustainable crop production in water -scarce areas. The deficit irrigation options with P nutrition can influence the root physiology which may aggravate nutrient uptake.

Methods: The experiment was conducted with green gram, taking three irrigation regimes *viz.* irrigation at vegetative, flowering and pod formation (I1), at vegetative and flowering (I2) and vegetative and pod formation (I3) as main plots; three P doses [100% (P1), 85% (P2) and 115% (P3) of recommended P doses] as sub-plots and foliar K (K1) application and control (K2) as sub-sub plots.

Result: I1 resulted in higher soil moisture storage followed by I2 and the first water stress appeared under I3. P3 improved the root length density (RLD), root surface area (RSA) and root volume (RV) at maximum intensity under I2 as compared to I1. The maximum grain yield production (29 q ha^{-1}) was observed under I1P3 followed by I1P1. Among the deficit irrigation treatments, I2P3 produced the maximum grain yield merely 11% less than the best treatment (I1P3). Under the condition of irrigation water unavailability, skipping one irrigation during the pod formation period, supplemented with a 15% higher dose of P can result in a satisfactory grain yield of winter green gram.

Key words: Deficit irrigation, Phosphorus, Physiology, Root, Water productivity.

INTRODUCTION

The shortage of freshwater resources is now becoming critical day by day and may become a threat to all mankind in future. More than 60% of the total human freshwater consumption every year is consumed by agriculture directly or indirectly (Singh *et al.,* 2019). Globally irrigation in agriculture consumes massive amounts of water (Fereres and Soriano, 2007). Also, there are some areas where irrigation sources are scanty for growing crops after the rainy season like red-laterite areas of the eastern part of India where the available soil moisture after the rainy season was about 110 to 140 mm unable to sustain one crop during rabi season (Rajeshwar and Mani, 2015). Water stress in these regions can impact plant growth and physiological behaviour and ultimately, impair crop yield (Sekhon *et al.,* 2010). Therefore, the management of irrigation water must be so efficient that it saves water without much compromising on crop productivity. Scientists reported the promising results of deficit irrigation in achieving potential water utilization of various crops (Soureshjani *et al.,* 2019). Green gram (*Vigna radiata* L.) is such crop which suits these situations because it is short-season grain legume without specific climatic and soil requirements, with lower water requirements and most importantly it is tolerant to drought (Rajni and Kumawat, 2022).

The skipping of irrigation may cause water stress to crops and potential yield decrement (Mukherjee *et al.,* 2022). So, the development of plant roots, their active influence and behavioural vicissitudes under water stress situations can be modified with the application of phosphorus (Ichsan *et al.,* 2020). In addition, K has the role of reducing the influence of water stress on the physiological activities of plants by regulating water potentials in plants. The application of potassium regulates the opening-closure of the stomatal and helps plants to respond to water stress (drought-induced closure) and maintain water potential in tissues (Zahoor *et al.,* 2017). So, it has been hypothesized that- 1) skipping one irrigation at flowering or pod formation can reduce the water requirement of the crop which as will only produce a miniature effect on plant physiology; 2) the application of

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higher doses of P can improve root growth that can extract more water under water scare condition; 3) the application of K can reduce the ill effect of water stress in plants. To test these hypotheses a research assessment was carried out in a split-split plot design with three factors- irrigation, basal P application and foliar K application. The objectives of the experiment were set as 1) to study the amount of water stress faced by irrigation treatments; 2) to study the improvement of root activity under different irrigation and P treatments; 3) to study the irrigation effect, P and K application on plant physiology, growth and yield.

MATERIALS AND METHODS

Site description

Field experiment was conducted in the 2022-2023 cropping season in the red-laterite region of easter Odisha, India (20°15′N, 85°41′E, 13 m above mean sea level). 27 and 13°C were the mean maximum and minimum temperatures during the cropping season, respectively with effective rainfall of 22 mm (Fig 1). The details of soil physical and chemical properties are shown in Table 1.

