PLANT SCIENCE TODAY
Vol 12(sp3): 01–08
https://doi.org/10.14719/pst.8902

eISSN 2348-1900

RESEARCH ARTICLE

Performance of rice genotypes at different phosphorus levels on root morphological traits and plant enzyme activity through hydroponics based screening

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Received: 15 April 2025; Accepted: 17 June 2025; Available online: Version 1.0: 21 November 2025

Cite this article: Sanjivkumar V, Manikandan K, Balaji T, Vijayakumar M, Paramasivan M, Manikandan M, Baskar K, Bhakiyathu Saliha B . Performance of rice genotypes at different phosphorus levels on root morphological traits and plant enzyme activity through hydroponics based screening. Plant Science Today. 2025;12(sp3):01–08. https://doi.org/10.14719/pst.8902

Abstract

Soil phosphorus (P) deficiency has emerged as one of the major limiting factors in rice production. The development and deployment of tolerant cultivars are one of the plausible approaches to combat low P-tolerance in rice. Thus, the study was carried out to identify P-stress-tolerant rice genotypes through nutrient solution culture. Based on this preview, a hydroponics experiment was conducted at Radio Isotope laboratory, Tamil Nadu Agricultural University, Coimbatore. The treatment comprised of fertilizer levels viz. 0, 2.5 and 10 ppm P and seven rice genotypes viz. TNRH -18, ADT- 47, CB08509, CB08504, AD07038, ASD -16 and AS06016. This lab experiment was laid out in completely randomized block design (CRBD) with three replications. The results revealed that under different phosphorus levels the rice genotypes viz. TNRH-180 registered higher root volume (1.07 cm^3), root length (35.29 cm), total no. of roots per plant (33.53 nos.) and no. of lateral roots (15.02 nos.) and it was followed by CB08504. The plant enzymes viz. acid phosphatase activity was found to be superior in the rice genotype CB08509 under 0 ppm P level (4.41 µmol pNpp) at 30 days old seedlings. At higher P levels the plant enzyme activity was found to be lower. Regarding adenosine triphosphate enzyme, CB08504 and TNRH-180 registered higher activity in 30 & 60 days old seedlings. Farmers and breeders can prioritize these rice genotypes for cultivation in phosphorus deficient soil ecosystem. By utilizing phosphorus tolerant rice genotypes can reduce the amount of phosphorus fertilizer required, minimizing environmental impacts and reducing input costs.

Keywords: phosphorus levels; plant enzymes; rice genotypes; root architecture; yoshida nutrient solution

Introduction

Rice (*Oryza sativa* L.) is a principal calorific food crop for humankind, providing 21 % of the energy and 15 % of the protein requirements (1). Rice farming is the major livelihood for many people around the world. Hence, cost effective rice farming strategies are critical for maintaining considerable profit margins for growers and inexpensive market pricing for consumers. Rice production is confronted by several biotic and abiotic stresses, thereby reducing productivity which in turn reduces the income levels of the farmers. Besides, the high cost of cultivation also reduces the profit margin for farmers since a farmer must purchase all inputs in retail and sell the products wholesale. Insect pests, diseases and weeds mainly cause biotic stress while abiotic factors involve stress caused by drought, salinity, submergence, and nutrient deficiency. Among the various plant nutrients, phosphorus (P) is a key macro-nutrients indispensable for the optimum growth and development of many crops, including rice. Although P exists in the soil in sufficient quantity, it may not be available to plants, as the phosphate form of fertilizer P may bind to chemicals and/or organic matter in soil, reducing the P use efficiency. The unavailable form of P will be made available to plants only when bound inorganic phosphate is released by hydrolysis (2). A deficiency of P in rice results in stunted growth with narrow leaves and spindly stems with a significant reduction in the number of tillers, leaves, panicles, and grains per panicle. Additionally, it delays the flowering and maturity by one week to 20 days. In severe conditions, plants may not flower at all and even if they flower, many empty grains are formed with poor quality (3). Eventually, severe P deficiency leads to greater yield losses in rice (4). India mainly depends on the import of phosphatic fertilizers, which increases the burden on the country's revenue. Increased fertilizer costs and the gradual depletion of phosphate rock (a source of P fertilizer) have necessitated the development of plant varieties with improved tolerance to P deficiency.

