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SOIL FERTILITY, WATER PRODUCTIVITY, ECONOMICS AND ENERGETICS OF *RABI* GROUNDNUT (*ARACHIS HYPOGAEA* L.) AS INFLUENCED BY BALANCED IRRIGATION WATER AND PHOSPHORUS INPUTS IN SOUTHERN TELANGANA, INDIA

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ABSTRACT

A field experiment was conducted during *rabi* 2024-25 at the Regional Agricultural Research Station, Palem, Southern Telangana, to evaluate the combined influence of irrigation scheduling and phosphorus management on water productivity, soil fertility, economics and energetics of *rabi* groundnut (*Arachis hypogaea* L.). The experiment was laid out in a split-plot design with three irrigation schedules (IW: CPE ratios of 0.6, 0.8 and 1.0) as main plot treatments and five phosphorus management practices (30 kg P_2O_5 ha^{-1}, 40 kg P_2O_5 ha^{-1}, 30 kg P_2O_5 ha^{-1} + seed treatment with PSB @ 30 g kg^{-1} seed, 40 kg P_2O_5 ha^{-1} + seed treatment with PSB @ 30 g kg^{-1} seed and STCR-based P_2O_5 recommendation) as sub-plot treatments, replicated thrice. Post-harvest soil pH, EC, organic carbon, available nitrogen and potassium were not significantly affected by irrigation schedules or phosphorus levels, whereas soil available phosphorus increased significantly with higher phosphorus application, particularly with 40 kg P_2O_5 ha^{-1} + PSB. The highest water productivity was observed at IW: CPE ratio of 0.6, while IW: CPE ratio of 1.0 produced superior economic returns and energy outputs due to enhanced crop growth and yield. Overall, assured irrigation (IW: CPE ratio of 0.8-1.0) combined with 40 kg P_2O_5 ha^{-1} + PSB proved effective for achieving sustainable and profitable *rabi* groundnut production under Southern Telangana conditions.

Keywords **:** Groundnut, IW: CPE ratio, Phosphorus management, Water productivity, Economics, Energetics.

Introduction

Groundnut (*Arachis hypogaea* L.) is a major oilseed and legume crop cultivated extensively under irrigated conditions during *rabi* season in Southern Telangana. The crop has high economic importance owing to its oil, protein and fodder value (Veeranna *et al*., 2022). However, increasing pressure on irrigation water resources and low phosphorus use efficiency in Indian soils pose major challenges to sustainable groundnut production.

Irrigation scheduling using climatological approaches such as the IW: CPE ratio helps in optimizing water application by synchronizing crop water requirement with atmospheric evaporative demand (Doorenbos and Pruitt, 1977). Excess irrigation leads to inefficient water use, nutrient losses and poor soil aeration, while deficit irrigation induces moisture stress during critical growth stages such as flowering, pegging and pod development ultimately reducing yield (Behera *et al*., 2015; Soni and Raja, 2017). Phosphorus, the second most important macronutrient after nitrogen, plays a crucial role in energy transfer, root development and biological nitrogen fixation in groundnut. However, a major portion of applied phosphorus becomes unavailable due to fixation in soils (Subba Rao, 1988; Khan *et al*., 2010).

Although chemical phosphorus fertilizers are widely used, their efficiency is low due to fixation in soil, leading to poor phosphorus use efficiency and environmental concerns (Whitelaw, 2000; Mahdi *et al*., 2010). Phosphate solubilising bacteria (PSB), a group of plant growth-promoting rhizobacteria, enhance phosphorus availability by solubilizing fixed phosphates through organic acid production and enzymatic activity (Alam *et al*., 2002; Antoun and Kloepper, 2001).

Integration of chemical phosphorus fertilizers with biological inputs such as phosphate solubilizing bacteria (PSB) has been reported to enhance phosphorus availability, nutrient uptake and soil fertility by solubilizing fixed forms of phosphorus (Rodriguez and Fraga, 1999; Whitelaw, 2000). PSB improves phosphorus use efficiency and reduce the dependence on chemical fertilizers, thereby supporting sustainable crop production systems (Gyaneshwar *et al*., 2002; Jilani *et al*., 2007). Therefore, sustainable groundnut production requires a balanced approach that optimizes both irrigation water and phosphorus inputs. In this context, the present study was undertaken to evaluate irrigation-phosphorus combinations for sustainable *rabi* groundnut production in Southern Telangana.