Experimental design and treatments

The experiment was set up in a split-plot design having three replications. Irrigation treatments, basal application of P and foliar spray of K were in main, sub and sub-sub-plots, respectively. The levels of irrigation: at the vegetative, flowering and pod formation stages (I1); at the vegetative and flowering stages (I2); at the vegetative and pod formation stages (I3). P application as 100% (P1), 85% (P2) and 115% (P3) of the recommended dose of P as basal. K was sprayed as 2% KCl (K1) during vegetative and flower initiation stages along with control (K2). Green gram seeds (variety Samrat-PDM 139) were sown @ 25 kg ha^{-1} by a manual furrow opener giving a spacing of 25 cm × 10 cm. N, P_2O_5 and K_2O were applied @25: 40: 25 Kg ha^{-1}.

Sample analysis

Soil moisture storage and evapotranspiration

The actual evapotranspiration (ETa) was computed as:

$$ET_a = P + I + C - D - R - \Delta S \quad ....(1)$$

Where,
P = Precipitation amount stored in the root zone.
I = Irrigation given (cm).
C = Capillary rise.
D = Deep percolation.
R = Surface runoff.
C, D and R = Zero.
The change in soil moisture storage in a particular period is:

$$\Delta S = \int_0^z \int_{t_1}^{t_2} \left(\frac{\partial \theta}{\partial t}\right) \partial z \partial t \quad ...(2)$$

Where,
θ = Soil water content (depth-basis).
t_1 and t_2 = Start and end points.
z = Root zone depth (0-40 cm).

Gravimetric measurement of soil moisture was performed by sampling soil using a screw auger for the depth of 0-10, 10-20, 20-30 and 30-40 cm; and thereby, oven-drying the soil at 105°C. The gravimetric moisture content thus obtained was converted to volumetric moisture content by multiplying with bulk density.

Soil water stress coefficient (Ks)

The soil water stress coefficient (Ks) was computed following Nandi *et al.* (2023), a modified version of Allen *et al.* (1998):

$$K_s = \frac{(\theta_v - \theta_{WP}) \times Z_r}{(TAW - RAW)} \quad ....(3)$$

Where,
θv and θwp = Real-time volumetric water content and moisture content at permanent wilting point ($mm^3\ mm^{-3}$).
The value of TAW and RAW are expressed as follows

$$TAW = (\theta_{FC} - \theta_{WP}) Z_r \quad ....(4)$$

$$RAW = p*TAW \quad ....(5)$$

Where,
TAW and RAW = Total and readily available water (cm).
θ_{FC} and θ_{WP}= Volumetric moisture content at field capacity and permanent wilting point.
p = Fraction of TAW that is readily available which is considered 0.5 for the crop (Allen *et al.,* 1998).

Plant sampling and analysis

A root auger of 10 cm diameter and 15 cm height was used to sample the root after harvesting the shoot portion carefully. The detailed analysis was performed with a root scanner plus WinRHIZO image analysis software (Himmelbauer *et al.,* 2004). The parameters obtained were root surface area, root volume, root length, root diameter *etc.* Root length density was calculated by dividing root length by the volume of the sample cylinder.

Statistical analysis

The analysis has been done with STAR (Statistical Software for Agricultural Research)-IRRI (International Rice Research Institute). The first factor is irrigation which is main plot and P and K management are second and third factors acting as sub plot and sub sub-plot, respectively. Duncan's multiple range test (DMRT) was performed to compare the treatments at a 5% level of significance.

RESULTS AND DISCUSSION

Soil water storage depletion

Root zone soil water storage is mostly responsible for the proper growth and development of plant at different phenophases. So, to obtain satisfactory plant growth the water necessary meet their needs and no periods of moisture starvation prevails. Fig 2(a-c) shows the

Table 1: Hydro-physical properties and chemical characteristics of the experimental site.

Soil depth (mm)	Sand, silt, clay (%)	Textural class	BD (Mg m^{-3})	WHC (%)	θFC (%)	θPWP (%)	pH	SOM (g kg^{-1})	Available N (kg ha^{-1})	Available P_2O_5 (kg ha^{-1})	Available K_2O (kg ha^{-1})
0-150	26, 21, 53	Sandy clay loam	1.3	51	27	14	6.3	3.6	152	10	112
150-300	21, 18, 61	Sandy loam	1.4	47	24	12	6.2	2.7	116	7	94
300-450	18, 17, 65	Sandy loam	1.4	43	23	12	6.2	2.4	107	7	82

BD = Bulk density; WHC= Water holding capacity; SOM = Soil organic matter.