The phosphorus deficiency is considered as one of the greatest limitations in the productivity of crops, mainly in the tropics and subtropics. About 30 % of the crop production in the world is

affected by lack of macronutrients in soil. Knowing that the use of fertilizers to correct the phosphorus concentration in the soil is expensive, the development of tolerant cultivars may represent an effective solution for the problem. However, further studies require strategies to develop P low levels tolerant genotypes. Several papers report plant strategies for low phosphorus levels tolerance and one of the main strategies that may be very useful for this tolerance is root plasticity. Exploitation of genetic variation in plants in nutrient efficiency has been increasingly explored and emerging as a variable alternative approach to crop production in low nutrient environment. In the present study an attempt was made to exploit the rice genotypes for root morphological characteristics and enzyme activity under low phosphorus condition.

Materials and Methods

The hydroponics experiment was conducted at Radio Isotope (Tracer) Laboratory, Department of Soil Science and Agricultural Chemistry, Tamil Nadu Agricultural University, Coimbatore. The rice genotypes were chosen based on higher yield obtained and performed well under phosphorus stress condition. The treatment comprised of fertilizer levels viz. 0, 2.5 and 10 ppm P and seven rice genotypes viz. TNRH -18, ADT- 47, CB08509, CB08504, AD07038, ASD -16 and AS06016. This lab experiment was laid out in completely randomized block design (CRBD) with three replications.

Protocol for screening rice genotypes under hydroponics condition

Seed sterilization and germination

The dormancy of rice seeds was broken by keeping them in convection oven at 40 ^{0}C for 48 hrs. Seeds were properly sterilized with sterilizing agents (calcium hypochlorite) to avoid fungal and bacterial infection at the germination stage.

The rice seeds were germinated on germination paper by roll towel method. A piece of germination paper of size 23 x 23 cm was taken, wetted and dipped in normal water. Another small piece of germination paper was cut and kept separately. The seeds were covered by thin plastic sheet of size 23 x 7 cm. The sterilized seeds were arranged in two rows on germination paper with a 2 cm distance in between two seeds. The seeds were covered with small piece of germination paper and plastic sheets. Using permanent marker, the name of the variety/ genotype, date of sowing was labelled on a plastic sheet. The germination paper was properly rolled and tied with a rubber band. The rolled germination papers were kept in container / beaker containing water in a slanting position. The water level was adjusted up to 1/2 of the height of rolled paper. The container was kept under laboratory condition at 27±1^{0}C temperature. The seedlings were allowed to grow up to 10 days after sowing (Fig. 1).

A seedling float system was constructed using 38 cm × 26 cm × 1.5 cm Styrofoam sheets, each with 49 holes (1.5 cm diameter, arranged in a 7×7 array with 4.2 cm × 2.8 cm spacing). These floats were placed in 56 cm × 33 cm trays. (Fig. 2).

Preparation of modified Yoshida medium reagents

All macronutrient (Sr.No.1-5) stock solutions (1 L) were prepared separately. Micronutrients stock solution was prepared by dissolving solutions (Sr. No. 6, 7 and 8) in one reagent bottle. Every time freshly prepared solution was taken (Sr. No.9) and covered with foil. Cleaned and dried plastic trays were filled with 12 L of water. Add 15 mL of each Yoshida medium reagent in water. Adjusted the pH of culture solution to 4.5 by Nitric acid (100 %) and NaOH with handy pH meter (Table 1).

Fig. 1. Roll towel method for rice seedling germination.

Fig. 2. General view of hydroponics experiment.

Transfer of seedlings to seedling floats

Ten days after sowing, the germinated seedlings were transferred to styrofoam sheet floated on culture solution (pH 4.5). Seedlings stem portion were wrapped with piece of sponge and placed in a hole of Styrofoam sheet. The seedlings were carefully handled while transferring from germination paper to seedling floats to avoid injuries. The trays containing culture solution were kept under greenhouse conditions at 25-30 ^{0}C. Every day the nutrient culture solution was checked and maintained the pH of 4.5. Nutrient solutions have been changed every 7 days. This experiment was conducted for 60 days.

Plant enzyme analysis

Acid Phosphatase enzyme activity

200 mg of fresh tissue was taken from fully expanded leaves at various growth stages. Fresh samples were ground in a cold mortar using 5 mL of 0.2 M sodium acetate buffer (pH 5.8). The extract was centrifuged at 10000 rpm for 10 min at 4 °C. 50 µL of enzyme was added to 450 µL of buffer and the enzyme activity was assayed using p-nitrophenol phosphate (PNPP) as a substrate and expressed in mmol of p-NPP hydrolyzed h^{-1} (5).

Adenosine triphosphatase (ATPase) enzyme activity

One gram of fresh tissue was taken from third or fourth leaves at various growth stages. The samples were ground in a cold mortar using 0.125 M sucrose buffer. The extract was centrifuged at 10000 rpm for 10 min at 4 °C. 200 µL enzyme were assayed using 0.25 M sucrose as substrate and expressed in µg of Pi g^{-1} h^{-1} (6).

