Biological Forum – An International Journal 15(3): 370-378(2023)

ISSN No. (Print): 0975-1130
ISSN No. (Online): 2249-3239

Genetic Plasticity for Root Architectural Traits in Backcrossed Population Derived from Wild Rice (*Oryza rufipogon* Griff) under Low Soil Phosphorous condition

Honnappa[1]*, Anantha M. Siddaiah[1], Padmashree R.[1], C. Gireesh[1], Kalyani M. Barbadikar[1], J.R. Diwan[2], Manoj C. A.[1], Basavaraj P.S.[1], Muralidhara B.[1], Ajita V.[1] and Banoth Vinesh[3]
[1]ICAR-Indian Institute of Rice Research, Hyderabad (Telangana), India.
[2]University of Agricultural Sciences Raichur (Karnataka), India.
[3]ICAR-Indian Institute of Seed Science, Kushmaur, Mau (Uttar Pradesh), India.

(Corresponding author: Honnappa)*

(Received: 17 January 2023; Revised: 18 February 2023; Accepted: 21 February 2023; Published: 22 March 2023)
(Published by Research Trend)

ABSTRACT: Soil phosphorous (P) deficiency is one of the limiting factors in rice production and productivity contributing more than 50% of soil with P deficient, particularly in upland and rainfed lowland cultivations. Since P is diffusion limited in depleted zones developed around roots, root architecture traits are become prime importance for P acquisition including root length, root volume, root density in terms of fresh and dry weight basis which will ultimately support to the above ground portion of the plant growth. *Oryza rufipogon* Griff ,a cultivated wild relative (CWR) of rice which is known to be a good source for low P tolerance trait. Hence the present study was undertaken to assess genetic variation along association between interrelated traits in relation to the low soil P conditions for the backcrossed populations derived from the cross between Samba mahasuri and (*Oryza rufipogon* Griff). The results revealed that, MSS due to genotypes were highly significant ($p<0.01$ and $p<0.05$) for all the traits under study, *viz.*, number of tillers per plant , root length, root volume, shoot fresh and dry weight, root fresh and dry weight, root to shoot ratio on dry weight basis considering both two seasons of low P and one season of control conditions respectively, except for shoot length under low P during Rabi and root to shoot ratio on wet weight basis under control during Kharif season. Wide range of genetic variation were recorded for the traits such as root length, root fresh and dry weight, shoot fresh and dry weight and root to shoot ratio on wet weight basis with high GCV and PCV and high heritability coupled with high GAM. Inter-correlation among the component traits such as numbers of tillers per plant, root length, shoot length, root volume, shoot fresh and dry weight, root fresh and dry weight and root to shoot ratio on wet and dry weight basis exhibited strong association between them, even considering under stress and control conditions.

Keywords: *Oryza rufipogon* Griff, Root architecture, Low soil phosphorous, Root volume, Root length.

INTRODUCTION

Rice is playing crucial part in global agriculture, since from its domestication process; almost half of the world's population is fed by the world's most significant staple food crop, rice (*Oryza sativa* L.). The Asian wild rice, *Oryza rufipogon* Griff (2n=24, AA) commonly known as red rice or brown bread rice, is a perennial wild ancestor for cultivated rice which is used as a valuable germplasm resource in introgression and transferring of novel traits into the commercial bred elite cultivated rice lines due to its richness in genetic diversity (Londo *et al*., 2006). Globally, rice occupies an area of 161 M ha with production of 487 mt of milled rice with China being the largest producer, Whereas, India stands first with area under rice cultivation of 43 mha and second largest producer of rice with 109 Mt (World rice statistic, IRRI, 2018).

Rice essentially requires 16 mineral nutrients for development (De Datta and Broadbent 1988), of which nitrogen (N), phosphorus (P) and potassium (K) are applied to rice fields as chemical fertilizers in large quantities. N and P are fundamental to crop development because they form the basic component of many organic molecules, nucleic acids, proteins (Lea and Miflin 2010) and involved in the major functions like, energy storage and transfer, maintenance of membrane integrity, so it is mobile within the plants, taken up as phosphate (Pi) form and particularly important in early growth stage which promotes tillering, root development, early flowering and ripening. The global demand for N, P and K is of 118763, 45858 and 37042 thousand of tones for the year of 2020 respectively. So, it is forecasted to grow annually by 1.5, 2.2, and 2.4% respectively (FAO, 2020). There is increasing demand for fertilizer consumption which exceeding the current grain production rates, which indicate a declining trend in nutrient-use efficiency. In addition, fertilizer prices are increasing due to high energy costs of production with scarcity natural available resources. Currently, P deficiency occurs to about 50% of the agricultural soils in many Asian, African and South America countries (Lynch, 2011). Therefore, the balanced and sustainable use of P fertilizer is of paramount importance (Vinod and Heuer 2012).

P is the second most limiting mineral nutrient in almost all soils, and phosphorus availability is particularly limiting on highly weathered acid soils of the tropics and subtropics due to its fixation by Al and Fe oxides on the surface of clay minerals. P deficiency under field condition results in stunted plants, reduced tillering ability and numbers of flowers, older leaves are narrow, short, very erect, and has a "dirty" dark green color stems become thin and spindly. The number of leaves, panicles, grains per panicle, number of fertile spikelets per panicle is also reduced, and young leaves may appear to be healthy but older leaves turn brown and die. But key responses in the plant under P limiting conditions includes changes in the root system architecture (RSA), increased root to shoot ratio, promotion of lateral and hairy root development (Raghothama, 1999) reduction in photosynthetic rate, increased activity of high-affinity Pi transporters, secretion of APases, ribonucleases and organic acids; membrane phospholipid replacement with glycolipids and sulfolipids; and dark green to purple coloration of leaves due to increased synthesis of anthocyanin (Dobermann and Fairhurst 2000) and starch.

Tolerance to nutrient deficiency is associated with the genotype's nutrient use efficiency and genotypic variation in nutrient use efficiency is closely related to root nutrient acquisition capacity and utilization. For the development of nutrient-efficient rice, a holistic approach should be followed combining optimized fertilizer management with enhanced nutrient uptake *via*., a vigorous root system, leading to increased grain filling and yield. Despite an increasing number of N- and P-related genes and QTLs being reported, very few are actively used in molecular breeding programmes (Vinod and Heuer 2012). In addition to improved and sustainable agro-management options, higher yielding and more nutrient efficient genotypes have to be developed in order to secure rice production (Vinod and Heuer 2012), in light of the high energy costs and increasingly scarce resources, future agricultural systems have to be more productive and more efficient in terms of inputs such as fertilizer and water. Selection of rice cultivars which can extract phosphorus from P-limiting soils, which have a higher P fertilizer use efficiency, is therefore considered an important cost effective management. The development of rice varieties with high yield under low-nutrient conditions has therefore become a breeding priority.

One third of the cultivable lands in the world lack required level of P in the soil for optimum plant growth and development (MacDonald *et al*., 2011), in countries such as India and China, apart from mineral deficiencies such as (zinc and boron) nutrient deficiencies have significantly stagnated or limited crop yields. To better answer the P crisis in rice farming, the development of P efficient rice genotypes, which are adapted to low P soils, would be a promising solution (Cordell *et al*., 2009; Rose *et al*., 2011). In this study, genetic variation and plasticity in response to low P are assessed for root architectural traits of backcrossed populations (BC_1F_3 and BC_1F_4) derived from *O. rupipogon* and Samba masuri.