Materials and Methods

A field experiment was conducted during the *rabi* season of 2024-25 at the Regional Agricultural Research Station, Palem, located in the Southern Telangana Zone, to evaluate the effect of irrigation schedules and phosphorus levels on soil nutrient status, water productivity, economics and the energetics of groundnut (*Arachis hypogaea* L.). The experimental site is situated at an altitude of 478 m above mean sea level, at 16°30′49.98″ N latitude and 78°15′06.60″ E longitude. A uniform recommended dose of 40 kg N ha^{-1} through urea and 50 kg K_2O ha^{-1} through muriate of potash was applied to all treatments, while phosphorus (P_2O_5) was applied as per treatment specifications. Gypsum was applied at 500 kg ha^{-1} at the pegging initiation stage. Seeds were treated with phosphate solubilizing bacteria (PSB) at 30 g kg^{-1} seed using 5% jaggery solution as an adhesive, shade-dried and sown immediately thereafter as per the treatments. The groundnut variety K-6 was used, with a spacing of 22.5 cm × 10 cm.

The experiment was laid out in a split-plot design with three irrigation schedules as main plots: I_1- IW: CPE ratio of 0.6, I_2- IW: CPE ratio of 0.8 and I_3- IW: CPE ratio of 1.0 and five phosphorus treatments as sub-plots: P_1- 30 kg P_2O_5 ha^{-1}, P_2- 40 kg P_2O_5 ha^{-1}, P_3- 30 kg P_2O_5 ha^{-1} + PSB seed treatment @ 30 g kg^{-1} seed, P_4- 40 kg P_2O_5 ha^{-1} + PSB seed treatment @ 30 g kg^{-1} seed and P_5-STCR based P_2O_5 recommendation. Thus, a total of fifteen treatment combinations were tested with three replications.

Data on water productivity, soil fertility, economics and energetics were recorded using standard procedures. Total irrigation water applied was measured and used to compute water productivity as the ratio of pod yield to total water applied. Post-harvest soil samples were collected and analyzed for pH, EC, organic carbon and available N, P and K. Economic indicators such as cost of cultivation, gross returns, net returns and benefit-cost ratio were calculated based on prevailing market prices. Energetic parameters, including energy input, gross energy output and net energy output were estimated using standard energy coefficients. The experimental data were statistically analyzed using analysis of variance (ANOVA) appropriate for a split-plot design following the procedures outlined by Panse and Sukhatme (1985) and Gomez and Gomez (1984). Treatment means were compared at the 5% level of significance (P = 0.05), and critical difference (CD) values were calculated for parameters showing significant F-test results.

Results and Discussion

Effect of irrigation schedules and phosphorus levels on post-harvest available soil nutrient status

pH, EC (dS m^{-1}) and OC (%)

The post-harvest soil physico-chemical properties namely soil pH, electrical conductivity (EC), and organic carbon (OC, %), are presented in Table 1. Statistical analysis revealed that these parameters were not significantly influenced by irrigation schedules, phosphorus levels or their interaction effects. Soil reaction after harvest remained nearly neutral, with pH values ranging from 7.37 to 7.48 indicating that the imposed treatments did not appreciably alter soil reaction, possibly due to the buffering capacity of the soil and the moderate rates of phosphorus application. The EC values varied narrowly from 0.15 to 0.17 dS m^{-1}, which are well within the safe limits for crop growth, suggesting the absence of soluble salt accumulation and confirming that the irrigation and nutrient management practices were environmentally safe. Similarly, soil organic carbon content showed only marginal variation ranging from 0.30 to 0.32% and remained unaffected by the treatments likely due to the short duration of the experiment and lack of organic amendments. Overall, the results indicate that the irrigation and phosphorus management practices adopted in the present study did not adversely affect soil physico-chemical properties under *rabi* groundnut cultivation.