Table 1. Details of Yoshida nutrient solution for preparation of 1 L stock solution

S.No.	Element	Reagent (AR grade)	(g /L)
		Macronutrients	
1	N	Ammonium nitrate (NH_4NO_3)	91.4
2	K	Potassium sulphate monohydrate (K_2SO_4) or	71.4
		Potassium dihydrogen phosphate (KH_2PO_4) or	46.2
		Dipotassium phosphate (K_2HPO_4)	8.6
3	Ca	Calcium chloride dihydrate ($CaCl_2.2H_2O$)	58.71
4	Mg	Magnesium sulphate, 7-hydrate ($MgSO_4.7H_2O$)	162.0
5	Mn	Manganous chloride, 4-hydrate ($MnCl_2.4H_2O$)	0.75
		Micronutrients	
6	Mo	Ammonium molybdate, 4-hydrate $(NH_4)_6Mo_7O_{24}$-$4H_2O$	0.032
7	B	Boric acid (H_3BO_3)	0.460
8	Cu	Cupric sulphate 5-hydrate ($CuSO_4.5H_2O$)	0.015
9	Fe	Ethylene diamine tetraacetic acid ferric sodium salt	0.124

Statistical analysis

The data on various characters studied during the investigation were statistically analyzed (7). The data collected on various characters of the experiment were analyzed based on the procedure (8). Wherever, the treatment differences were found significant, the critical differences were worked out at five per cent probability level and values furnished.

Results and Discussion

Root volume

The root volume observed at 30 DAS and 60 DAS revealed that at 60 DAS there was an increase in root volume compared to 30 DAS. The root volume showed a gradual decrease from 0 ppm to 2.5 ppm P and then gradual increase at 10 ppm P at 30 DAS. At 60 DAS, the root volume ranged from 0.87 to 2.36 cm^3. There was a significant increase in root volume from 0 ppm P. Among the rice genotypes, CB08504 registered the highest root volume (2.63 cm^3) and the lowest root volume in ADT- 47 (0.87cm^3) (Fig. 3). This might be due to root hair growing longer and denser in response to low P availability. Root hair length and density were strongly influenced by genotype, phosphorus (P) treatment, and varietal group. Among all rice genotypes, Azucena exhibited the shortest yet most densely packed root hairs under both P conditions. Reduced P availability led to an average 15 % increase in root hair length, with variation among genotypes ranging from 9.7 % to 31.3 %. Similarly, low P levels resulted in an average 10 % rise in root hair density, with genotypic responses spanning 4.4 % to 24.1 %, ultimately contributing to a greater overall root volume (9). Phosphorus application significantly affects root volume, especially at 60 DAS, where the interaction with genotype becomes very important. Different rice genotypes exhibit varying root volumes, highlighting genetic differences in root development. The application of phosphorus at higher levels generally increases the root volume of the tested rice genotypes at 60 DAS. The decrease of root volume at 30 DAS as phosphorus increases, could be due to the young plants not having a large enough root system to need or properly utilize the increased phosphorus at that growth stage. Selecting rice genotypes with higher root volume can improve nutrient uptake and overall plant growth. Optimizing phosphorus application is crucial for maximizing root development, especially during later growth stages.

Root length

At 30 DAS and 60 DAS the P levels and genotypes showed a significant influence on root length and its interaction effect were also significant. The rice genotypes viz. TNRH-180, CB08509 showed higher root length observed at 30 DAS and 60 DAS (Fig. 4). It might be due to modification root morphology at low phosphorus supply. Root parameters are highly response due to phosphorus deficiency and hence root elongation takes place. When horsegram (*Macrotyloma uniflorum* (Lam.) Verde.) was grown in a phosphorus deficient nutrient solution, a decrease in the solution's pH and an increase in the plant's cation-to-anion ratio was observed. In bromocresol purple agar, H^+ efflux from the roots of P-deficient plants was clearly visible. Phosphorus deficiency also caused a marked increase in root cell length. These findings indicate a strong relationship between H^+ excretion, root cell elongation, and overall