different soil moisture storage under different irrigation treatments; where, the peaks appeared due to the application of irrigation water and the depletion of soil moisture by plant uptake and/or evaporation caused trough in the curve. Regarding irrigation treatments, soil moisture depleted at a rate of about 2.5 and 4.3 mm d^{-1} during early vegetative and peak vegetative periods, respectively. I3 more drastically reduced the soil moisture storage up to pod formation period; from where it increased water storage to 84 mm due to irrigation and lastly the decreased to the least amount (62 mm) at maturity period (Fig 2c). In case of I2, the steady depletion of soil moisture occurred from pod initiation to harvest. With the dying of soil, roots sensed resistance to grow and thus decreased development of finer roots and increased metabolites deposition in roots to increase strength which ultimately cause lesser water extraction. Hao *et al.,* (2015) similarly experienced higher water extraction in well water treatment (50% ETc) than water stresses ones (100% and 75% ETc) in maize. It was observed that effect of P came to exist starting from peak vegetative period and proceeded afterward. P2 resulted the maximum water storage followed by P1. P induced the higher root growth implied more water extraction than lesser P application resulting less water available to the treatments (Mukherjee *et al.,* 2022). The effect of P was mostly observed under I1 and I2, there was no such effect of P application observed under I3. The available water content improved the plant physiology including root growth which emphasized due to the ample availability of P in the root zone soil and thus, showing good interaction; on the other hand, the lesser amount of available water presence for I3 hindered the transportation of P to the roots and from roots to other parts of the plants. There are similar findings as observed from Sarkar *et al.,* (2017) and Chtouki *et al.* (2022).

Soil water stress coefficient

Soil water stress coefficient (Ks) emphasizes the moisture-supplying capacity of soil that depends on available soil water content, soil water depletion and available water capacity (Nandi *et al.,* 2022). Ks shows no water stress up to the vegetative period, thereafter stress appeared at different quantities (Fig 3a-c). I2 showed miniature stress with Ks around 0.9 at initiation of flowering but that stress intensified at pod formation and maturity period with 35 and 67% stress, respectively. While under I3, the amount of water stress was comparatively higher about 40 and 45% at flowering and pod initiation periods; although that stress reduced to 10% at the pod formation period but increased to a maximum of 55% during the maturity period denoting heavily stress affected plants. Where I1 showed the least water stress which was 5, 15 and 27% during the vegetative, pod formation and maturity period of green gram, respectively. The stress under I3 was significantly higher than I2. Regarding the effect of P on water stress modification, it was observed that P significantly modified the water stress. P2 was recorded to produce the least

