Journal of Soil Salinity and Water Quality 17(1), 44-50, 2025
DOI: https://doi.org/10.56093/jsswq.v17i1.160811

Phosphorus Dynamics under Saline Water Irrigation and Phosphorus Fertilization in Cowpea

Pooja Devi Jat[1], Chiranjeev Kumawat[1*], KK Sharma[1], SK Dadhich[1], Arvind Kumawat[2], Rajhans Verma[1] and Manish Yadav[3]

[1]*Department of Soil Science and Agricultural Chemistry, Sri Karan Narendra Agriculture University, Jobner-303 329, Rajasthan, India*
[2]*College of Dairy Science & Technology, Sri Karan Narendra Agriculture University, Jobner-303 329, Rajasthan, India*
[3]*ICAR-Central Soil Salinity Research Institute, Karnal-132 001, Haryana, India*
**Corresponding author's E-mail: chiranjeev.soils@sknau.ac.in*

Abstract

Soil salinity is one of the major problems in arid and semi-arid areas around the world. Salinity results in soil and water degradation. Cowpea is very sensitive to salinity and sodicity as compared to cereals and oilseed crops. Salinity reduced germination percentage and germination index. In saline soils, availability of phosphorus is low due to immobilization of applied P, fixation of P by Ca. The requirement of phosphorus for pulses is more important than nitrogen and potassium but the availability of phosphorus is low in Rajasthan. The experiment consisted of twelve treatment combinations including three levels of saline irrigation water [normal (1.26) and 6 dS m^{-1} keeping Cl^-: SO_4^{2-} ratio in 3:1 and 1:3] and four levels of phosphorus application (0, 10, 20 and 30 mg kg^{-1}). The experiment was conducted in pots and carried out in completely randomized design (CRD) with three replications. Phosphorus transformation in soil, yield attributes and yield of the crop were observed significantly higher with normal (1.26 dS m^{-1}) irrigation water and 30 mg kg^{-1} phosphorus application in soil. The result indicated that irrigation with normal (1.26 dS m^{-1}) water and 30 mg kg^{-1} phosphorus application in soil to the cowpea crop significantly increased the different forms of soil phosphorus *viz.,* Al-P, Fe-P, saloid-P, organic-P and total-P, effective number of nodules per plant, nodule index, fresh and dry weight of nodules, plant height, pods per plant, seeds per pod, seed index, seed and straw yield.

Key words: Cowpea, Saline water irrigation, Nodules, Phosphorus transformation

Introduction

One of the most significant pulse crops is the cowpea [*Vigna unguiculata* (L.)]. It may thrive in regions with little rainfall and is drought-tolerant. Cowpea grain's nutritional value includes 23.4% protein, 55-66% carbohydrates, 0.08-0.11% fiber, 3.9% fat, 1.2% calcium, 0.005% iron, and numerous essential amino acids, including phenylalanine, lysine, and leucine. The vegetable cowpea pod is composed of 0.1% fat, 8.0% carbohydrates, 4.1% protein, and 84.4% moisture. Because of the shade effect of their broad, drooping leaves, cowpeas are known to be drought-hardy by nature. A cowpea crop can add 30-80 kg of nitrogen per hectare to the soil (Silva *et al.,* 2025). An estimated 23.40 million tons of pulse crops are produced annually on 29.03 million hectares of land in India, with a yield of 806 kg ha^{-1} (Singh *et al.,* 2023). The total area planted to pulses in Rajasthan is 6.018 million ha, with an average yield of 636 kg ha^{-1} and an annual production of 4.49 million tons with a yield of 3.2 thousand tones and an average productivity of 658 kg ha^{-1}, cowpeas occupy 50 thousand hectares of land (Puniya and Kumawat, 2024).

The main issue in arid and semi-arid regions of the world is salinity. Degradation of soil and water, biodiversity loss, climate change, low farm income, increased rural poverty, and a drop in the yield of many agricultural products are all consequences of salinity (Gebremeskel *et al.,* 2018). Compared to cereals and oilseed crops, pulses are extremely vulnerable to salt and sodicity. In sorghum, salinity decreased the following: seedling fresh weight, seedling dry weight, seedling vigour index, seedling shoot length, seedling root length, germination index, and germination % (Dehnavi *et al.,* 2020). The extent of salt-affected soil in India is 6.73 million hectares, and it is growing daily. 0.38 million ha land of Rajasthan are degraded by salts (Narayanan and Chellappan, 2024). Cations like Ca^{2+} and Mg^{2+} and anions like Cl^-, SO_4^{2-}, carbonate, and bicarbonate are the primary substances that contribute to salinity. The physical, chemical, and biological characteristics of soil are weakened by these salts, which eventually affect crop production and growth. By reducing nutrient uptake and altering the physical, chemical, and biological characteristics of the soil, the ongoing use of saline irrigation water has a negative impact on soil fertility (Ding *et al.,* 2020). Due to ionic imbalance, toxicity of certain ions, and inadequate food availability, salinity causes osmotic stress in plants, which lowers crop output (Lata *et al.*, 2017).