Available soil nitrogen (kg ha^{-1})

The post-harvest available nitrogen content of the soil is presented in Table 2. Statistical analysis indicated that the available nitrogen status of the soil was not significantly influenced by different irrigation schedules, phosphorus levels or their interaction effects. The available nitrogen values after harvest ranged from 149.2 to 170.2 kg ha^{-1} across the treatments. The absence of significant variation among treatments suggests that nitrogen dynamics in the soil were largely governed by native soil fertility and crop uptake rather than the imposed irrigation and phosphorus management practices. Moreover, groundnut being a leguminous crop with symbiotic nitrogen fixation might have contributed to maintain a relatively uniform nitrogen status in the soil after harvest.

Available soil phosphorus (kg ha^{-1})

The results pertaining to post-harvest available soil phosphorus are presented in Table 2. The data revealed that available phosphorus was significantly influenced by different phosphorus levels whereas irrigation schedules and the interaction between irrigation and phosphorus levels did not exert a significant effect.

Among the phosphorus treatments, application of 40 kg P_2O_5 ha^{-1} + PSB recorded the highest post-harvest available phosphorus content (64.3 kg ha^{-1}). This treatment was significantly superior than 30 kg P_2O_5 ha^{-1} (59.7 kg ha^{-1}) and 30 kg P_2O_5 ha^{-1} + PSB (60.7 kg ha^{-1}), while being statistically on par with 40 kg P_2O_5 ha^{-1} alone (63.8 kg ha^{-1}) and the STCR-based recommendation (62.4 kg ha^{-1}).

The increased availability of soil phosphorus under the 40 kg P_2O_5 ha^{-1} + PSB treatment can be attributed to the synergistic effect of a higher phosphorus dose combined with PSB inoculation. Phosphate solubilizing bacteria are known to enhance phosphorus availability by solubilizing native and applied phosphorus through the production of organic acids, reducing phosphorus fixation and improving its mobility in the rhizosphere. These findings are in agreement with the results reported by Ramesh (2022), who also observed improved soil available phosphorus with integrated phosphorus and PSB application.

Available soil potassium (kg ha^{-1})

The post-harvest available potassium content of the soil is presented in Table 2. The results indicated that available potassium was not significantly affected by irrigation schedules, phosphorus levels or their interaction effects. The available potassium values ranged from 389.7 to 416.1 kg ha^{-1} across different treatments. The non-significant variation in potassium status may be attributed to the inherently high potassium content of the soil and the relatively lower removal of potassium by the groundnut crop during the cropping season. Similar trends have been reported in earlier studies of Tandon, 1995 where short-term irrigation and fertilizer management practices did not cause marked changes in soil available potassium.

Water applied (mm)

The quantity of irrigation water applied varied markedly among the irrigation schedules (Table 3). The IW: CPE ratio of 1.0 received the highest amount of water (761.5 mm), followed by IW: CPE ratio of 0.8 (624.7 mm), while the IW: CPE ratio of 0.6 recorded the lowest water application (481.6 mm). As no effective rainfall occurred during the cropping period, the total water applied was entirely through irrigation in all treatments. Although IW: CPE ratio of 1.0 supplied more water, it did not necessarily result in proportionate yield gains due to possible losses through deep percolation and nutrient leaching. In contrast, IW: CPE ratio of 0.8 conserved irrigation water by reducing irrigation frequency without adversely affecting crop performance. These observations are in agreement with Behera *et al*. (2015). Across phosphorus levels, the total water applied remained uniform (622.6 mm), as irrigation schedules alone governed water application. Therefore, differences in crop performance among phosphorus treatments were attributed to phosphorus nutrition and PSB inoculation rather than variations in water supply.