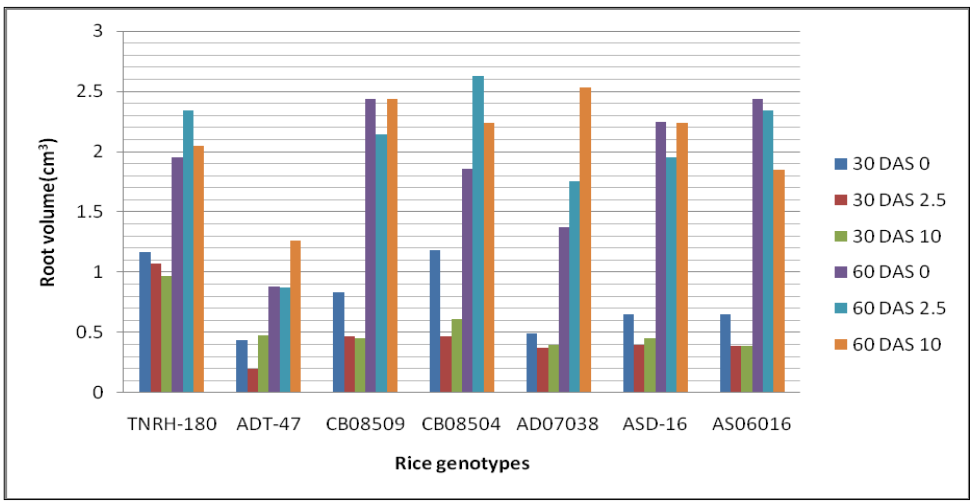

Fig. 3. Root volume (cm^3) of rice seedlings as influenced by genotypic divergence and phosphorus levels.

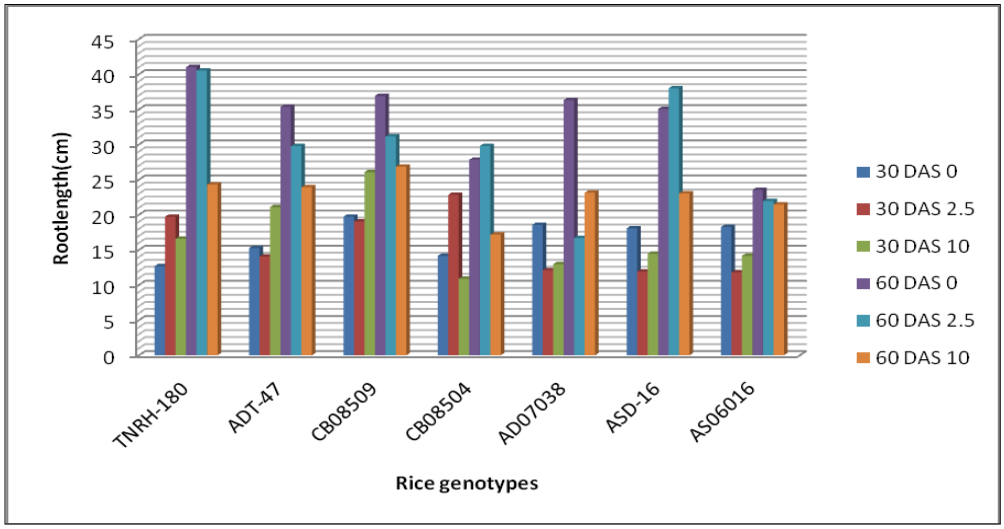

Fig. 4. Root length (cm) of rice seedlings as influenced by genotypic divergence and phosphorus levels.

root growth under phosphorus-deficient conditions (10). Isogenic lines viz. Dro1-NIL exhibited a larger root surface area in the lower soil layer, which enhanced phosphorus (P) acquisition from the subsoil and led to increased biomass and P uptake under the applied treatment. In contrast, the qsor1-NIL showed greater root surface area and longer root hairs, contributing to higher biomass and P uptake under the phosphorus omitted condition. Although the exact mechanism remains uncertain, it is suggested that the pleiotropic effect of qsor1specifically, promoting root hair elongation may offer a more carbon efficient strategy for P acquisition compared to extending nodal and lateral roots when phosphorus is scarce in deeper soil layers (11). Roots of rice genotypes grown in root rhizotron having soil P (P_2O_5 ≤ 7.59kg/ha), with and without P supplementation were compared for difference in total root length, lateral branching, surface area and volume. Significant differences were observed among the genotypes, due to inherent genetic makeup and in their response to P deficiency stress. While an average decrease in all four root traits was recorded, few genotypes showed P deficiency inducing lateral root development manifested as total root length, root surface area and volume. The three genotypes (Buddha, R-RF-78 and Cross 116) were identified as P deficiency tolerant rice genotypes, for use in further P efficient development of rice varieties (12). Phosphorus application significantly affects root length at both growth stages. Different rice genotypes exhibit varying root lengths, highlighting genetic differences in root development. The interaction of genotype and phosphorus level is significant at both 30 and 60 DAS. This means that the optimal phosphorus level for root length development, is dependent on the genotype of rice. Optimizing phosphorus application is crucial for maximizing root development.