Phosphorus availability is limited in saline soils because to immobilization of applied P, fixation of P by Ca, slow diffusion of P, and antagonism caused by excess chloride and sulphate. High concentrations of Cl^- in saline soils may negatively impact phosphorus intake because phosphorus and Cl^- are taken via the same mechanism (Germano *et al.,* 2022). Consequently, in saline conditions, P content and absorption are often low. Although phosphorus is more crucial for pulses than nitrogen and potassium, Indian soils have limited phosphorus availability. Only 15% to 30% of the phosphorus that is sprayed is used by plants; the remainder is transformed into an insoluble form. As a component of ADP, ATP, DNA, RNA, phosphate enzyme, nucleotides, phospholipids, and phosphorylated sugars, P is needed for the growth of *Rhizobium* bacterium, which is in charge of biological nitrogen fixation. Applying phosphorus to legumes not only benefits the current crop but also has a positive impact on the next non-legume crop. Additionally, phosphorus is crucial in protein synthesis, nucleic acid, amino acids, phytin, and other substances (Bawa, 2020). Keeping all these facts in the mind the present study was carried out to quantify the performance of cowpea and phosphorous transformation in soil under saline irrigation and applied fertilizer phosphorus.

Materials and Methods

During the 2020-21 *kharif* season, the pot experiment was carried out at the cage house of the Department of Plant Physiology at S.K.N. College of Agriculture, Jobner (Raj.). Geographically, Jobner is located in the Jaipur district of Rajasthan at 26°5' North latitude and 75°28' East longitude. It is 427 meters above mean sea level. This area of Rajasthan is located in the semi-arid eastern plain zone, or agroclimatic zone III-A. With 1.81 g kg^{-1} soil organic carbon and 128.72, 15.23, and 145.75 kg ha^{-1} of accessible N, P, and K, respectively, the soil had a sandy loam texture with an alkaline response (pH 7.90). Twelve treatment combinations were used in the experiment, which included four levels of phosphorus administration (0, 10, 20, and 30 mg kg^{-1}) and three levels of saline irrigation water [normal (1.26) and 6 dS m^{-1} maintaining Cl^-: SO_4^{2-} ratio in 3:1 and 1:3]. Three replications and a completely randomized design were used for the experiment, which was carried out in pots. Cylindrical ceramic pots (20 cm in diameter and 28 cm in height) were filled with soil. 10 kilograms of soil were in each pot. Broken stone fragments were positioned over the bottom hole when the pots were being filled to allow for unrestricted drainage.

To test the impact of rainfall, every pot was kept in the covered cage house. The required Cl^- and SO_4^{2-} of Na^+, Ca^{2+}, and Mg^{2+} were added in a 3:1 solution ratio to reach the EC level of 6 dS m^{-1} (Table 1). The number of elements (cations

Table 1. Ionic composition of saline waster used for irrigation

EC (dS m^{-1})	Na^+ Meq L^{-1}	Ca^{2+} Meq L^{-1}	Mg^{2+} Meq L^{-1}	Cl^- Meq L^{-1}	SO_4^{2-} Meq L^{-1}	Final EC (dS m^{-1})
1.26 (Normal)	9.43	1.0	1.2	2.2	6.0	1.26
6 (Cl^- : SO_4^{2-}, 3:1)	25.5	11.1	11.1	38.4	12.8	6.12
6 (Cl^- : SO_4^{2-}, 1:3)	21.8	11.1	11.1	12.8	38.4	6.00

and anions) were measured in water to determine the development of salinity. Before planting, soil was treated by adding 0, 10, 20, and 30 mg kg^{-1} of phosphorus using a single super phosphate. A phosphorus fractionation scheme developed by Chang and Jackson (1958), refined by Peterson and Corey (1966) was used to identify the different forms of phosphorus, including Ca-P, Al-P, Fe-P, and saloid-P.