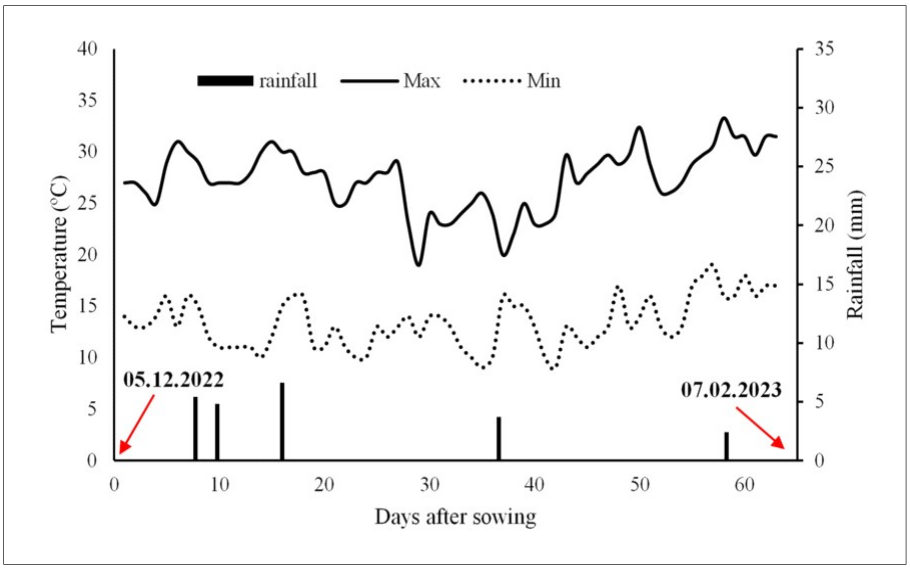
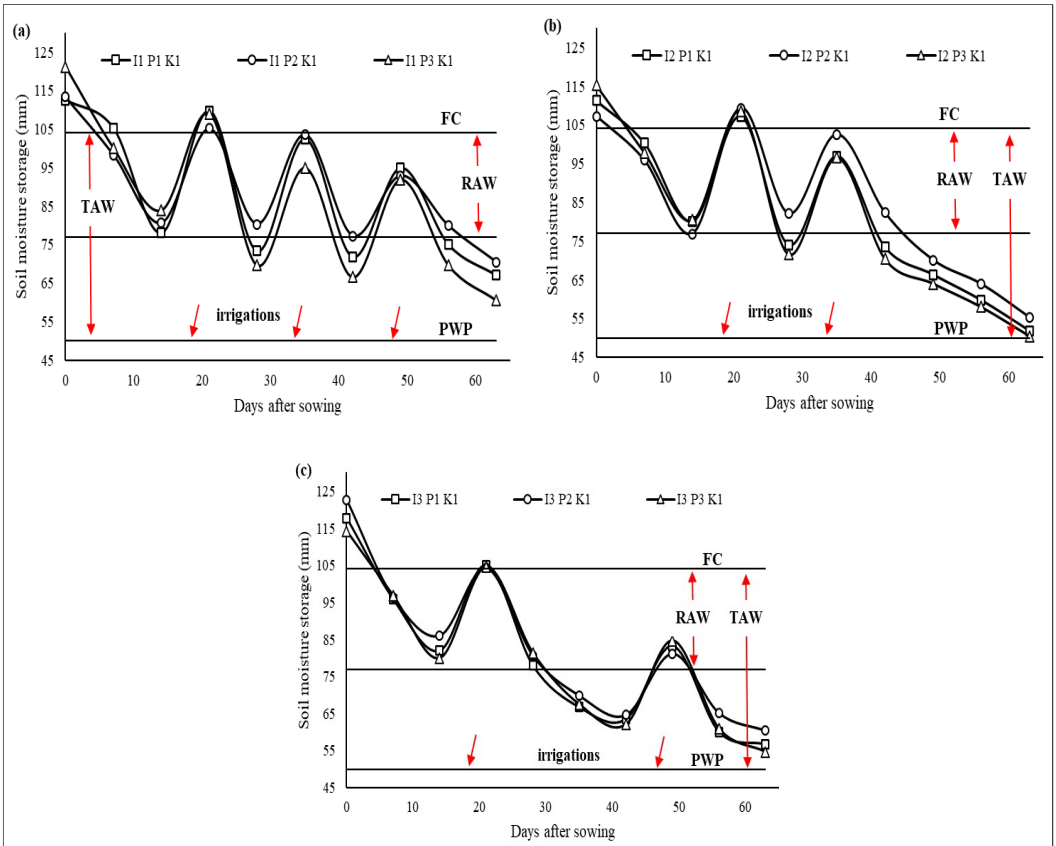


Fig 1: Daily distribution of maximum, minimum temperature (°C) and rainfall (mm) during the growing period of green gram in 2022-2023 cropping seasons.



[FC = Water storage at field capacity; PWP = Water storage at permanent wilting point; RAW = Readily available water; TAW = Total available water; I1=Irrigation at vegetative, flowering and pod formation; I1= Vegetative and flowering; I3= Vegetative and pod formation; P1= 100% recommended dose of P; P2= 85%; P3= 115%; K1= Foliar spray of 2% KCl; K2= No spray.

Fig 2: Temporal distribution of root zone (0-400 mm) soil water storage in green gram under different irrigation and P management practices.

amount of water stress followed by P1 and the most water stress was recorded under P3 which resulted in 18% stress during the vegetative period, 35% at flowering and 18% at pod formation period; although, all the stresses at the critical phenophases under P3 were below the critical limit (<40%). The interaction between I and P was significant mainly during flowering, pod formation and maturity periods. The stress appearance under P3 was due to the plant water extraction causing a decrement in soil water storage that positively impacted on plant growth. A similar reflection was also reported by Saha *et al.* (2020).