Total number of roots

The total number of roots per plant observed at 30 DAS and 60 DAS revealed that at 60 DAS there was an increase in total number of roots per plant compared to 30 DAS. At 30 DAS the P levels and genotypes showed a significant influence on total number of roots per plant. At 30 DAS the total number of roots per plant showed a gradual decrease from 0 ppm to 2.5 ppm P. At 30 DAS and 60 DAS among the rice genotypes, CB08504 (33.2 nos.) and AS06016 (36.1 nos.) registered a greater number of roots per plant and lesser number of roots per plant in AS06016 (16.28 nos.) and ADT-47 (15.95 nos.) (Fig. 5, 6). It might be due to change in root architecture because of carbon budget of the whole plant with no additional specific effect caused by the phosphorus deficiency on root system. The effects of phosphorus deficiency on leaf expansion, biomass production, and root development in maize were examined to evaluate whether changes in root system behavior result from alterations in the plant's carbon allocation. Shortly after the onset of P deprivation, root growth showed a slight increase, but it declined sharply in the later stages. However, the elongation rate of the main (axile) roots remained consistent throughout the study (13). Phosphorus levels significantly impact the number of roots per plant

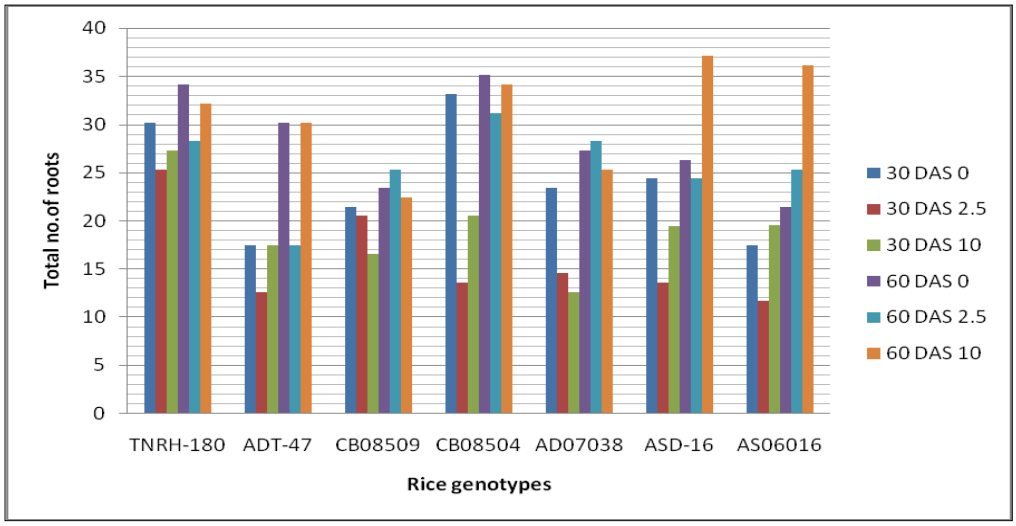

Fig. 5. Total no. of roots per plant of rice seedlings as influenced by genotypic divergence and phosphorus levels.