Water productivity (kg ha^{-1} mm^{-1})

Water productivity data presented in Table 3 indicated that irrigation schedules and phosphorus levels significantly influenced water productivity, while their interaction effect was non-significant. Among irrigation schedules, the IW: CPE ratio of 0.6 recorded the highest water productivity (4.56 kg ha^{-1} mm^{-1}), which was significantly superior to IW: CPE ratios of 0.8 (3.67 kg ha^{-1} mm^{-1}) and 1.0 (3.25 kg ha^{-1} mm^{-1}). This clearly suggests that moderate irrigation scheduling improved water-use efficiency by minimizing excess water application and associated losses. In contrast, frequent irrigation at IW: CPE ratio of 1.0 resulted in reduced water productivity due to inefficient water utilization and possible nutrient leaching. Similar trends were reported by Balasubramanian *et al*. (2020).

Across phosphorus treatments, application of 40 kg P_2O_5 ha^{-1} + PSB achieved the highest water productivity (4.36 kg ha^{-1} mm^{-1}), which was significantly higher than lower phosphorus levels and the STCR-based recommendation, while remaining comparable with 40 kg P_2O_5 ha^{-1} alone (3.96 kg ha^{-1} mm^{-1}). The enhanced water productivity under integrated phosphorus and PSB application can be attributed to improved root growth, increased nutrient availability and better moisture utilization efficiency. These results are in agreement with the findings of Dutta and Mondal (2006).

Economics (Rs. ha^{-1})

The economics of groundnut cultivation indicated that the cost of cultivation varied only marginally among irrigation schedules and phosphorus levels (Table 4). Higher IW: CPE ratios incurred slightly higher costs due to increased irrigation frequency, while treatments involving PSB had a marginally higher cost because of seed inoculation expenses. Among irrigation schedules, IW: CPE ratio of 1.0 resulted in the highest gross returns (Rs. 1,79,515 ha^{-1}) and net returns (Rs. 96,838 ha^{-1}) as well as a slightly superior B:C ratio (2.17), owing to better crop growth and higher pod yield under assured moisture conditions. However, returns under IW: CPE ratios of 0.6 and 0.8 were largely comparable.

With respect to phosphorus management, the application of 40 kg P_2O_5 ha^{-1} + PSB proved to be most economically viable treatment, recording the highest gross returns (Rs. 1,90,519 ha^{-1}), net returns (Rs. 1,09,785 ha^{-1}) and B:C ratio (2.36). This was attributed to enhanced phosphorus availability and improved yield performance, which offset the marginal increase in input cost. Overall, integrated phosphorus fertilization with PSB and adequate irrigation scheduling emerged as the most profitable practice for *rabi* groundnut cultivation.

Energetics (GJ ha^{-1})

Energy input did not vary appreciably among irrigation schedules and phosphorus levels, indicating that the imposed treatments had only a marginal effect on total energy consumption (Table 5). In contrast, gross and net energy outputs were significantly influenced by irrigation schedules and phosphorus levels, while their interaction effects remained non-significant. Irrigation scheduled at IW: CPE ratio of 1.0 resulted in the highest gross energy outputs (127.2 GJ ha^{-1}) and net energy outputs (107.7 GJ ha^{-1}), which can be attributed to assured moisture availability, improved crop growth and enhanced biomass and pod yield.

Among phosphorus treatments, the application of 40 kg P_2O_5 ha^{-1} in combination with PSB recorded the maximum gross energy outputs (132.9 GJ ha^{-1}) and net energy outputs (113.4 GJ ha^{-1}), reflecting the synergistic effect of chemical phosphorus fertilization and microbial inoculation in improving nutrient availability, uptake efficiency and crop productivity. Overall, the results demonstrate that while energy inputs remain largely stable, optimizing irrigation scheduling and integrated phosphorus management significantly enhances energy output and energy-use efficiency in *rabi* groundnut cultivation.

Conclusion

It can be concluded that irrigation schedules and phosphorus levels did not adversely affect post-harvest soil properties, while soil available phosphorus improved significantly with higher phosphorus application, especially with PSB inoculation. Irrigation at IW: CPE ratio of 1.0 enhanced economic returns and energy outputs, whereas IW: CPE ratio of 0.6 achieved the highest water productivity through efficient water use. Among phosphorus treatments, 40 kg P_2O_5 ha^{-1} + PSB proved most effective in improving soil phosphorus availability, water productivity, profitability and energy efficiency. Overall, adopting optimum irrigation (IW: CPE ratio of 0.8-1.0) along with 40 kg P_2O_5 ha^{-1} + PSB is recommended for sustainable and profitable *rabi* groundnut cultivation.