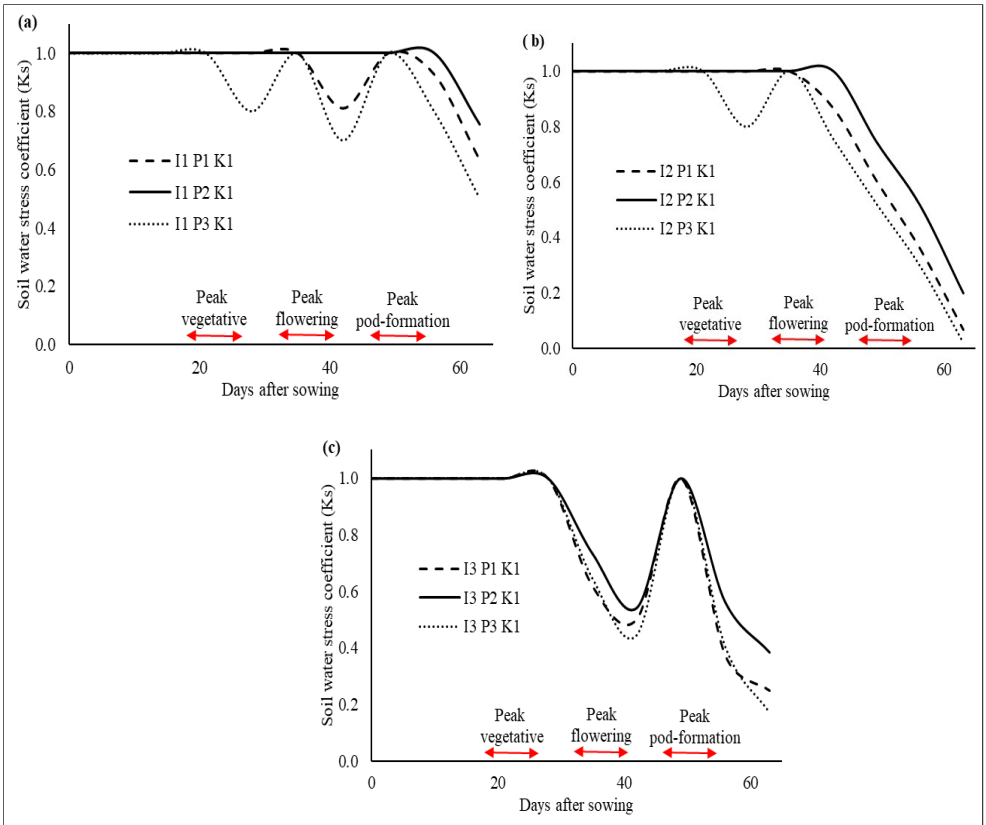
Root morphology

Root length density

Variation of root distribution is observed accompanied by soil moisture content in the root zone (Fig 4a). The effect of K was observed as non-significant and because of that only the effect of irrigation and P were shown and discussed in this section. P significantly improved root length density (RLD) and the maximum improvement was noticed under full irrigation (I1) followed by deficit irrigation (I3). The RLD variations as observed in our study among different irrigation treatments go hand in hand with the observations of Kang *et al.,* (2000), who reported a 14% higher decrement of RLD at severe water stress as compared to medium water deficit. The interesting observation was the interaction of P and I. Fig 4a shows that the maximum (27%) increase in RLD from P1 to P3 was observed under I2, where the increase was merely 14% in the case of I1. The improvement of roots under water deficit I2 condition was more with the supply of P. Lynch (2013) observed the development of long taproots because of greater water availability at lower depths. While the decrement from P1 to P2 was almost the same for both I1 and I2 irrigation treatments. On the other hand, the application of lesser P (P2) produced lesser RLD but the P1 and P3 showed no significant differences in RLD values. There are several reports describing the decrement of RLD under the deficiency of P (Duan *et al.,* 2021; Hadir *et al.,* 2020). When grown under Limited phosphorus (P) availability root elongation gets inhibited and thus exhibits a shallower architecture (Sharma *et al.,* 2017). On the other hand, Teng *et al.* (2013) reported an increase in RLD under the influence of elevated P-fertilizer rate in wheat.