MATERIAL AND METHODS

Plant Material. A BC_1F_3 and BC_1F_4 populations consisting of 192 introgression lines derived from a cross between low P sensitive cultivar (Samba Mahsuri) as the recipient parent and *O. rufipogon* as a donar parent along with low P sensitive checks like., BPT-5204, Ratnachudi, ISM, Tanu and low P tolerant checks such as Swarna and Rasi were used in the present study.

Specialized Low Soil Phosphorous Plots. The experiment was carried out at ICAR-IIRR, Hyderabad, India, which is located at an altitude of 542.3 m above mean sea level, 17°19′ North and 78°23′ East, and positioned in the southern zone of Telangana state, India. The root traits screening under field conditions was carried out in a specialized experimental plot of the ICAR-IIRR, Hyderabad, which has low levels of P for two successive growing seasons as a wet seasons *Kharif*-2018 (June- November) and dry season *Rabi*-2018-19 (December-May). The low P plot at ICAR-IIRR was developed by not applying P for a quite long time (>20 years). At present, the available P (that is, Olsen P) in this plot is estimated to be the low P plot at ICAR-IIRR was developed by not applying P for a quite long time (>20 years) and at present, the available P (that is, Olsen P) in this plot is estimated to be <2 kg/ha.

Phenotypic Screening of Root Architectural under Low Soil P Conditions. The seeds were sown in a nursery bed and 21-day old seedlings were transplanted to the main field. The seeds were planted following a spacing of 20 cm × 10 cm in augmented block design, no P fertilizer was applied to the low soil P plot. However, the recommended dose of P fertilizer was applied to a normal soil P plot (P: 60 kg/ha). Other essential nutrients like nitrogen (100 kg/ha) and potash (40 kg/ha) were applied as per recommended agronomic practices to raise a good crop. At maximum tillering stage nearly after 45 to 50 days after transplanting (DAT) plants were uprooted from the field by destructive method without causing much damage to the roots system, roots were washed with running water to remove soil debris and excess water that remained on the surface of the roots was removed by blotting with absorbent paper. Root volume were measured by using measuring cylinder as a water displacement method containing known initial volume of water with rise in the final volume and it is expressed in mL. The root and shoot length were measured in cm by using meter scale reading and root and shoot fresh weight along with their dry weight were measured in g by using electronic balance meter. The root and shoot ratio on both wet and dry weight basis were calculated from fallowing formulae. The statistical analysis related to Anova, genetic variability and correlation were worked out by using augmented *RCBD* package in R software studio (*version* 3.5.2) to understand the phenotypic response of 198 entries for root architectural traits.

$$\text{Root to shoot ratio (wet weight basis)} = \frac{\text{Fresh root weight}}{\text{Fresh shoot weight}}$$

$$\text{Root to shoot ratio (dry weight basis)} = \frac{\text{Dry root weight}}{\text{Dry shoot weight}}$$

RESULTS AND DISCUSSION

Anova: The MSS due to ten root architectural traits of 198 ILs (BC_1F_3 and BC_1F_4) were given in Table 1. The results revealed that, MSS due to genotypes were highly significant ($p<0.01$ and $p<0.05$) for all the traits under study, considering both two seasons of low P and one season of control conditions respectively *viz.,* number of tillers per plant (1.03**, 1.24**, 2.78*), shoot length (86.32**, 71.71, 91.89**), root length (10.25*, 13.13**, 8.79*), root volume (9.72**, 3.45*, 26.04**), shoot fresh weight (19.71*, 4.38**, 106.93**), shoot dry weight (0.61**, 0.38**, 6.71**), root fresh weight (5.07**, 1.71**, 57.01**), root dry weight (0.11*, 0.05**, 3.36**), root to shoot ratio on wet weight basis (0.05, 0.07**, 0.03*) and root to shoot ratio on dry weight basis (0.02**, 0.03**, 0.04**) except for shoot length under low P during Rabi and root to shoot ratio on wet weight basis under control during *Kharif* season. Similarly MSS due to entries (checks + genotypes) were significant ($p<0.01$ and $p<0.05$) for most of the traits under study, considering both two seasons of low P and one season of control conditions respectively *viz.,* number of tillers per plant (1.08**, 1.23**, 4.33), shoot length (72.85**, 74.25, 83.76**), root length (11.36**, 14.30**, 10.03**), root volume (9.41**, 3.36*, 26.19**), shoot fresh weight (29.59**, 4.21, 110.05**), shoot dry weight (0.83**, 0.43**, 6.72**), root fresh weight (6.75, 1.62**, 57.70), root dry weight (0.17**, 0.02*, 3.37**), root to shoot ratio on wet weight basis (0.06**, 0.07, 0.03) and root to shoot ratio on dry weight basis (0.02, 0.48**, 0.03**) except for tiller number under control condition during Rabi; root to shoot ratio on dry weight basis under first season (*Kharif*) of low P; shoot length and shoot fresh weight in second (*Rabi*) season of low P; root fresh weight under low P during *Kharif* season and during Rabi season under control condition; and root to shoot ratio on wet weight basis during Rabi under both low P and control conditions (Table 1). The overall result of ANOVA revealed that, MSS due to genotypes, checks and entries (checks + genotypes) were significant for most of the root architectural traits and for two different regime of P under investigations, as a whole, root length, root volume, shoot dry weight and root dry weight plant had larger significant difference or effect than other traits studied and variability among the genotypes were significant for root architectural traits, especially under low P, so these findings confirm the presence of significant differences for root attributing traits in the experimental material and offers scope for further investigations to the variability studies. Similar finding were reported by Da-Silva *et al.* (2016) and observed existence significant difference among 42 wheat cultivars for root traits such as root dry matter, root length, root volume and diameter, root density and root to shoot ratio under low and high P levels.

Assessment of Genetic Variability. The recorded data for root architectural traits of introgression lines under low soil P and control soil P conditions were subjected to the analysis such as range, mean, phenotypic coefficient of variability (PCV), genotypic coefficient of variability (GCV), broad sense heritability (h^2bs) and genetic advance as *per cent* mean (GAM) by using *RCBD* package in R software studio (*version* 3.5.2) to know the phenotypic response of the traits. The comparison of characters as regards to the extent of genetic variation and it could be better judged by the estimation of GCV and PCV (Rathi *et al.*, 2010). The findings of the present experiment given in Table 2 and frequency distribution in Fig. 1 and details were presented in box plot graphical representation. Number of tillers per plant has exhibited GCV and PCV of (24.57 and 27.84%), (34.87 and 37.41%) and (17.10 and 23.16) % while, heritability and GAM was (77.88 and 44.73%), (86.90 and 67.06%) and (60.21 and 17.72%) respectively, considering under both low P and control conditions. The trait has reported wide range of GCV and PCV it indicates that it is influenced by environment however, the trait also exhibited high heritability and GAM hence, high heritability coupled with high GAM indicates trait was under the influence of additive gene action and selection would be useful. Similar observations were reported Fageria *et al.* (2013); Zai- Hua *et al.* (2006); Wissuwa *et al.* (2002); Vejchasarn *et al.* (2016); Wissuwa *et al.* (1998). The reduced number of tillers under low soil P as compared to control condition were observed, it indicates the requirement of P at early growth stage. In literature Choudhury *et al.* (2007) reported as P application during active tillering stage is most efficiently utilized for grain filling and production, hence any P stress at tillering stage in turn will greatly affect the grain production in rice. Similarly Katyal (1978) reported as that within 7 to 21 days after transplanting DAT effect of P stress will be observed on plant growth and tiller development. Studies from Rodríguez *et al.* (1999); Fioreze *el al.* (2012) have shown that P nutrition could directly alter the pattern of tiller emergence and consequently influence the number of ears per unit of area. Wissuwa *et al*. (2015) reported that P deficiency symptoms can be seen in early stages (14 after sowing) of crop development, visibly reduced growth, reduced number of green leaves, reduced number of tillers per plant and reduced height as that of control conditions.