Total organic phosphorus was calculated by subtracting the sum of all inorganic phosphorus from total phosphorus, and total P was recovered using the perchloric acid digestion procedure. At 40 days, the number of nodules and their effective number per plant were counted during the flowering stage. Five plants were chosen at random. The effective number of nodules per plant was determined by counting the number of healthy, pink nodules and recording the mean value. An electronic scale was used to weigh the effective root nodules, and the average was calculated and recorded as the fresh weight of effective root nodules $plant^{-1}$. The nodules were subsequently dried in an oven at 70°C until their weight remained constant, and the average was calculated. A formula was used to calculate the nodule index, or the number of nodules per centimeter of taproot (Sandhu *et al.,* 1992).

$$\text{Nodule index} = \frac{\text{Number of nodules plant}^{-1}}{\text{Length of tap root (cm)}}$$

The data of growth, yield and P dynamics were analyzed with analysis of variance of completely randomized design. The treatment means of different parameters were compared using least significant difference at 5% level of significance ($P<0.05$).

Results and Discussion

Effect of saline water irrigation on soil phosphorus dynamics

The data pertaining to the effect of chloride and sulphate dominated saline irrigation water and phosphorus application on different forms of soil P (Ca-P, Al-P, Fe-P, saloid-P, organic-P and total-P) have been summarized in Table 2. Significantly maximum Ca-P (87.31 mg kg^{-1} soil) was found in Cl^- dominated saline irrigation water as compared to SO_4^{2-} dominated saline irrigation water. Al-P, Fe-P, saloid-P, organic-P and total-P (30.58, 27.65, 7.69, 68.08 and 212.15 mg kg^{-1} soil, respectively) were obtained in C_0 and minimum in C_1. Al-P, Fe-P, saloid-P, organic-P and total-P except Ca-P decreased significantly with increasing levels of EC of irrigation water and the decrease was more in Cl^- dominated salinity as compared to SO_4^{2-} salinity but Ca-P increase was more in C_1 (3:1) as compared to C_2 (1:3).

The relative proportion of different forms of inorganic phosphorus depends on a number of soil characteristics, including pH, organic carbon,

Table 2. Effect of saline water irrigation and phosphorus levels on soil P dynamics (mg kg^{-1} soil)

Treatments	Ca-P	Al-P	Fe-P	Saloid-P	Organic-P	Total-P
			Salinity of irrigation water (dS m^{-1})			
C_0-1.26 (Normal)	78.1	30.5	27.6	7.69	68.0	212.1
C_1-6 (3:1)*	87.3	18.4	19.3	4.93	47.9	177.9
C_2-6 (1:3)*	81.3	23.4	22.4	5.84	54.5	187.6
SEm±	2.06	0.64	0.60	0.17	1.46	4.89
LSD (p=0.05)	5.94	1.84	1.74	0.48	4.22	14.12
			Phosphorus levels (mg P kg^{-1} soil)			
P_0 (Control)	70.7	19.3	18.4	4.50	48.6	161.7
P_{10}	79.5	21.4	22.0	5.10	52.2	180.4
P_{20}	85.3	24.3	23.8	6.48	57.0	197.0
P_{30}	93.3	31.5	28.2	8.52	69.4	231.0
SEm±	2.38	0.73	0.69	0.19	1.69	5.65
LSD (p=0.05)	6.86	2.12	2.00	0.56	4.88	16.31

*(Cl^- : SO_4^{2-})

$CaCO_3$, CEC, and texture (Devra *et al.,* 2014). Increasing the amount of $CaCO_3$ in soil significantly decreased the amount of saloid-P and Fe-P forms, while increasing Ca-P due to the solubilization of $CaCO_3$. Nasrin *et al.* (2016), Singh *et al*. (2016) and Sarker *et al*. (2025) also found that Ca-P was the most prevalent form of P fixation in soil, while saloid-P was less prevalent.

Effect of phosphorus levels on soil phosphorus dynamics

Significantly maximum Ca-P, Al-P, Fe-P, saloid-P, organic-P and total-P (93.33, 31.56, 28.25, 8.52, 69.42 and 231.08 mg kg^{-1} soil, respectively) were observed with application of 30 mg P kg^{-1} and minimum in control (Table 2). The presence of $CaCO_3$ enhances the formation of Ca-bound phosphorus (Ca-P), which occurs due to the reaction between phosphate ions and calcium ions released from the solubilization of $CaCO_3$. This results in the precipitation of relatively less soluble calcium phosphates, such as dicalcium phosphate (DCP), octacalcium phosphate (OCP), and hydroxyapatite, which are dominant in calcareous soils. Research findings by Nasrin *et al.* (2016) and Singh *et al.* (2016) supported this observation, indicating that Ca-P is the most prevalent form of phosphorus fixation in calcareous and alkaline soils, whereas the proportion of saloid-P is relatively lower. This suggests that phosphorus availability in such soils is largely controlled by calcium interactions rather than iron or aluminum complexes, which are more common in acidic soils. The findings proved that among all forms of P, the Ca-P fraction showed the highest accumulation, while the saloid-P in all fertilizer-treated pots showed the lowest value.