Average root diameter

The average diameter (RD) denotes the dominance of finer or coarser roots under different I and P treatments in green



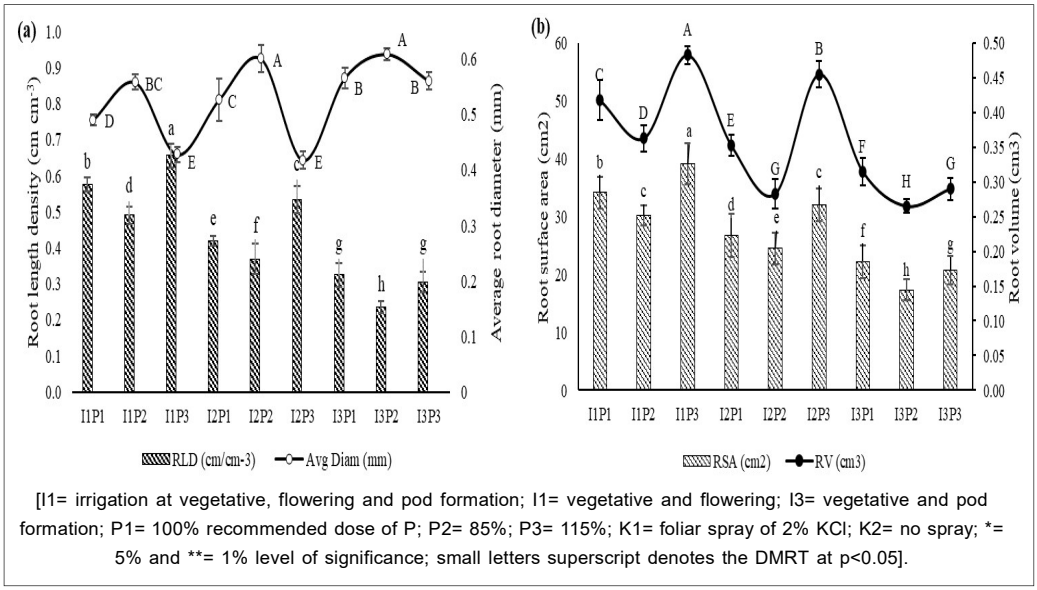
[I1= irrigation at vegetative, flowering and pod formation; I1= vegetative and flowering; I3= vegetative and pod formation; P1= 100% recommended dose of P; P2= 85%; P3= 115%; K1= foliar spray of 2% KCl; K2= no spray.

Fig 3: Soil water stress coefficient under in green gram under different irrigation and P management practices.

gram (Fig 4a). The figure implies that with the decrement of irrigation frequency, RD increased, while RD decreased with the improved amount of P application. P produced finer roots under I1 and I2, although, P application showed no such significant effect of RD under I3. More number of finer roots were produced under slight water stress (I2) with the application of higher P (P3) fertilizer. A similar P's effect under water stress was reported by Mataa *et al.* (2019) while working with common beans. Plants develop short suberized roots when water stress appears as the top soil starts to dry which is the survival mechanism of plants for reducing water loss from plant roots (Whitmore *et al.,* 2011).

Yield and evapotranspiration

Table 2 shows the effect of I, P and K on the grain yield, evapotranspiration and water productivity of green gram. It shows that I3 produced the maximum grain yield which was 18 and 47% greater than I1 and I2. The application of P improved grain yield irrespective of irrigation management. P3 produced the maximum grain yield of 721 kg ha^{-1} followed by P1. P1 and P3 improved 26 and 35% grain yield over P2 under I2 and improved 32 and 40% grain yield over P2 under I1. The application of the higher amount of P (P3) only increased by 8% grain yield under I3. Photosynthesis-driven grain yield of crops decreases with the reduction in the relative water content (RWC) of leaves.



[I1= irrigation at vegetative, flowering and pod formation; I1= vegetative and flowering; I3= vegetative and pod formation; P1= 100% recommended dose of P; P2= 85%; P3= 115%; K1= foliar spray of 2% KCl; K2= no spray; *= 5% and **= 1% level of significance; small letters superscript denotes the DMRT at p<0.05].

Fig 4: The root morphological characteristics (a) Root length density (RLD) and average root diameter (RD) and (b) root surface area (RSA) and root volume (RV) under different irrigation and P management practices in green gram.