Shoot length per plant for present study was varied from 21.00 to 60.57 cm, 19.37 to 62.11 cm under low soil P and 23.00 to 80.14cm under control soil P with an average of (41.62, 37.20 and 49.45) cm, whereas, the root length was varied from 8.65 to 24.50 cm, 10.12 to 23.06 cm under low soil P and 16.00 to 31.33 cm under control soil P with an average of (17.18, 16.21 and 20.98) cm, respectively. Both shoot and root length shows significant variation under study for both low soil P hereafter called as stress condition and control conditions (Table 1), indicating effect of P stress for the control of the trait for shoot and root growth. Earlier authors were revealed as phosphorus deficient plants generally tend to exhibit retarded shoot and root growth as reported by Lynch (1995). Da-Silva, *et al.* (2016); Fageria and Knupp (2013) reported as a linear increase in root length from active tillering initiation to flowering and thereafter, root length was more or less constant or reached to plateau so for the present study all the root observations were preferred at 45 days after transplanting (DAT). Kirk (1997) mentioned that long and fine roots provide a greater absorbing surface for the nutrients than short roots, so breeding for long root will increase opportunity to absorb more nutrients from the rhizosphere soil. GCV and PCV for the trait shoot length was (19.71 and 20.52)%, (15.75 and 22.31)% and (17.88 and 21.16)% while, heritability and GAM was (92.20 and 39.04)%, (60.81 and 22.93)% and (71.41 and 31.17)% similarly, GCV and PCV for the trait root length was (5.75 and 15.83)%, (9.61 and 16.44)% and (20.75 and 21.96)% with heritability and GAM of (30.20 and 14.31)%, (34.19 and 11.60)% and (89.25 and 40.43)% respectively, considering under two seasons of low P and one season of control conditions. Wide range of variation for GCV and PCV observed for the traits shoot and root length however, shoot length has exhibited high heritability coupled with high GAM while, root length has reported medium to high magnitude of heritability and GAM both considering both under low P and control environment, hence medium to high heritability coupled with high GAM indicates the traits are governed by additive gene and selections for such traits may rewarding. Similar observations were reported Fageria *et al.* (2013); Zai-Hua *et al.* (2006); Wissuwa *et al.* (2002); Vejchasarn *et al.* (2016); Wissuwa *et al.* (1998); Deng *et al.* (2018). Increased root length is associated with longer and more branched roots per unit of root dry matter (Hill *et al*., 2006). Root elongation enhances the porosity and oxygen release capacity of plants which leads to iron oxidation and release of protons, therefore, increase in root length helps in surviving in P poor soil (Kirk, 1997). Root volume per plant for test genotypes varied from 2.00 to 14.36 ml, 1.40 to 12.40 ml under stress and 3.20 to 26.30 ml under control condition with an average of (5.71, 4.37 in low P and 11.08 control) ml. Differential pattern of root volume have been observed and there is a significant phenotypic difference has been exhibited by the test genotypes under study considering both under low P and control conditions (Table 1). GCV and PCV for the trait root volume was (44.69 and 48.11) %, (33.22 and 44.48) % and (32.65 and 49.51) % while, heritability and GAM was (86.29 and 85.63) %, (55.80 and 51.20) % and (43.48 and 44.41) % respectively, considering under two seasons of low P and one season of control conditions. Wide range of variation of GCV and PCV were observed for the trait root volume, indicating that the trait is influenced by the environmental effect, however, the trait also exhibited moderate to high heritability coupled with high GAM, indicating that trait under control of additive gene action and selection for such traits may gainful for breeding under stress conditions, in literature similar finding were reported done by Fageria *et al.* (2013); Zai- Hua *et al.* (2006); Wissuwa *et al.* (2002).

GCV and PCV for shoot fresh weight was (44.70 and 56.70)%, (45.84 and 47.96)% and (39.62 and 48.20)% while, heritability and GAM was (62.16 and 72.70)%, (91.33 and 90.37)% and (67.54 and 67.17)% similarly, GCV and PCV for the trait shoot dry weight was (48.40 and 54.31)%, (59.50 and 69.99)% and (51.01 and 54.89)% with heritability and GAM of (79.41 and 88.98)%, (62.27 and 74.35)% and (86.36 and 97.79)% respectively, considering under two seasons of low P and one season of control conditions. Wide range of variation for GCV and PCV observed for the traits shoot fresh weight and dry weight; however both shoot fresh weight and dry weight were exhibited high heritability coupled with high GAM. Hence high heritability coupled with high GAM indicates the traits are governed by additive gene and selections for such a trait may reward. From the literature similar kind work on root related traits and their genetic variation were reported by Fageria *et al.* (1988); Chaubey *et al.* (1994). Both shoot fresh weight and shoot dry weight revealed considerable amount of variation under study for both stress and control conditions (Table 1 and box plot graph Fig. 1), indicating influence of P stress for the control of the trait. In literature Ahadiyat *et al.* (2014) reported increase in shoot biomass with increased P application and mentioned that at low dose of P (45 kg/ha P_2O_5) obtained more than 25 g of shoot biomass, with increase in P dose from (90 to 135Kg/ha) reported increased shoot biomass more than 30 g. P deficiency tolerance has either been measured directly as dry weight or grain yield produced on low-P soils (IRRI 1985; Fageria *et al.,* 1988), or indirectly by correlated traits such as tiller number (Hung 1985) or relative tiller number as suggested by Chaubey *et al.* (1994).

GCV and PCV for root fresh weight was (45.64 and 49.58) %, (41.32 and 47.24) % and (40.93 and 57.96) % while, heritability and GAM was (84.73 and 86.66) %, (76.50 and 74.55) % and (49.89 and 59.65)% similarly, GCV and PCV for the trait root dry weight was (47.42 and 62.17)%, (35.73 and 72.19)% and (77.70 and 88.99)% with heritability and GAM of (58.18 and 74.61)%, (24.50 and 36.48)% and (76.23 and 39.96)% respectively, considering under two seasons of low P and one season of control conditions. Wide range of variation for GCV and PCV observed for the traits root fresh weight and dry weight; however, root fresh weight exhibited medium to high heritability coupled with high GAM, hence selection may gain full for root fresh weight, whereas root dry weight exhibited low to high heritability coupled with high GAM, low heritability accompanied with high genetic advance, it reveals that character is governed by additive gene action, low heritability due to high environmental effect hence selection may not be rewarded for breeding of such traits. In literature Matsuo *et al*. (2009) reported that morphological characters such as shoot weight tend vary among different nutrient conditions. Both root fresh weight and dry weight revealed considerable amount of variation under investigation for both stress and control conditions (Table 1), indicating influence of P stress for the control of the trait. Similar experimental findings were revealed by Ming *et al.* (2002); Choudhury *et al.* (2007). Studies from Da-Silva, *et al.* (2016) reported that increase in root dry weight will contribute to increasing P mobilization capacity of rice plant in P deficient soils. Deng *et al.* (2018) reported increased root dry weight, root length and density with increase P application rates. Similarly Ismail *et al.* (2007) worked on identification of rice genotypes for P efficiency, reported genotypic differences due to ability to capture soil P and utilize it in biomass production and Wissuwa *et al.* (1998) reported that low P availability was clearly the growth-limiting factor of the P-deficient soil as shown by a 50.40% reduction in dry weight and a 46.70% reduction in tiller number relative to P-fertilized conditions. Wide range of variation for GCV and PCV observed for both root to shoot ratio on wet and dry weight basis; however root to shoot ratio on wet weight basis exhibited high heritability coupled with medium to high GAM, hence selection may gainful, while for root to shoot ratio on dry weight basis exhibited low to high heritability coupled with medium high GAM, low heritability accompanied with high genetic advance, it reveals character is governed by additive gene action , low heritability due to high environmental effect hence selection may not be rewarding for breeding of such a traits. The wide range of variation noticed for most of the root characters studied it reveals these cope of selection for development of desirable type genotypes with better root traits especially under stress conditions such as low P stress condition.

