Effectiveness of the Classification for the Phosphorus Use Efficiency Traits at the Seedling Stage in Lentil

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Research article

Keywords: Lentil, Phosphorus efficiency, classification, hydroponics, adequate and deficit mediums

Posted Date: December 2nd, 2020

DOI: <https://doi.org/10.21203/rs.3.rs-117870/v1>

Abstract

Background: Understanding the morphology of the root system in lentils is critical for the identification of root characteristics for breeding cultivars with enhanced phosphorus use efficiency (PUE) to better adapt to poor P environments. PUE and variability in root morphological characteristics at the early vegetative stage were investigated among 40 indigenous and exotic lentil genotypes in a hydroponic phenotyping system.

Results: A prerequisite for developing P-efficient crop cultivars is to categorise existing germplasm. In this experiment, 40 lentil genotypes were grown for 24 days under P deficit ($3 \mu\text{m KH}_2\text{PO}_4$) and P adequate ($250 \mu\text{m KH}_2\text{PO}_4$) conditions in hydroponics. Lentil genotypes exhibited significant variability for root, biomass, and P efficiency traits. Different techniques have identified various genotypes of lentils based on the efficiency of phosphorus uptake (PUPE) and the efficiency of phosphorus utilization (PUTE). IG 568229 showed the highest PUPE, while the wild ILWL-15 lentil showed the lowest PUPE in both media. The wild lentil ILWL-95 showed maximum PUTE under P adequate medium. The IC 560135, IG 334, IG 560157 and IG 568229 genotypes were found to be highly efficient at both P levels and to be ideal for a large range of P levels without having a drastic impact on biomass output.

Conclusions: The primary step for breeding more P-efficient crop plants is the classification of the germplasm. IC 560135 and IC 268238 contrasting lentil lines may be useful for mapping population development, mapping and tagging of gene(s), QTLs for PUE in lentil. These efficient P crops also ensure food and nutritional security, in addition to reducing the cost of cultivation.

Background

The cultivated lentil is a diploid ($2n = 2x = 14$) cool-season food legume, with a genome size of around 4063 Mbp [1]. Lentil (*Lens culinaris* Medik. ssp. *culinaris*) is one of the crops originating in the Neolithic Near East that has been associated with the birth of agriculture since early times [2-3]. In South Asia, North America, North Africa, and West Asia, it is primarily cultivated. Minerals, dietary proteins (18-34 percent), prebiotic carbohydrates, fibres, and carbohydrates are abundant in the grains. They play an important role in combating micronutrient deficiencies and alleviating malnutrition in developing countries [4-6]. Owing to their lower glycemic index, modern lifestyle problems such as obesity, cardiovascular diseases and diabetes are addressed by lentils in the diet. [7].

The world's largest producers of lentils were Canada, India and Turkey, accounting for almost 71 percent of total global production. In 2017, almost 7.59 million tonnes of lentils were produced worldwide in an area of 6.58 million ha [8]. Canada ranks first with an area of 2.47 million ha and India is second with an area of 1.66 million ha. New Zealand ranks first with $2,607 \text{ kg ha}^{-1}$ in productivity and China ranks second with $2,314 \text{ kg ha}^{-1}$. At the global level, India's productivity, with 736 kg ha^{-1} , is much lower than the global average of 1153 kg ha^{-1} [8-9].

Lentils are grown in marginal and sub-marginal rainfed agroecosystems in the Indian subcontinent, where inadequate and unbalanced fertiliser use is normal, with medium to low available P being the main cause of lower Indian soil productivity. In India, the use of nutrients (NPK) is generally considered to be low, with the use of P and K in particular being very poor. The average rates of NPK applications are much lower than those normally recommended. In the long run, the imbalanced use of nitrogen does not increase yield or payback and

greatly decreases available P [10]. P deficiency is present in most Indian soils. P depletion will continue to surpass net P additions, and P depletion will continue to increase over the timeframe affecting crop production.

During 2005, the available demand for P fertiliser inputs in agriculture was 14.5 Tg P yr⁻¹ globally and the estimated demand in 2050 will reach to 22-27 Tg P yr⁻¹ (Tg: teragram; 1Tg=10¹² g= 1 million metric tons)[11]. The world's leading producers of phosphatic fertiliser are the United States, China, and Morocco [12]. The US and China have been forced by potential domestic demand to stop rock phosphate exports to others [13]. The predicted global population of 9.7 billion and adequate food production in 2050 rely on the effective future P usage strategy [14]. Phosphorus (P) is vital to the development of plants, growth, cell membranes, the production of DNA, and is important to all living things. It is involved in many key functions, such as DNA synthesis, glycolysis, membrane synthesis, ATP synthesis, energy transfer, photosynthesis, redox reactions, respiration, transformation of sugar and starch, enzyme activation / inactivation, carbohydrate metabolism, nutrient movement, signalling, nitrogen fixation, and trait inheritance [15-17].