Table 1: Physico-chemical properties of soil as influenced by different irrigation schedules and phosphorus levels in groundnut.

Treatments	pH	EC (dS m^{-1})	OC (%)
Main plot (I- Irrigation schedules)			
I_1 : IW: CPE of 0.6	7.41	0.16	0.32
I_2 : IW: CPE of 0.8	7.41	0.16	0.30
I_3 : IW: CPE of 1.0	7.43	0.15	0.31
S Em±	0	0	0
C.D(P=0.05)	NS	NS	NS
Subplot (P- Phosphorus levels)			
P_1 : 30 kg P_2O_5 ha^{-1}	7.42	0.16	0.31
P_2 : 40 kg P_2O_5 ha^{-1}	7.37	0.15	0.30
P_3 : 30 kg P_2O_5 ha^{-1} + Seed treatment with PSB @ 30g kg^{-1} seed	7.43	0.16	0.32
P_4 : 40 kg P_2O_5 ha^{-1} + Seed treatment with PSB @ 30g kg^{-1} seed	7.38	0.16	0.31
P_5 : STCR based P_2O_5 Recommendation	7.48	0.16	0.31
S Em±	0.1	0	0
C.D(P=0.05)	NS	NS	NS

Interaction			
Effect of phosphorus levels with same level of irrigation schedules			
S Em±	0.20	0.20	0.20
C.D(P=0.05)	NS	NS	NS
Effect of phosphorus levels with different irrigation schedules			
S Em±	0.20	0.20	0.20
C.D(P=0.05)	NS	NS	NS
Initial values	7.40	0.16	0.31

Table 2: Post harvest available soil N, P_2O_5 and K_2O (kg ha^{-1}) as influenced by different irrigation schedules and phosphorus levels in groundnut.

Treatments	**Available N**	**Available P_2O_5**	**Available K_2O**
Main plot (I- Irrigation schedules)			
I_1 : IW: CPE of 0.6	162.4	61.5	404.7
I_2 : IW: CPE of 0.8	160.2	62.5	402.6
I_3 : IW: CPE of 1.0	157.8	62.5	410.3
S Em±	2.4	0.6	5.9
C.D(P=0.05)	NS	NS	NS
Subplot (P- Phosphorus levels)			
P_1 : 30 kg P_2O_5 ha^{-1}	156.1	59.7	401.7
P_2 : 40 kg P_2O_5 ha^{-1}	167.4	63.8	408.6
P_3 : 30 kg P_2O_5 ha^{-1} + Seed treatment with PSB@30g kg^{-1} seed	149.2	60.7	413.4
P_4 : 40 kg P_2O_5 ha^{-1} + Seed treatment with PSB@30g kg^{-1} seed	170.2	64.3	416.1
P_5 : STCR based P_2O_5 Recommendation	157.7	62.4	389.7
S Em±	8.5	0.9	6.4
C.D(P=0.05)	NS	2.6	NS
Interaction			
Effect of phosphorus levels with same level of irrigation schedules			
S Em±	0.2	0.2	0.2
C.D(P=0.05)	NS	NS	NS
Effect of phosphorus levels with different irrigation schedules			
S Em±	0.2	0.2	0.2
C.D(P=0.05)	NS	NS	NS
Initial values	147.5	48.5	392.5

Table 3: Water applied, Effective rainfall, Total water and Water productivity of groundnut as influenced by different irrigation schedules and phosphorus levels.