Correlation Analysis. Associations between ten important root architectural traits with grain yield per plant were studied for 196ILs (BC_1F_3& BC_1F_4) along with 6 checks under two seasons of low P and control conditions, the details of the results were given in Table 3 and their graphical representation given in Fig. 2A, 3A & B. Among the ten root traits studied, root volume (0.086, 0.038 & 0.074), shoot fresh weight (0.037, 0.076 & 0.011) and shoot dry weight (0.103, 0.030 & 0.081) shows positive non-significant association with the seed yield per plant respectively, whereas remaining traits such as number of tillers per plant, shoot length, root length, root fresh and dry weight, root to shoot ratio on wet and dry weight basis show non-significant association with the grain yield per plant, considering both under two seasons of low P and control conditions. The overall inter correlation among the root traits contributed to seed yield per plant through the influence of following independent traits. Number of tillers per plant shows significant positive inter correlation with root volume (0.320**, 0.237** & 0.222**), shoot fresh weight (0.337**, 0.348** & 0.325**), root fresh weight (0.350**, 0.377** & 0.235**). Similarly shoot length shows significant positive inter correlation with root volume (0.269**, 0.190** & 0.136**), shoot fresh weight (0.347**, 0.290** & 0.342**), shoot dry weight (0.255**, 0.173* & 0.131*), root fresh weight (0.276**, 0.259** & 0.297**) and root dry weight (0.259**, 0.141* & 0.169*). Significant association of shoot length contributing to increased dry matter production and hence indirectly to grain yield per plant, similarly as the below ground systems of the plant growth increases like., root volume, root fresh and dry weight directly contributing to the growth of the above ground portion such as increased shoot length and shoot weight which interns increases higher dry matter production.

Similarly root length shows positive significant correlation with root volume (0.284**, 0.212** & 0.280**), shoot fresh weight (0.269**, 0.209** & 0.278**), shoot dry weight (0.245**, 0.156* & 0.152*), root fresh weight (0.274**, 0.256** & 0.284**), root dry weight (0.247**, 0.166* & 0.242**) and with root to shoot ratio on dry weight basis (0.223**, 0.132* & 0.179**). Further root volume also shows positive significant association with shoot fresh weight (0.682**, 0.695 & 0.610**), root fresh weight (0.713**, 0.600** & 0.719**), root dry weight (0.746**, 0.390** & 0.250**) and root to shoot ratio on dry weight basis (0.666**, 0.178* & 0.273**). Similarly shoot fresh weight show positive significant association with shoot dry weight (0.745**, 0.595** & 0.179**), root fresh weight (0.808**, 0.768** & 0.861**), root dry weight (0.796**, 0.469** & 0.311**) and root to shoot ratio on dry weight basis (0.693**, 0.184** & 0.225**) *vice versa* is true. Shoot dry weight shows positive significant association with root fresh weight (0.881**, 0.595** & 0.150*) and root dry weight (0.905**, 0.509** & 0.608**) *vice versa* is true. Root fresh weight with root dry weight (0.946**, 0.614** & 0.310**), root to shoot ratio on wet weight basis (0.205**, 0.172* & 0.468**) and root to shoot ratio on dry weight basis (0.837**, 0.341** & 0.254**). Finally root to shoot ratio on wet weight basis shows positive significant correlation with root to shoot ratio on dry weight basis (0.918**, 0.839** & 0.685**) and *vice versa* is true, considering both under two seasons of low P and control conditions respectively. High significant inter correlation were reported by the root systems like root length, root volume and root fresh and dry weight, it indicates that a large root system might be the most important trait for P acquisition on P stress soils and therefore breeding for P efficient crops by root traits may useful. Further number of tillers per plant shows positive significant and positive non-significant correlation with root length (0.198**, 0.181** & 0.109) and shoot dry weight (0.341**, 0.242** & 0.056), similarly root volume with shoot dry weight (0.705**, 0.454** & 0.056); root to shoot ratio on wet weight basis with root to shoot ratio on dry weight basis (0.171**, 0.214** & 0.067) *vice versa* is true, considering under both two seasons of low P and control conditions respectively. The significant association of number of tillers per plant with root length and shoot dry weight; root volume with shoot dry weight; and root to shoot ratio on wet weight basis with root to shoot ratio on dry weight basis were observed only under low P environment, it indicates that under stress conditions there may be triggering of the regulatory or may be of functional genes which are common for these traits and acting strongly under P stress as compared to the control conditions. In literature similar results were reported from Gunes *et* *al.* (2006) who studied correlation for root traits and revealed that selection of genotypes under low P availability in soils could use dry weight of shoot and root as indicators. Wissuwa *et al.* (2015) studied and reported correlation for total weight, leaf weight, stem weight, root weight, dry leaf number, dry leaf weight and plant height under low P (800 µg P) and high P (1550 µg P).

Table 1: Analysis of variance for root architectural traits of BC_1F_3 and BC_1F_4 ILs under low P and control soil P conditions during *Kharif* and Rabi seasons (2018-19).