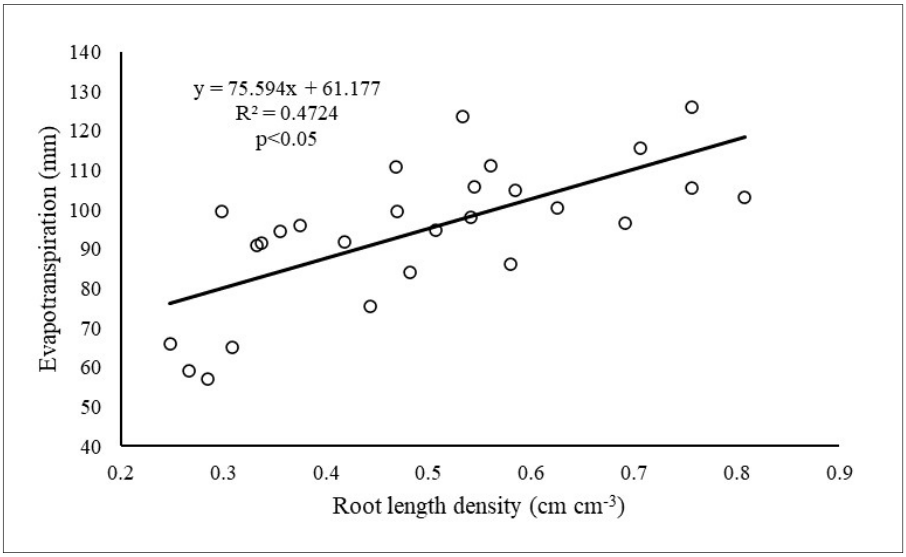


Fig 5: Relationship of root length density and evapotranspiration of green gram.

Table 2: Grain yield and evapotranspiration of green gram under different irrigation, P and K management practices.

	Yield (kg ha^{-1})	ET (mm)
Irrigation (I)		
I1	716.0^{a}	161.7^{a}
I2	606.5^{b}	142.8^{b}
I3	478.6^{c}	143.0^{b}
LSD (p<0.05)	87.0**	2.6*
Phosphorus (P)		
P1	642.4^{b}	147.3^{b}
P2	437.6^{c}	134.4^{c}
P3	721.1^{a}	153.7^{a}
LSD (p<0.05)	13.8*	2.3*
Potassium (K)		
K1	606.9	136.4
K2	593.9	134.7
LSD (p<0.05)	ns	ns
Interactions		
I*P	**	*
I*K	ns	ns
P*K	ns	ns
I*P*K	ns	ns

While, responses to water deficit are the reduction of transpiration and thereby reduction of photosynthesis resulting in significant consequences on grain yield (Álvarez *et al.,* 2011). Similarly, Trout and DeJonge (2017) reported a decline in grain yield with a reduction in irrigation amount.

Evapotranspiration amount was varied among different I and P treatments. I1 resulted in 13% higher ET than I2; while P1 and P3 produced 9 and 14% higher ET than P2, respectively (Table 2). The implication of I1P3 recorded the highest ET of 173 mm followed by I1P1 of 158 mm. The introduction of P1 and P3 also improved 6 and 10% ET under I2. However, not so not-so-significant enhancement of ET by P was observed under I3. The improvement of ET with the improvement of RLD either by P application or supplement irrigation has previously been provided by Kazemi *et al.* (2021) and is presented in Fig 5.

CONCLUSION

Skipping of one irrigation either at flowering or at pod formation period caused a significant reduction of soil water storage as well as a noteworthy increment of stress intensity to crops. In addition, the application of reduced P doses aggravated the stress situation by providing little support to root growth. Full irrigation and higher doses of P resulted in the highest plant growth and productivity. Higher P doses under moderate water stress conditions improved the maximum root growth, plant physiological traits, nutrient uptake and ultimately grain yield. Therefore, with the context of low water facilities for cultivation, irrigations applied only at vegetative and flowering periods along with just 15% above the recommended dose of phosphorus can secure a satisfactory grain yield of winter green gram.

CRediT authorship contribution statement

All authors contributed to the preparation of the manuscript. Treatment formulation, field observations, data collection and analysis were performed by J. Jena, M. Layek, R. Nandi and G. H. Santra. The writing of the first draft was performed by R. Nandi. G. H. Santra and G. Sahu – review and editing, Data curation, Visualization. J. Jena: data collection, laboratory analysis. M. Layek: data collection, laboratory analysis. K. Sar: review and editing.

Data availability

Data will be made available on request.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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