The shoot is more affected by the P deficiency than the root and leads to the higher root: shoot ratio [18]. Lack of P supply in crops contributes to dark green foliage colour, and stunting growth with reddish-purple tips interferes with the electron transport chain by reducing orthophosphate accumulation in chloroplast stroma, inhibiting ATP synthase, and failure of photosynthesis [19,20]. The mechanism of soil phosphorus absorption is a very complex phenomenon because in acid soils, P is bound to Fe and Al and in alkaline soils to Ca[21]. Some figures indicate that the P deficit is approximately 5.7 billion ha and that the estimated P concentrations are below the critical level (0.1 to 10 mM) for crop plants in soil solutions [22]. The PUE for crops is dependent on the utilisation of P efficiency and P uptake. PUPE is the ability of the plant to take P from the soil, while PUTE is the ability of the plant to assimilate into biomass / yield the P taken up. The PUE of crops [23, 24] will be enhanced by improvements in either PUPE or PUTE. In wheat [25], maize [26], brassica [27], rice [28], cowpea [29], mungbean [30-31], field pea [32], soybean [33], sorghum [34], pearl millet [35], chickpea [36], and pigeonpea [37], there was a high genetic diversity in crops for PUE and its component traits.

There are many studies available on the PUE in cereal and oilseed crops and very little work is done to investigate the response of lentils to different P levels. The PUE depends on the environmental conditions of both P absorption, P efficiency of utilization, and the nature crop of species [38]. Due to variation in root characteristics such as root architecture, root hair, root density, and specific root volume, the PUPE varies between genotypes, along with root capability to secrete organic acids in the rhizosphere [39-44]. Variation in the quantities of P present in the soil, P distribution in the plant, and biomass, the PUTE differs in cultivars [45]. Researchers noted that cereals > legumes > oilseed crops [46] are the order of efficiency in nutrient use in crops. Under regulated conditions, the variation of PUE in lentils and its relationship with root architectural features was not adequately discussed under variable P supply. These studies can result in an efficient P lentil crop being developed.

The goal of the current study was therefore to evaluate the genetic variation of the efficiency characteristics of the use of phosphorus in different genotypes of lentils and to identify genotypes of lentils on the basis of different methods for use in the breeding programme.

Results

Analysis of variation for traits affecting P and heritability (broad-sense):

For all characteristics tested with adequate P and P deficiency mediums, ANOVA indicated a very significant variability within lentil genotypes. **(Table 2)**. The interaction between genotype and P treatment was very significant, indicating that the root characters examined in two P-mediums were significantly influenced by the genotypes. The coefficient of variation varied from 6.24 percent (TRV) to 38.94 percent (PUTE). The heritability broad-sense ranged from 0.59 to 0.79. The total surface area (TSA) showed 0.79 percent, the highest broad-sense heritability followed by PRL, RAD (0.78 percent each), and the lowest in PUTE (0.12 percent).

Variation of candidate characteristics under sufficient P and P deficit medium: Candidate traits within lentil genotypes showed wide ranges of significant variation at both P levels (Table 3). It was noted that ranges under P deficit were smaller and P adequate was high, but larger ranges were seen under P deficit, PRL, RAD, TRV, and PUTE. Under the adequate P and P deficit media, PRL ranged from 13.67 cm to 35.33 cm and from 22.33 to 50.67 cm. The root average diameter range showed from 0.28 to 0.52 mm and from 0.37 to 0.65 mm P adequate and P deficit mediums. Under P adequate and P deficit media, TRV ranged from 0.15 to 1.08 cm³ and from 0.11 to 1.13 cm³, respectively. Under P adequate and P deficit, the PUTE ranged from 0.12 to 0.37 mg and 0.05 to 8.02 mg, respectively. All the characteristics studied were significantly influenced by P concentrations. It was noted that under the P deficit medium, mean genotypic values of PRL (-33.33 percent), RAD (-24.13 percent), RSR (-51.49 percent), PUTE (-79.68 percent) are significantly lower compared to attributes under the sufficient P medium. In contrast, TRL (43.62 percent), PA (58.33 percent), TSA (48.39 percent), TRV (35.11 percent), TRT (70.33 percent), RF (51.94 percent), RC (81.10 percent), TDW (113.61 percent), SDW (143.24 percent), RDW (27.76 percent), P concentration (PC) (224.80 percent) and PUPE (521.43 percent) showed higher genotypic mean values for the P deficit medium.