		Mean Sum of Squares														
Source of variation	***d.f.***	**TN**			**SL**			**RL**			**RV**			**SFW**		
Seasons		***Kharif***	**Rabi**		***Kharif***	**Rabi**		***Kharif***	**Rabi**		***Kharif***	**Rabi**		***Kharif***	**Rabi**	
Generations		**BC_1F_3**	**BC_1F_4**		**BC_1F_3**	**BC_1F_4**		**BC_1F_3**	**BC_1F_4**		**BC_1F_3**	**BC_1F_4**		**BC_1F_3**	**BC_1F_4**	
Environments		**P_0**	**P_0**	**Control**	**P_0**	**P_0**	**Control**	**P_0**	**P_0**	**Control**	**P_0**	**P_0**	**Control**	**P_0**	**P_0**	**Control**
Blocks	3	0.80 *	2.25 **	7.23 *	910.79 **	315.51 **	497.49 **	16.84	31.11 **	9.28	42.99 **	8.51 **	36.07 **	83.65 **	6.26 **	156.71 *
Entries	197	1.08 **	1.23 **	4.33	72.85 **	74.25	83.76 **	11.36**	14.30 **	10.03**	9.41 **	3.36 *	26.19 **	29.59 **	4.21	110.05 **
Checks	5	1.27 **	1.66 **	2.64	14.06	197.44 **	28.68	45.14 **	73.42 **	32.56 **	22.56 **	2.99	11.35	236.47 **	0.88	171.37 **
Genotypes	191	1.03 **	1.24 **	2.78*	86.32 **	71.71	91.89 **	10.25*	13.13 **	8.79*	9.72 **	3.45 *	26.04 **	19.71 *	4.38 **	106.93 **
Genotypes vs. Checks	1	10.19 **	0.61	285.94 **	499.80 **	780.92 **	251.72 **	0.52	26.17 **	123.86 **	3.43	3.57	189.67 **	1121.82 **	7.33 **	831.04 **
Residuals	15	0.23	0.16	1.75	6.73	35.99	26.27	8.90	1.41	5.79	1.33	1.52	14.72	7.46	0.38	34.71
CD $_{(0.05)}$ A		1.44	1.21	3.98	7.82	18.07	15.45	8.99	3.58	7.25	3.47	3.73	11.57	8.22	1.85	17.75
CD $_{(0.05)}$ B		1.55	1.32	4.30	8.43	19.52	16.69	9.71	3.86	7.82	3.75	4.03	12.49	8.88	2.00	19.18
CD $_{(0.05)}$ C		0.72	0.62	2.00	3.89	9.04	7.71	4.49	1.79	3.62	1.74	1.85	5.78	4.11	0.94	8.89
CD $_{(0.05)}$ D		1.19	1.00	3.30	6.47	14.98	12.81	7.45	2.96	6.01	2.87	3.09	9.59	6.81	1.53	14.73
CV (%)		13.30	13.60	19.15	5.68	15.61	11.25	14.76	7.16	13.20	17.73	22.81	12.35	16.93	13.97	14.12
Environments		**P_0**	**P_0**	**Control**	**P_0**	**P_0**	**Control**	**P_0**	**P_0**	**Control**	**P_0**	**P_0**	**Control**	**P_0**	**P_0**	**Control**
Blocks	**3**	1.72 **	0.77 **	13.19 **	16.58 **	7.04 **	89.93 **	0.27 **	0.06**	1.52*	0.16 **	0.09 *	0.01	0.03 **	0.10 *	0.01
Enrties	**197**	0.83 **	0.43 **	6.72 **	6.75	1.62 **	57.70	0.17 **	0.02*	3.37 **	0.06 **	0.07	0.03	0.02	0.48 **	0.03 **
Checks	**5**	2.98 **	0.73 **	3.55 *	33.50 **	1.77	46.54 **	0.96 **	0.05	2.17	0.20**	0.04	0.10 **	0.02 **	0.01	0.01
Genotypes	**191**	0.61 **	0.38 **	6.71 **	5.07 **	1.71 **	57.01**	0.11 *	0.05**	3.36 **	0.05	0.07 **	0.03 *	0.02 **	0.03 **	0.04 **
Genotypes vs. Checks	**1**	0.77 **	0.42 **	6.80 **	6.05 **	1.62 **	57.99 **	0.15 **	0.29**	3.40 **	0.05 **	0.07 **	0.03 *	0.02 **	3.36 *	0.03 **
Residuals	**15**	0.12	0.11	0.92	0.77	0.40	28.57	0.04	0.04	0.80	0.01	0.02	0.01	0.01	0.02	0.01
CD $_{(0.05)}$ A		1.06	0.98	2.88	2.64	1.92	16.11	0.63	0.58	2.69	0.27	0.40	0.32	0.46	0.47	0.21
CD $_{(0.05)}$ B		1.15	1.07	3.11	2.85	2.07	17.39	0.68	0.62	2.92	0.29	0.45	0.34	0.51	0.51	0.23
CD $_{(0.05)}$ C		0.53	0.49	1.45	1.32	0.96	8.06	0.31	0.28	1.34	0.14	0.21	0.17	0.23	0.23	0.11
CD $_{(0.05)}$ D		0.87	0.81	2.39	2.19	1.58	13.36	0.53	0.47	2.24	0.23	0.34	0.28	0.38	0.38	0.17
CV (%)		8.96	4.92	5.31	18.29	22.60	14.37	19.92	5.45	14.39	14.57	20.53	17.42	12.38	7.55	17.29

Where * and ** indicates Mean sum of squares were significant at $P<0.05$ and $P<0.01$ respectively, Entries (Checks + Genotypes) CD $_{(0.05)}$ A: Two test treatment (same blocks), CD $_{(0.05)}$ B: Two test treatment (different blocks), CD $_{(0.05)}$ C: Control treatment means (Checks), CD $_{(0.05)}$ D: Test treatment and control treatment, CV (%): Coefficient of variation

Note 1: TN: Tiller number per plant, SL: Shoot length (cm), RL: Root length (cm), RV: Root volume (cm), SFW: Shoot fresh weight (g), SDW: shoot dry weight (g), RFW: Root fresh weight (g), RDW: Root dry weight (g), RSRWW: Root to shoot ratio on wet weight basis (g), RSRDW: Root to shoot ratio on dry weight basis (g), P_0: Low phosphorus (0% of P), Control: RDF (60% of P)

Note 2: Observations were recorded @ 45 days after transplanting (DAT)

Table 2. Estimates of genetic variability parameters for root architectural traits of BC_1F_3 & BC_1F_4 ILs under low P and control conditions during *Kharif* and Rabi seasons (2018-19).

					Phenotypic variability			CV (%)			
Sr. No.	**Traits**	**Seasons**	**Gen.**	**Env.**	**Min**	**Max**	**Mean**	**GCV**	**PCV**	**h^2(bs)**	**GAM (5%)**
1.	TN	*Kharif*	BC_1F_3	P_0	1.02	6.31	3.07	24.57	27.84	77.88	44.73
		Rabi	BC_1F_4	P_0	1.00	5.40	2.82	34.87	37.41	86.90	67.06
				Control	1.20	8.00	4.92	17.10	23.16	60.21	17.72
2.	SL	*Kharif*	BC_1F_3	P_0	21.00	60.57	41.62	19.71	20.52	92.20	39.04
		Rabi	BC_1F_4	P_0	19.37	62.11	37.20	15.75	22.31	60.81	22.93
				Control	23.00	80.14	49.45	17.88	21.16	71.41	31.17
3.	RL	*Kharif*	BC_1F_3	P_0	8.65	24.50	17.18	5.75	15.83	30.20	14.31
		Rabi	BC_1F_4	P_0	10.12	23.06	16.21	9.61	16.44	34.19	11.60
				Control	16.00	31.33	20.98	20.75	21.96	89.25	40.43
4.	RV	*Kharif*	BC_1F_3	P_0	2.00	14.36	5.71	44.69	48.11	86.29	85.63
		Rabi	BC_1F_4	P_0	1.40	12.40	4.37	33.22	44.48	55.80	51.20
				Control	3.20	26.30	11.08	32.65	49.51	43.48	44.41
5.	SFW	*Kharif*	BC_1F_3	P_0	2.10	21.60	7.68	44.70	56.70	62.16	72.70
		Rabi	BC_1F_4	P_0	2.33	18.61	5.38	45.84	47.96	91.33	90.37
				Control	4.02	29.82	16.39	39.62	48.20	67.54	67.17
6.	SDW	*Kharif*	BC_1F_3	P_0	0.24	1.26	0.78	48.40	54.31	79.41	88.98
		Rabi	BC_1F_4	P_0	0.26	1.61	0.80	59.50	69.99	62.27	74.35
				Control	0.80	2.04	1.20	51.01	54.89	86.36	97.79
7.	RFW	*Kharif*	BC_1F_3	P_0	1.21	12.30	4.48	45.64	49.58	84.73	86.66
		Rabi	BC_1F_4	P_0	1.32	7.50	2.81	41.32	47.24	76.50	74.55
				Control	2.53	19.80	11.18	40.93	57.96	49.89	59.65
8.	RDW	*Kharif*	BC_1F_3	P_0	0.13	1.04	0.45	47.42	62.17	58.18	74.61
		Rabi	BC_1F_4	P_0	0.10	1.13	0.36	35.73	72.19	24.50	36.48
				Control	0.21	1.36	0.74	77.70	88.99	76.23	39.96
9.	RSRWW	*Kharif*	BC_1F_3	P_0	0.28	0.95	0.62	32.85	35.91	83.66	61.98
		Rabi	BC_1F_4	P_0	0.18	0.91	0.56	33.47	39.22	72.83	58.93
				Control	0.38	0.99	0.71	22.46	28.49	62.14	36.52
10.	RSRDW	*Kharif*	BC_1F_3	P_0	0.19	0.93	0.56	21.33	42.53	25.15	22.07
		Rabi	BC_1F_4	P_0	0.10	0.98	0.45	16.07	44.93	12.79	11.86
				Control	0.18	1.00	0.61	38.23	41.78	83.71	72.15