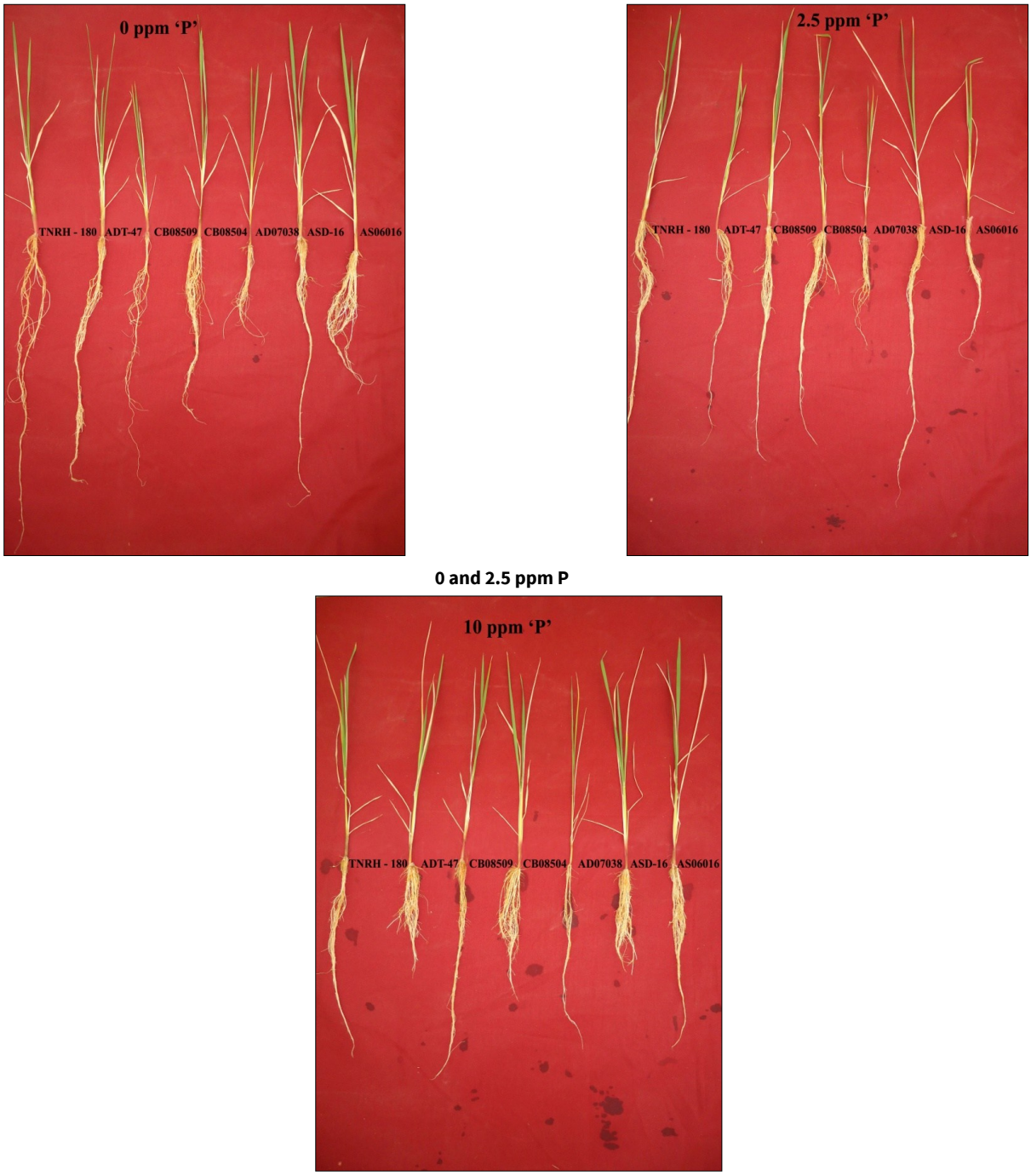

Fig. 6. Root length of rice genotypes at different P levels at 60 DAS.

at both stages (30 DAS and 60 DAS). Genotypic differences play an important role in root development, with TNRH-180 and ASD-16 being some of the better performers. There is a significant interaction between phosphorus levels and genotypes, Rice genotypes respond differently to phosphorus availability.

Number of lateral roots

The number of lateral roots observed at 30 DAS and 60 DAS revealed that at 60 DAS there was an increase in number of lateral roots compared to 30 DAS. At 30 DAS and 60 DAS the P levels and genotypes showed a significant influence on number of lateral roots. The number of lateral roots showed a gradual decrease from 0 ppm to 2.5 ppm P and then slightly increased at 10 ppm P. Similar trend was noticed at 60 DAS.

Among the rice genotypes CB08504 registered the highest number of lateral roots (15.6 nos. and 16.6nos. at 30 DAS and 60 DAS) and the lowest number of lateral roots in AD07038 (7.16 nos.) and ASD-16 (7.49 nos.) (Table 2). It may be due to phosphorus deprivation affecting the emergence of new axile roots and elongation of laterals roots. Six rice genotypes differing in tolerance to phosphorus deficiency were grown in a vermiculite sand medium under varying P supplies to study lateral root growth and P uptake. P deficiency promoted lateral root elongation and development, with considerable genotypic variation. Increased lateral root length, rather than number, mainly contributed to higher root surface area. Phosphorus uptake showed strong positive correlations with total root surface area and lateral root traits under P limitation (14 -16). There is significant variation among genotypes in their response to phosphorus. CB08504 and TNRH-180 are among the better performers, with ADT-47 and ASD-16 having consistently lower root counts. AS06016 shows steady improvement in root number as it matures, especially under higher phosphorus levels. The change in

Table 2. No. of lateral roots of rice as influenced by genotypic divergence and phosphorus levels