P uptake efficiency (PUPE), P utilization efficiency (PUTE), and Biomass:

The main and interactive effects of genotypes and P levels were significant for PUPE, PUTE, and biomass traits (Table 2). Maximum and minimum biomass was observed at P deficit in P2208 (0.083 g) and IG 936(0.04 g), while adequate medium, maximum and minimum biomass in P was observed in IC560135 (0.84 g) and ILWL-15 (0.06 g). The overall biomass reduction was seen in IC 560135 (69 percent), while the minimum biomass reduction was observed in genotype IG 136607 (0.15 percent).

Efficiency of P uptake (PUPE) ranged from (0.01 mg P / gm of plant to 0.089 mg P / gm of plant) under the P deficit medium, with maximum P uptake in genotype IC 268238. The sufficient P medium, PUPE ranged from (0.23 mg P / gm of the plant to 3.66 mg P / gm of the plant), the highest PUPE in the IG 568229 , and the lowest PUPE in the wild ILWL-15 lens in both P mediums. Many of the genotypes differed significantly in response. Generally, there was a decrease in the PUPE of genotypes under P stress. In the event of a P deficit situation, ILWL 95 and IPL 406 showed a steady improvement in P uptake efficiency relative to P in an adequate medium environment (S3Table).

The PUTE is the capacity of any plant to assimilate the P taken into biomass and consequently the yield of grain. In the use of P under a P deficit medium, lentil genotypes showed significant differences between them. Under P deficit conditions, the PUTE ranged from 0.05 mg to 8.02 mg. ILWL 15 showed the highest PUTE and P 2208 showed the lowest PUTE, while PUTE ranged from 0.13 mg to 0.37 mg in the adequate P state. The ILWL-

95 showed the highest PUTE, while in the IG 69568 genotype, the lowest PUTE was found. There was a rise in PUTE for genotypes under P stress. Just four genotypes (i.e. IG 560183, IPL 406, L 4076, and P 2208) showed a gradual decrease in PUTE under medium P deficit rather than adequate P (S3Table). The plant stress factor (percent) was reflected in Fig.1 for phosphorus. One wild lentil (ILWL-15) and two exotic lentil germplasm lines (IG 136607 & IG-Y-50) showed the lowest biomass reduction (< 10%) and the lowest growth and developmental effect in P deficit medium. One of the advanced breeding line, L 4698, followed by a indigenous line IC 268238, showed drastic biomass reduction affecting growth and development.

Classification of genotypes for P efficiency:

Technique 1: Substantial variations between the parameters taken under identical conditions were shown by the genotypes of lentils. In the case of a sufficient medium P, genotype IC560135 (14 out of 15) obtained a maximum score and a minimum score of IC 268238 (7 out of 15). (Table 4). Most of the high-scoring lentil genotypes for TRL, TSA, RC, Biomass, PUPE, and PUTE were under inefficient groups. Under the P deficit medium, the IG-Y-50 genotype scored the highest (13 out of 15), while the lowest score was by L 4649, IG 936, and IG 568229 (8 out of 15) (Table 5). The bulk of the high scoring genotypes got an efficient score for TRL, PA, TSA, biomass, and PUPE. The overall performance of the lentil genotypes was assessed by summing up the adequate conditions for the individual P deficit score and the P in Table 6. IC 560135 (26 out of 30), followed by three genotypes (IG-Y-50 (23 out of 30), IG 334 (23 out of 30), and L 699 (23 out of 30), obtained the maximum point score. The lowest points were scored by IC 268238 (16 out of 30) and ILWL-15 (17 out of 30).

Technique 2: The genotypes of lentils were classified into four groups based on PUTE (Fig 2) and PUPE (Fig . 3) under two P levels. The genotypes ILL 10821, IPL 321, P2116, IG334, IG560157, and IG568229 were categorised as ER under the P deficit medium, whereas they were ENR with the exception of P2116 under the sufficient P supply. Similarly, under deficit P, germplasm IG134349, IC560135, was ENR, as was ER at an adequate P medium. Six genotypes (HM-1, IC268238, Fasciated Mutant, IC560181, IG49, IG73920) were INR in both P mediums, while the wild lentil entries ILWL-95 and ILWL-15 were found to be IR.

In Figure 3, the genotypes L4649, IG69568, IC560135, IG134349, P3233, and IG560183 were ER for deficient P and adequate P media. The ILL10821 genotype was ENR in both P environments; similarly, the IG73920 genotype was INR. The IC268238 genotype was INS to P deficit, whereas the LL699, IG334, IG560157, and IG568229 genotypes were INR to adequate P-medium, whereas the P-deficit conditions were subsequently turned into ENR. In both P-mediums, the ILWL-95, ILWL-15, IG73798, IG129185, IG49, IG112078, and P2208 genotypes were INR.