Where: CV (%): Coefficient of variation, PCV and GCV: Phenotypic and genotypic coefficient of variation**,** h^2(bs): Heritability (broad sense), GAM: Genetic advance as *per cent* of mean, Gen: Generation, Env: Environment

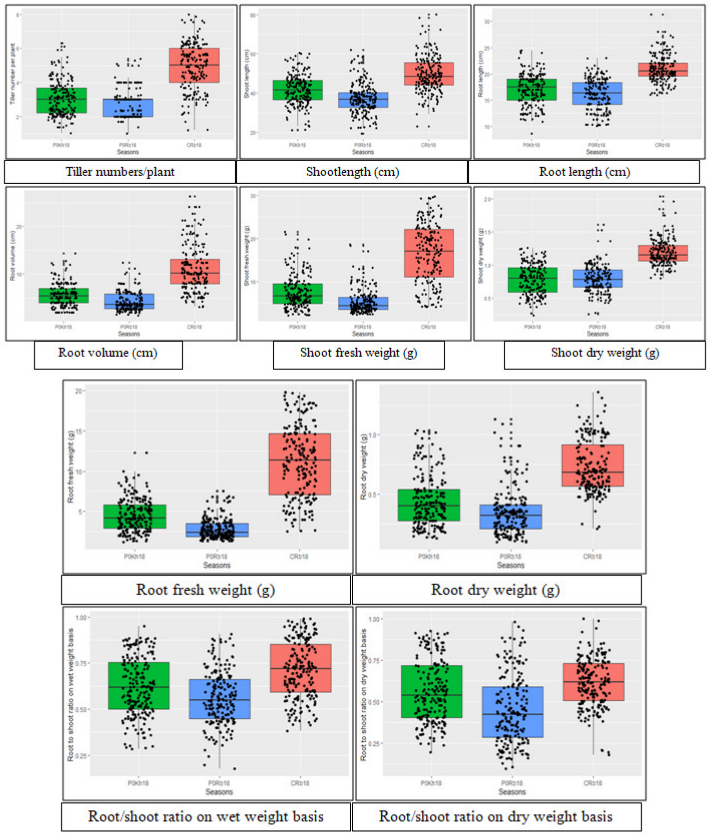
Note1: TN: Tiller number per plant, SL: Shoot length (cm), RL: Root length (cm), RV: Root volume (cm), SFW: Shoot fresh weight (g), SDW: shoot dry weight (g), RFW: Root fresh weight (g), RDW: Root dry weight (g), RSRWW: Root to shoot ratio on wet weight basis (g), RSRDW: Root to shoot ratio on dry weight basis (g), P_0: Low phosphorus (0% of P), Control: RDF (60% of P)

Note 2: Observations were recorded @ 45 DAT (days after transplanting)

Table 3: Character association for root architectural traits in BC_1F_3 & BC_1F_4 ILs under low P and control conditions during *Kharif* and Rabi seasons (2018-19).

Traits	Seasons	Gen.	Env.	TN	SL	RL	RV	SFW	SDW	RFW	RDW	RSRWW	RSRDW	GY
TN	*Kharif*	BC_1F_3	P_0	**1**	0.022	0.198**	0.320**	0.337**	0.341**	0.350**	0.368**	-0.009	0.374**	0.092
	Rabi	BC_1F_4	P_0	**1**	0.000	0.181**	0.237**	0.348**	0.242**	0.377**	0.088	-0.055	-0.030	-0.018
			Control	**1**	0.043	0.109	0.222**	0.325**	0.056	0.235**	0.129	-0.103	0.084	0.039
SL	*Kharif*	BC_1F_3	P_0		**1**	0.079	0.269**	0.347**	0.255**	0.276**	0.259**	-0.184**	0.201**	0.062
	Rabi	BC_1F_4	P_0		**1**	0.067	0.190**	0.290**	0.173*	0.259**	0.141*	-0.117	0.092	-0.019
			Control		**1**	-0.009	0.136**	0.342**	0.131*	0.297**	0.169*	0.048	0.076	0.009
RL	*Kharif*	BC_1F_3	P_0			**1**	0.284**	0.269**	0.245**	0.274**	0.247**	-0.006	0.223**	0.011
	Rabi	BC_1F_4	P_0			**1**	0.212**	0.209**	0.156*	0.256**	0.166*	-0.022	0.132*	-0.002
			Control			**1**	0.280**	0.278**	0.152*	0.284**	0.242**	0.080	0.179**	0.102
RV	*Kharif*	BC_1F_3	P_0				**1**	0.682**	0.705**	0.713**	0.746**	0.030	0.666**	0.086
	Rabi	BC_1F_4	P_0				**1**	0.695**	0.454**	0.600**	0.390**	-0.136*	0.178*	0.038
			Control				**1**	0.610**	0.056	0.719**	0.250**	0.402**	0.273**	0.074
SFW	*Kharif*	BC_1F_3	P_0					**1**	0.745**	0.808**	0.796**	-0.329**	0.693**	0.037
	Rabi	BC_1F_4	P_0					**1**	0.595**	0.768**	0.469**	-0.408**	0.184**	0.076
			Control					**1**	0.179**	0.861**	0.311**	0.005	0.225**	0.011
SDW	*Kharif*	BC_1F_3	P_0						**1**	0.881**	0.905**	0.199**	0.686**	0.103
	Rabi	BC_1F_4	P_0						**1**	0.595**	0.509**	-0.193**	0.014	0.030
			Control						**1**	0.150*	0.608**	-0.030	-0.143*	0.081
RFW	*Kharif*	BC_1F_3	P_0							**1**	0.946**	0.205**	0.837**	0.085
	Rabi	BC_1F_4	P_0							**1**	0.614**	0.172*	0.341**	-0.018
			Control							**1**	0.310**	0.468**	0.254**	0.046
RDW	*Kharif*	BC_1F_3	P_0								**1**	0.182**	0.918**	0.083
	Rabi	BC_1F_4	P_0								**1**	0.090	0.839**	-0.043
			Control								**1**	0.032	0.685**	0.093
RSRWW	*Kharif*	BC_1F_3	P_0									**1**	0.171**	0.060
	Rabi	BC_1F_4	P_0									**1**	0.214**	-0.096
			Control									**1**	0.067	0.053
RSRDW	*Kharif*	BC_1F_3	P_0										**1**	0.073
	Rabi	BC_1F_4	P_0										**1**	-0.029
			Control										**1**	-0.100
GY	*Kharif*	BC_1F_3	P_0											**1**
	Rabi	BC_1F_4	P_0											**1**
			Control											**1**