Treatments	**Water applied (mm)**	**Effective rainfall (mm)**	**Total water (mm)**	**Water productivity (kg ha^{-1} mm^{-1})**
Main plot (I- Irrigation schedules)				
I_1 : IW: CPE of 0.6	481.6	0	481.6	4.56
I_2 : IW: CPE of 0.8	624.7	0	624.7	3.67
I_3 : IW: CPE of 1.0	761.5	0	761.5	3.25
S Em±	-	-	-	0.1
C.D(P=0.05)	-	-	-	0.3
Subplot (I- Phosphorus levels)				
P_1 : 30 kg P_2O_5 ha^{-1}	622.6	0	622.6	3.45
P_2 : 40 kg P_2O_5 ha^{-1}	622.6	0	622.6	3.96
P_3: 30 kg P_2O_5 ha^{-1} + Seed treatment with PSB @ 30g kg^{-1} seed	622.6	0	622.6	3.77
P_4: 40 kg P_2O_5 ha^{-1} + Seed treatment with PSB @ 30g kg^{-1} seed	622.6	0	622.6	4.36
P_5: STCR based P_2O_5 Recommendation	622.6	0	622.6	3.59
S Em±	-	-	-	0.2
C.D(P=0.05)	-	-	-	0.5
Interaction				
Effect of phosphorus levels with same level of irrigation schedules				
S Em±	-	-	-	0.2
C.D(P=0.05)	-	-	-	NS
Effect of phosphorus levels with different irrigation schedules				
S Em±	-	-	-	0.2
C.D(P=0.05)	-	-	-	NS

Table 4: Cost of cultivation, Gross & Net returns (Rs. ha^{-1}) and B:C ratio of groundnut as influenced by different irrigation schedules and Phosphorus levels.

Treatments	**Cost of Cultivation (Rs. ha^{-1})**	**Gross returns (Rs.ha^{-1})**	**Net returns (Rs. ha^{-1})**	**B:C ratio**
Main plot (I- Irrigation schedules)				
I_1 : IW: CPE of 0.6	76879	159294	82415	2.07
I_2 : IW: CPE of 0.8	79810	166433	86622	2.08
I_3 : IW: CPE of 1.0	82678	179515	96838	2.17
Subplot (P- Phosphorus levels)				
P_1 : 30 kg P_2O_5 ha^{-1}	79210	151355	72144	1.91
P_2 : 40 kg P_2O_5 ha^{-1}	79992	174135	94143	2.18
P_3 : 30 kg P_2O_5 ha^{-1} + Seed treatment with PSB @ 30g kg^{-1} seed	79934	166891	86957	2.08
P_4 : 40 kg P_2O_5 ha^{-1} + Seed treatment with PSB @ 30g kg^{-1} seed	80733	190519	109785	2.36
P_5 : STCR based P_2O_5 Recommendation	79077	159171	80094	2.01

Table 5: Energetics (GJ ha^{-1}) of groundnut as influenced by different irrigation schedules and phosphorus level.

Treatments	**Energy input (GJ ha^{-1})**	**Gross energy output (GJ ha^{-1})**	**Net energy output (GJ ha^{-1})**
Main plot (I- Irrigation schedules)			
I_1 : IW: CPE of 0.6	19.45	115.7	96.2
I_2 : IW: CPE of 0.8	19.51	120.1	100.5
I_3 : IW: CPE of 1.0	19.6	127.2	107.7
S Em±	-	0.7	0.7
C.D(P=0.05)	-	2.6	2.6
Subplot (P- Phosphorus levels)			
P_1 : 30 kg P_2O_5 ha^{-1}	19.49	112.2	92.7
P_2 : 40 kg P_2O_5 ha^{-1}	19.54	125.3	105.8
P_3 : 30 kg P_2O_5 ha^{-1} + Seed treatment with PSB @ 30g kg^{-1} seed	19.45	119.0	99.5
P_4 : 40 kg P_2O_5 ha^{-1} + Seed treatment with PSB @ 30g kg^{-1} seed	19.52	132.9	113.4

P_5 : STCR based P_2O_5 Recommendation	19.58	115.5	95.9
S Em±	-	3.2	3.2
C.D(P=0.05)	-	9.3	9.3
Interaction			
Effect of phosphorus levels with same level of irrigation schedules			
S Em±	**-**	**0.2**	**0.2**
C.D(P=0.05)	**-**	**NS**	**NS**
Effect of phosphorus levels with different irrigation schedules			
S Em±	**-**	**0.2**	**0.2**
C.D(P=0.05)	**-**	**NS**	**NS**

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