Rice genotypes	30 DAS				60 DAS			
	Phosphorus levels (ppm)				Phosphorus levels (ppm)			
	0	2.5	10.0	Mean	0	2.5	10.0	Mean
TNRH-180	12.7	14.6	10.7	12.70	15.76	16.56	12.73	15.02
ADT-47	7.8	3.9	6.8	6.19	9.80	7.98	9.80	9.19
CB08509	9.7	10.7	11.7	10.74	10.71	11.92	13.74	12.12
CB08504	13.6	10.7	15.6	13.35	15.35	12.73	16.67	14.91
AD07038	9.7	7.8	3.9	7.16	11.51	8.79	7.88	9.39
ASD-16	11.7	6.8	3.9	7.49	13.74	9.60	9.80	11.04
AS06016	8.7	4.8	9.7	7.81	9.90	10.71	11.62	10.74
Mean	10.60	8.51	8.93	9.35	12.39	11.18	11.74	11.77
	SED	**CD(0.01)**			**SED**	**CD(0.01)**		
P	0.079	0.213			0.133	0.359		
G	0.120	0.325			0.203	0.548		
P*G	0.209	0.564			0.352	0.950		

plant reaction to phosphorus levels, between 30 and 60 DAS, shows the importance of understanding the plants' growth stages, when determining optimal growing conditions.

Acid phosphatase activity

There was an increase of rice genotype CB08509 in acid phosphatase activity at 60 DAS when compared to 30 DAS. P levels and genotypes showed a significant influence on acid phosphatase activity irrespective of stages (Table 3). It might be due to the phosphatase enzyme which is responsible for P hydrolysis from organic compounds, favoring P mobilization and translocation from senescence tissues. An increase in root surface phosphatase activity was often correlated with decrease in phosphorus level in root as well as in leaf. The phosphatase enzyme catalyzes the hydrolysis of organic phosphate monoesters and liberates the available Pi. Under low inorganic phosphorus condition induced higher Apase activity by 67 % and 29 % in root and 11 % and 58 % in leaf tissues as compared to NP (250µM) and HP (1mM) in Indian mustard (17). Phosphatase enzyme activity was higher in P deficit plants, but the plant enzyme activity was lowered when inoculated with AM fungi. Root surface phosphatase activity is increased when the leaf phosphorus concentration decreases (18). The phosphatase enzyme could improve the acquisition and reutilization of phosphorus and thus helping the plants to grow under P deficit conditions (19). An increase in secretion of phosphatase enzyme in response to P starvation is thought to promote the liberation of phosphorus from organic complexes in soil (20). Phosphorus levels significantly influence acid phosphatase activity, with a general decrease in enzyme activity at higher phosphorus levels, especially at 60 DAS. Genotypic differences are crucial in determining phosphatase activity, with certain genotypes like ADT-47 and CB08509 showing better activity, especially in low phosphorus conditions. The genotype × phosphorus interaction highlights the importance of selecting appropriate genotypes for specific phosphorus management practices. These genotypic differences suggest that some varieties are better adapted to mobilizing phosphorus in environments with low phosphorus availability, as indicated by their higher acid phosphatase activity at 0 ppm.

ATPase activity in roots

There was an increase in ATPase activity in the roots of TNRH 180 at 60 DAS compared to 30 DAS. During both the stages, the P levels and genotypes and their interaction showed a significant influence on ATPase activity in roots (Table 4). It might be since ATPase enzyme is responsible for the export of protons out of plant cells. This enzyme acts as a primary transporter by pumping protons out of the cell, thereby creating pH and electric potential difference across the membrane. ATPase responds to several environmental factors such as saline stress, nutrient supply and iron deficiency (21). In this study, increased ATPase enzyme activity was seen in P_0S_0 (0 % P + no seed treatment) (7.3 µg Pi $g^{-1}h^{-1}$) like the studies who demonstrated the involvement of ATPase in the adaptation of white lupin to P deficiency (21).