Correlation significant level=1%=0.180 **, 5%=0.138*, **Note:** TN: Tiller number per plant, SL: Shoot length (cm), RL: Root length (cm), RV: Root volume (cm), SFW: Shoot fresh weight (g), SDW: Shoot dry weight (g), RFW: Root fresh weight (g), RDW: Root dry weight (g), RSRWW: Root to shoot ratio on wet weight basis (g), RSRDW: Root to shoot ratio on dry weight basis (g), P_0: Low phosphorus (0% of P), Control: RDF (60% of P)



Tiller numbers/plant

Shootlength (cm)

Root length (cm)

Root volume (cm)

Shoot fresh weight (g)

Shoot dry weight (g)

Root fresh weight (g)

Root dry weight (g)

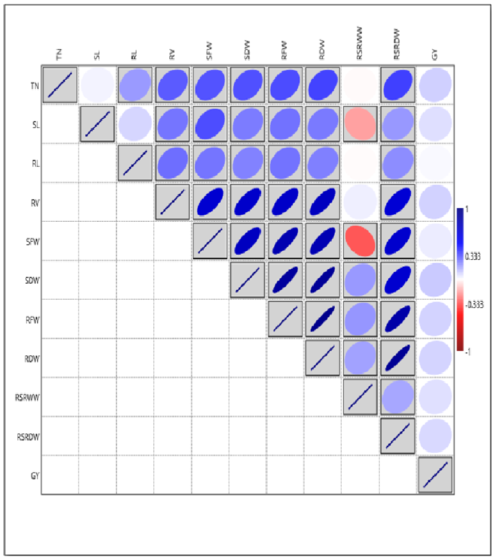
Root/shoot ratio on wet weight basis

Root/shoot ratio on dry weight basis

Note:

Green colour box = Frequency distribution of ILs(BC_1F_3) under low P condition during *Kharif* season (2018-19)
Blue colour box = Frequency distribution of ILs(BC_1F_4) under low P condition during Rabi season (2018-19)
Red colour box = Frequency distribution of ILs (BC_1F_4) under control condition during Rabi season (2018-19)

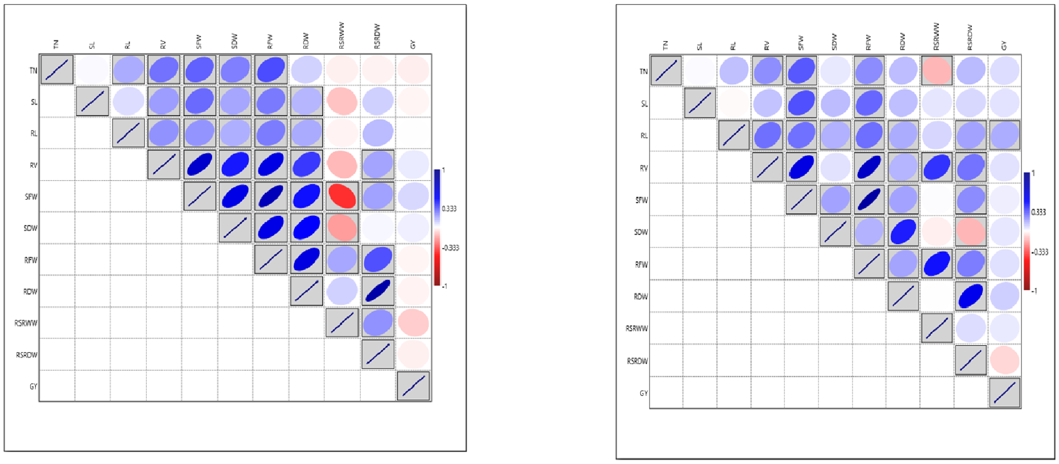
Fig. 1. Boxplots showing the frequency distribution for root architectural traits of BC_1F_3 and BC_1F_4 ILs under low phosphorus and control condition during *Kharif* and Rabi seasons (2018-19).



(A) Under low P condition

Note: TN: Tiller number per plant, SL: Shoot length (cm), RL: Root length (cm), RV: Root volume (cm), SFW: Shoot fresh weight (g), SDW: Shoot dry weight (g), RFW: Root fresh weight (g), RDW: Root dry weight (g), RSRWW: Root to shoot ratio on wet weight basis (g), RSRDW: Root to shoot ratio on dry weight basis (g), Red box: Indicates negative association and Blue box: Indicates positive association; Clockwise direction of the boxes indicates intensity of positive association, anticlockwise direction of the boxes indicates intensity of negative association

Fig. 2. Diagrammatic representation of association between root architectural traits of ILs (BC_1F_3) under low phosphorus condition during *Kharif* season (2018-19).



(A) Under low P condition

(B) Under control condition

Note: TN: Tiller number per plant, SL: Shoot length (cm), RL: Root length (cm), RV: Root volume (cm), SFW: Shoot fresh weight (g), SDW: Shoot dry weight (g), RFW: Root fresh weight (g), RDW: Root dry weight (g), RSRWW: Root to shoot ratio on wet weight basis (g), RSRDW: Root to shoot ratio on dry weight basis (g); Red box: Indicates negative association and Blue box: Indicates positive association; Clockwise direction of the boxes indicates intensity of positive association, anticlockwise direction of the boxes indicates intensity of negative association

Fig. 3. Diagrammatic representation of association between root architectural traits of ILs (BC_1F_4) under low phosphorus and control condition during Rabi season (2018-19).

CONCLUSIONS

The current study revealed that the root length, root volume, shoot dry weight, root dry weigh and root to shoot ratio are the best parameters for indicating the low soil P tolerance due to their high plasticity with availability of nutrients like P from the root zones. Presence of significant variation has been observed along with high GCV and PCV, high heritability coupled with high GAM reported for these traits for the test genotypes studied, indicate the potentiality of the ILs to contribute novel sources for improvement of these root traits under low soil P condition. The association studies of tiller number with root related traits reveals that, inter-correlation among the component traits such as numbers of tillers per plant, root length, shoot length, root volume, shoot fresh and dry weight, root fresh and dry weight and root to shoot ratio on wet and dry weight basis exhibited strong association between them, even considering under stress and control conditions.

Acknowledgement. Authors are grateful to the ICAR-IIRR for providing graded low P plots for phenotypic screening and molecular breeding lab facilities for developing population and screening of the material under Po condition.

Conflict of Interest. None.

REFERENCES

Ahadiyat, Y. R., Hidayat, P. and Susanto, U. (2014). Drought tolerance, phosphorus efficiency and yield characters of upland rice lines. *Emirates Journal of Food and Agriculture*, 25-34.

Chaubey, C. N., Senadhira, D. and Gregorio, G. B. (1994). Genetic analysis of tolerance for phosphorous deficiency in rice (*Oryza sativa* L.). *Theoretical and Applied Genetics*, *89*, 313-317.

Choudhury, A. T. M. A., Kennedy, I. R., Ahmed, M. F. and Kecskés, M. L. (2007). Phosphorus fertilization for rice and control of environmental pollution problems. *Pakistan Journal of Biological Sciences*, *10*(13), 2098-2105.

Cordell, D., Drangert, J. O. and White, S. (2009). The story of phosphorus: global food security and food for thought. *Global Environmental Change*, *19*(2), 292-305.