When phosphorus fertilizers are applied to the soil, a portion remains in the soluble form, which is immediately available to plants, while the rest undergoes chemical transformations and gets converted into less available forms, such as iron (Fe)-bound P, aluminum (Al)-bound P, calcium (Ca)-bound P, or occluded P, depending on the soil conditions. For instance, in acidic soils, phosphorus tends to react with iron and aluminum oxides, leading to the formation of Fe-P and Al-P complexes that reduce phosphorus availability. Conversely, in calcareous soils with high pH, phosphorus is more likely to precipitate as calcium phosphates, which can limit its solubility and plant accessibility. The application of different levels of phosphorus affects the equilibrium among these forms. Higher phosphorus application rates generally lead to an increase in the labile (readily available) phosphorus pool, as well as a gradual accumulation of phosphorus in less soluble fractions over time. Continuous phosphorus addition may enhance the buildup of residual and occluded phosphorus, which can contribute to long-term phosphorus availability in the soil. Additionally, phosphorus dynamics are influenced by microbial activity and organic matter content. Soil microbes play a crucial role in phosphorus mineralization, converting organic phosphorus into inorganic forms that can be utilized by plants. Organic matter also helps in phosphorus retention and prevents excessive fixation by soil minerals, thereby improving phosphorus use efficiency. Kratz *et al.* (2019) noted that, in accordance with the solubility product principle, Ca-P and Al-P are the immediate products shortly after the application of phosphorus fertilizer because of the relatively higher activities of Ca-P and Al-P in soil. These findings are in close conformity with those of Devra *et al.* (2014), Sudhakaran *et al.* (2018), Kumawat *et al.* (2022) and Mahmood *et al.* (2025).

Effect of saline water irrigation on growth and yield attributes

Saline water irrigation significantly affects the growth, physiological processes, and yield attributes. Significantly maximum total number of nodules per plant, effective nodules per plant, nodule index, fresh weight (g), dry weight (g), plant height (cm), number of pods per plant and number of seeds per pod (28.34, 23.26, 2.58, 204.48, 51.53, 71.70, 13.42 and 10.03, respectively) were observed irrigation with normal EC water (C_0) followed by SO_4^{2-}>Cl^- (C_2).

The lowest value of above parameters recorded under Cl^->SO_4^{2-} (C_1). This is might be due to the build-up of salinity with different saline irrigation water containing excessive Cl^- and SO_4^{2-} ions of Ca^{2+}, Mg^{2+} and Na^+ which adversely affects the plant growth results from high osmotic stress, low physiological availability of water and direct harmful effects of particular ions. Within plant

Table 3. Effect of saline water irrigation and phosphorus levels on nodulation

Treatments	Total nodules per plant	Effective nodules per plant	Nodule index	Fresh weight (g)	Dry weight (g)
		Salinity of irrigation water (dS m^{-1})			
C_0-1.26 (Normal)	28.3	23.2	2.58	204.4	51.5
C_1-6 (3:1)*	18.4	14.9	2.30	166.7	33.4
C_2-6 (1:3)*	20.3	16.7	2.44	169.1	36.1
SEm+	0.60	0.51	0.06	4.73	1.12
LSD (p=0.05)	1.73	1.47	0.18	13.66	3.23
		Phosphorus levels (mg P kg^{-1} soil)			
P_0 (Control)	18.9	12.9	2.22	146.6	29.5
P_{10}	21.0	16.7	2.41	176.7	37.0
P_{20}	22.7	19.6	2.54	193.6	44.1
P_{30}	26.7	24.0	2.59	203.4	50.8
SEm+	0.69	0.59	0.07	5.46	1.29
LSD (p=0.05)	1.99	1.70	0.21	15.78	3.73

*(Cl^- : SO_4^{2-})

cells and tissue, where salts compartmentalize in vacuoles and excess salt begins to degrade enzymatically, salt stress results in ion toxicity (Arif *et al.,* 2022). Early stage of the plant during the osmotic stress might delay leaf emergence, leaf expansion and promote leaf senescence before the major buildup of harmful ions (Rajendran *et al.,* 2009; Tavakkoli *et al.,* 2010; Maryum *et al.,* 2022).