Higher plants have developed various strategies of acquiring sparingly soluble nutrients from soil. In response to P deficiency, plants can acidify strongly the soil by reducing pH in soil. This pH decrease in the rhizosphere can dissolve P from calcium phosphate and increase the P availability in calcareous soils. It has been established that roots are attributed to release of a huge number of organic acids, predominantly as citric acid and malic acid into rhizosphere. Both genotype and phosphorus level significantly influence ATPase activity. TNRH-180 and CB08504 appear to maintain higher ATPase activity under low phosphorus, potentially indicating better phosphorus-use efficiency. ATPase activity is a

Table 3. Acid phosphatase activity (µmol pNpp) of rice as influenced by genotypic divergence and phosphorus levels

Rice genotypes	30 DAS				60 DAS			
	Phosphorus levels (ppm)				Phosphorus levels (ppm)			
	0	2.5	10.0	Mean	0	2.5	10.0	Mean
TNRH-180	2.48	2.32	1.42	2.07	2.83	2.10	1.04	1.99
ADT-47	4.28	3.99	1.88	3.39	4.56	4.16	2.74	3.82
CB08509	4.41	2.91	2.39	3.24	4.84	3.23	2.65	3.57
CB08504	3.00	2.58	2.27	2.61	3.19	3.07	2.99	3.08
AD07038	3.12	3.03	2.12	2.75	3.55	3.25	3.16	3.32
ASD-16	2.70	2.52	1.91	2.38	2.87	2.55	2.15	2.52
AS06016	3.15	2.11	1.31	2.19	3.45	2.39	1.64	2.49
Mean	3.31	2.78	1.90	**2.66**	3.61	2.96	2.34	**2.97**
	SED	**CD(0.01)**			**SED**	**CD(0.05)**		
P	0.022	0.059			0.024	0.066		
G	0.033	0.091			0.037	0.101		
P*G	0.058	0.158			0.065	0.175		

Table 4. ATPase activity (µ g Pi g^{-1} h^{-1}) of rice as influenced by genotypic divergence and phosphorus levels

Rice genotypes	30 DAS				60 DAS			
	Phosphorus levels (ppm)				Phosphorus levels (ppm)			
	0	2.5	10.0	Mean	0	2.5	10.0	Mean
TNRH-180	2.19	1.18	0.93	1.43	2.39	2.37	1.84	2.20
ADT-47	1.78	1.63	1.16	1.52	1.86	1.78	1.39	1.67
CB08509	2.04	1.88	1.54	1.82	2.08	2.05	1.75	1.96
CB08504	2.15	2.06	1.68	1.96	2.28	2.17	1.90	2.12
AD07038	1.59	1.43	0.89	1.30	1.66	1.57	0.86	1.36
ASD-16	1.68	1.58	1.22	1.49	1.92	1.80	1.49	1.74
AS06016	2.02	1.33	1.10	1.48	2.11	1.81	1.37	1.76
Mean	1.92	1.58	1.22	**1.57**	2.04	1.94	1.51	**1.83**
	SED	**CD(0.01)**			**SED**	**CD(0.05)**		
P	0.012	0.035			0.014	0.039		
G	0.019	0.053			0.022	0.060		
P*G	0.034	0.092			0.038	0.105		

crucial factor in rice plants' adaptation to varying P levels. The observed genotypic variations and the interaction between genotype and P level indicate that optimal P management strategies should consider the specific rice variety being cultivated. Furthermore, the increased ATPase activity under P deficiency and the role of rhizosphere acidification highlight the plant ability to mobilize P from the soil.

Conclusion

This hydroponic study effectively identified rice genotypes with superior phosphorus tolerance based on root morphological traits and plant enzyme activity. TNRH-180 and CB08504 demonstrated enhanced root development under low phosphorus conditions, indicating their potential for cultivation in phosphorus deficient soils. Furthermore, CB08509 exhibited higher acid phosphatase activity, suggesting an efficient mechanism for phosphorus mobilization, while TNRH-180 and CB08504 showed elevated ATP enzyme activity, indicating effective energy utilization. The study underscores the potential of utilizing hydroponic screening as a rapid and reliable method for identifying phosphorus tolerant rice genotypes. The findings suggest that farmers and breeders can prioritize these identified genotypes to enhance rice production in phosphorus limited environments. Optimizing phosphorus fertilization strategies based on these genotypic responses can minimize fertilizer input, reduce environmental impacts, and improve overall resource efficiency. This research contributes valuable insights towards developing sustainable rice cultivation practices in phosphorus deficient regions, ultimately aiming to ensure food security and improve farmer livelihoods.

Acknowledgements

The authors extend their heartfelt thanks to the Department of soil science and Agricultural Chemistry, Tamil Nadu Agricultural University, Coimbatore, Tamil Nadu, India, for offering the necessary facilities and support throughout the research period.

Authors' contributions

VS, KM, TB and MV contributed to the research activities, field establishment and drafting of the research article. MP, MM, KB and BBS reviewed and proofread the manuscript, performed statistical analysis on the data collected during the research, assisted with the analysis process and participated in sequence alignment. All authors reviewed and approved the final version of the manuscript.

Compliance with ethical standards

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.

Ethical issues: None

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Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

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