Da Silva, A., Bruno, I. P., Franzini, V. I., Marcante, N. C., Benitiz, L. and Muraoka, T. (2016). Phosphorus uptake efficiency, root morphology and architecture in Brazilian wheat cultivars. *Journal of Radioanalytical and Nuclear Chemistry*, *307*, 1055-1063.

De Datta, S. K. and Broadbent, F. E. (1988). Methodology for evaluating nitrogen utilization efficiency by rice genotypes. *Agronomy Journal*, *80*(5), 793-798.

Deng, Y., Teng, W., Tong, Y. P., Chen, X. P. and Zou, C. Q. (2018). Phosphorus efficiency mechanisms of two wheat cultivars as affected by a range of phosphorus levels in the field. *Frontiers in Plant Science*, *9*, 1614.

Dobermann, A. and Fairhurst, T. H. (2000). Nutrient disorders and nutrient management. *Potash and Phosphate Institute, Potash and Phosphate Institute of Canada and International Rice Research Institute, Singapore*, 191.

Fageria, N. K. and Knupp, A. M. (2013). Upland rice phenology and nutrient uptake in tropical climate. *Journal of plant nutrition*, *36*(1), 1-14.

Fageria, N. K., Moraes, O. P. and Vasconcelos, M. J. (2013). Upland rice genotypes evaluation for phosphorus use efficiency. *Journal of Plant Nutrition*, *36*(12), 1868-1880.

Fageria, N. K., Wright, R. J. and Baligar, V. C. (1988). Rice cultivar evaluation for phosphorus use efficiency. *Plant and Soil*, *111*, 105-109.

Fioreze, S. L., Castoldi, G., Pivetta, L. A., Pivetta, L. G., Fernandes, D. M. and Büll, L. T. (2012). Tillering of two wheat genotypes as affected by phosphorus levels. *Acta Scientiarum. Agronomy*, *34*, 331-338.

Gunes, A., Inal, A., Alpaslan, M. and Cakmak, I. (2006). Genotypic variation in phosphorus efficiency between wheat cultivars grown under greenhouse and field conditions. *Soil Science and Plant Nutrition*, *52*(4), 470-478.

Hill, J. O., Simpson, R. J., Moore, A. D. and Chapman, D. F. (2006). Morphology and response of roots of pasture species to phosphorus and nitrogen nutrition. *Plant and Soil*, *286*, 7-19.

Hung, H. H. (1985). Studies on tillering ability of rice under phosphorous stress. *Ph. D. Thesis*, A and M University, Texas.

IRRI (1985). IRRI annual report for 1984, International Rice Research Institute, Manila, The Philippines.

Ismail, A. M., Heuer, S., Thomson, M. J. and Wissuwa, M. (2007). Genetic and genomic approaches to develop rice germplasm for problem soils. *Plant molecular biology*, *65*, 547-570.

Katyal, J. C. (1978). Management of phosphorus in lowland rice. *Phosphorus in agriculture*, *73*, 21-34.

Kirk, G. J. D. (1997). Changes in rice root architecture, porosity, and oxygen and proton release under phosphorus deficiency. *The New Phytologist*, *135*(2), 191-200.

Lea, P. J. and Miflin, B. J. (2010). Nitrogen assimilation and its relevance to crop improvement. *Annual Plant Reviews, 42*, *42*, 1-40.

Londo, J. P., Chiang, Y. C., Hung, K. H., Chiang, T. Y. and Schaal, B. A. (2006). Phylogeography of Asian wild rice, *Oryza rufipogon*, reveals multiple independent domestications of cultivated rice, *Oryza sativa*. *Proceedings of the National Academy of Sciences*, *103*(25), 9578-9583.

Lynch, J. (1995). Root architecture and plant productivity. *Plant physiology*, *109*(1), 7.

Lynch, J. P. (2011). Root phenes for enhanced soil exploration and phosphorus acquisition: tools for future crops. *Plant physiology*, *156*(3), 1041-1049.

MacDonald, G. K., Bennett, E. M., Potter, P. A. and Ramankutty, N. (2011). Agronomic phosphorus imbalances across the world's croplands. *Proceedings of the National Academy of Sciences*, *108*(7), 3086-3091.

Matsuo, N., Ozawa, K. and Mochizuki, T. (2009). Genotypic differences in root hydraulic conductance of rice (*Oryza sativa* L.) in response to water regimes. *Plant and Soil*, *316*, 25-34.

Ming, F., Mi, G., Zhang, F. and Zhu, L. (2002). Differential response of rice plants to low-phosphorus stress and its physiological adaptive mechanism. *Journal of Plant Nutrition*, *25*(6), 1213-1224.

Nations, F. A. A. O. O. T. U. (2020). World fertilizer trends and outlook to 2020. *Rome: FAO*.

Raghothama, K. G. (1999). Phosphate acquisition. *Annual review of plant biology*, *50*(1), 665-693.

Rathi, S., Yadav, R. N. S. and Sarma, R. N. (2010). Variability in grain quality characters of upland rice of Assam, India. *Rice science*, *17*(4), 330-333.

Rodríguez, D., Andrade, F. H. and Goudriaan, J. (1999). Effects of phosphorus nutrition on tiller emergence in wheat. *Plant and Soil*, *209*, 283-295.

Rose, T. J., Rose, M. T., Pariasca-Tanaka, J., Heuer, S. and Wissuwa, M. (2011). The frustration with utilization: why have improvements in internal phosphorus utilization efficiency in crops remained so elusive? *Frontiers in Plant Science*, *2*, 73, 1-5.

Vejchasarn, P., Lynch, J. P. and Brown, K. M. (2016). Genetic variability in phosphorus responses of rice root phenotypes. *Rice*, *9*(1), 1-16.

Vinod, K. K. and Heuer, S. (2012). Approaches towards nitrogen-and phosphorus-efficient rice. *AoB Plants*, *1-18*

Wissuwa, M., Kondo, K., Fukuda, T., Mori, A., Rose, M. T., Pariasca-Tanaka, J. and Rose, T. J. (2015). Unmasking novel loci for internal phosphorus utilization efficiency in rice germplasm through genome-wide association analysis. *PLoS One*, *10*(4), e0124215.

Wissuwa, M., Wegner, J., Ae, N. and Yano, M. (2002). Substitution mapping of Pup1: a major QTL increasing phosphorus uptake of rice from a phosphorus-deficient soil. *Theoretical and Applied Genetics*, *105*, 890-897.

Wissuwa, M., Yano, M. and Ae, N. (1998). Mapping of QTLs for phosphorus-deficiency tolerance in rice (*Oryza sativa* L.). *Theoretical and Applied Genetics*, *97*(5-6), 777.

World rice statistics online query facility, IRRI, 2018; http://ricestat.irri.org:8080/wrs.

Zai-Hua, G. U. O., Ping, D. I. N. G., Li-Yuan, H. E. and Cai-Guo, X. U. (2006). Genetic analysis of agricultural traits in rice related to phosphorus efficiency. *Acta Genetica Sinica*, *33*(7), 634-641.

How to cite this article: Honnappa, Anantha M. Siddaiah, Padmashree R., C. Gireesh, Kalyani M. Barbadikar, J.R. Diwan, Manoj C. A., Basavaraj P.S., Muralidhara B., Ajita V. and Banoth Vinesh (2023). Genetic Plasticity for Root Architectural Traits in Backcrossed Population Derived from Wild Rice (*Oryza rufipogon* Griff) under Low Soil Phosphorous Condition. *Biological Forum – An International Journal, 15*(3): 370-378.