Effect of phosphorus levels on growth and yield attributes

Significantly maximum yield attributes (Table 3 and 4) total number of nodules per plant, effective nodules per plant, nodule index, fresh weight, dry weight, plant height, number of pods per plant and number of seeds per pod (26.76, 24.03, 2.59, 203.40, 50.80, 69.40, 13.09 and 10.65, respectively) were observed with application of 30 mg P kg^{-1} and minimum in control (P_0). By providing assimilates to the roots, phosphorus enhances nodule formation and biological N_2 fixation in addition to being crucial for root growth and development. It is the primary constituent of the co-enzymes ATP and ADP, which function as plants' "energy currency." Phosphorus plays a crucial role in plant physiology, influencing the synthesis of nucleic acids, proteins, and phospholipids, as well as enhancing photosynthetic activity. It is a key component in energy transfer processes, such as ATP synthesis, which is vital for plant growth and metabolic functions. Studies by Ayodele *et al.* (2014) and Verma *et al.* (2015) have also reported a significant increase in nodulation in cowpea with phosphorus application. This suggests that phosphorus availability not only supports overall plant growth but also enhances symbiotic nitrogen fixation, thereby improving legume productivity in phosphorus-deficient soils (Zhang *et al.*, 2025).

Effect of saline water irrigation and phosphorus levels on yield

The seed yield, straw yield and seed index of cowpea (6.41, 8.65 and 79.93, respectively) were recorded significantly higher in C_0 and minimum in C_1 (Table 4).

The reduction in the number of pods per plant and the number of seeds per pod may also be due to the loss of naturally occurring hormones under saline conditions. Many studies concluded that cowpea yield and nutrient uptake are significantly affected by soil salinity and phosphorus levels. Lower salinity levels result in higher yields and nutrient uptake compared to higher salinity levels. These findings are consistent with research conducted by Khare *et al.* (2025) on mungbean, Jat (2011) on chickpea, and Patel (2010) on fenugreek. The application of 30 mg P kg^{-1} resulted in a significantly higher seed yield (g pot^{-1}), straw yield (g pot^{-1}), and seed index (g) (6.24, 8.27, and

Table 4. Effect of saline water irrigation and phosphorus levels on growth and yield of cowpea

Treatments	Plant height (cm)	Number of pods per plant	Number of seeds per pod	Seed yield (g pot^{-1})	Straw yield (g pot^{-1})	Seed index (g)
Salinity of irrigation water (dS m^{-1})						
C_0-1.26 (Normal)	71.7	13.42	10.0	6.41	8.65	29.9
C_1-6 (3:1)*	56.9	8.22	6.94	3.41	5.86	21.9
C_2-6 (1:3)*	58.1	9.42	8.72	3.95	6.03	22.7
SEm+	1.5	0.28	0.23	0.13	0.19	1.89
LSD (p=0.05)	4.53	0.81	0.67	0.37	0.55	5.43
Phosphorus levels (mg P kg^{-1} soil)						
P_0 (Control)	58.3	8.93	6.83	3.30	5.29	20.0
P_{10}	60.2	9.55	7.66	4.10	6.37	23.1
P_{20}	61.0	10.2	9.10	4.70	7.47	26.1
P_{30}	69.4	13.0	10.6	6.24	8.27	29.9
SEm+	1.81	0.32	0.27	0.15	0.22	2.18
LSD (p=0.05)	5.23	0.94	0.77	0.43	0.63	8.71

*(Cl^- : SO_4^{2-})

79.98, respectively), while the control group (P0) showed the lowest. The increase in seed yield following phosphorus application may be attributed to the concurrent rise in the number of pods per plant. This can be explained by the fact that seeds serve as the primary sink for assimilates, which are mobilized from senescing leaves. As a result, enhanced phosphorus availability supports better nutrient partitioning, ultimately leading to higher seed yield. These findings also reported by Khan *et al*. (2012) and Khare *et al.* (2025), who also observed a positive correlation between phosphorus application and improved pod formation and seed output under saline water irrigation conditions.

Conclusion

The phosphorus transformation, yield attributes and yield of cowpea reduced under Cl^- dominated saline water irrigation as compared to SO_4^{2-} dominated saline water irrigation. The application of 30 mg P kg^{-1} resulted in higher productivity of cowpea and phosphorus transformation in semi-arid regions of Rajasthan. Phosphorus requirement of the crop was higher under Cl^- dominated irrigation water salinity that could be fulfilled by the additional phosphorus fertilization. The future research should focus on phosphorus transformation under cereal based cropping systems.

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Received: November 25, 2024; Accepted: February 12, 2025