Technique 3: By this approach, lentil lines were categorised into nine categories. The small variations between the genotypes can be easily distinguished as compared to previous approaches. It has been used at both P levels in order to distinguish and classify. IG 560183 and IG130033 were graded under the P deficit medium as MDM-MP, while under the adequate P medium, they were grouped into HDM-HP (Fig . 4). Under the P deficit condition, IC560135 was rated in the HDM-MP category, whereas in the HDM-HP category it was rated in the adequate P medium. HM1, IG69568, L5126, IG49, and P3233 were grouped as MDM-MP under P deficit medium, whereas under adequate P supply, they were categorised as MDM-LP. The L4698 genotype was under P deficit condition in the LDM-MP group, but the MDM-MP group was acquired under adequate P medium.

The IG-Y-50, LL699, and IG560185 genotypes were classified as HDM-MP under P deficit condition, while MDM-MP came under adequate P supply. Genotypes ILWL-95 and L4076 were classified as LDM-HP under adequate P supply, while genotype ILWL-95 jumped to MDM-HP under P deficit condition, and genotype L4076 obtained class LDM-MP. Genotype IG560206 under P deficit condition was listed as MDM-MP while it became MDM-HP with inadequate P supply. Genotypes IG560157 and IG568229 were labelled as MDM-MP under the P deficit condition, whereas they jumped to HDM-MP under adequate P supply.

The genotype IG136607 was rated as HDM-HP on the basis of the PUPE, at a P deficit state, and converted into MDM-MP at an adequate P supply (Fig . 5). Genotype IG 560183 was classified under P deficiency in MDM-HP, but in HDM-MP under P supply. The genotypes IG560157, IG568229, and IG130033 were grouped under the P deficit condition in MDM-MP, while in the adequate P medium they jumped into HDM-HP. Genotype IG560206 was reported to be MDM-MP in the P deficit, while it was reported to be MDM-LP in the adequate P medium. uThe ILWL-95 genotype was reported to be MDM-MP under the P deficit condition, LDM-LP class under adequate P medium. Under the P deficit, genotypes P3233 and IPL406 were noted as MDM-HP while under the adequate P medium as the MDM-MP category. Genotypes LL699, IG-Y-50, IG560185, and P2116 were classified at the P deficit level as HDM-MP, although they were adequately P-supplied in the MDM-MP class. At P deficit condition, genotypes L4618, IC560181, L4698, P2208, IG936, and Fasciated mutants were rated as LDM-MP, whereas MDM-MP was obtained under the adequate P supply medium.

Technique 4: This is a non-graphical method that makes use of 5 different index parameters. Stress Susceptible index (SSI), if the genotype has a lower index value than the genotype high tolerance score. High tolerance levels have been found for ILWL-95, L 4076, IC 268238, and IG 560185. For P (S4table), the genotype IG 560185 indicated by TOL is highly effective. The lower the index value for the index of tolerance, the greater the amount of tolerance. Genotypes that have high levels of tolerance are IG 560185 and ILWL-15. In the case of MP, GMP, and STI, the greater the index value , the higher the tolerance. Based on all of these three indices, genotype IC 560135 was found to be effective. The ILWL-15 genotype was not efficient. The IC 560135 genotype indicated by the multiple or mean score index (MSI) is P efficient and ILWL-15 as P inefficient.

Discussion

Variation in root traits and biomass related traits:

Lentil genotypes differed for their reaction to the P deficit mediums. Various crops showed variation for their reaction to P, wheat [47-48], oats, barley, triticale and rye [49], maize [50], cotton [51-52], groundnut [53], brassica [54], soybean [55], faba bean [56], common bean [57], lentil [58], and the mungbean [59]. Many studies routinely used targeting to few measures of P-use efficiency [60] and other studies targeted specific root architectural traits [61] and while another vital trait root hair formation was also considered [62]. All these studies, crop species showed substantial genotypic variation for different traits. In 40 different genotypes of lentils, the present studies found significant variations in the root traits along with PUPE, PUTE and biomass. The current study not only highlights the importance of understanding P-efficient germplasm under P-stress conditions, but also points to productive and responsive germplasm in P-adequate medium. (Fig. 2 and Table 6).

All root characteristics, but not PRL and RAD, were negatively influenced by the P-deficit growth medium. Among the output traits of plant dry biomass (TDW, SDW, RDW, and RSR), RSR had a positive impact. PUTE has

demonstrated a beneficial impact in the case of partitioning traits (PCON, PUPE, and PUTE). PRL, RAD, and RSR have historically been considered ideal traits for P deficit medium for selection [63] (Tables 2 and 3). This improvement in root system characteristics makes the plant capable of extracting more and more nutrients from deeper soil layers[64].

For the evaluation of germplasm in P stress and P-adequate conditions, various root architectural features have been considered as important characteristics. Our findings showed that the evaluated characteristics showed approximately normal distribution, substantial variance, medium to high heritability and significant correlations between characteristics. The genetic stability of the traits is demonstrated by high heritability and a lower coefficient of variation [65-67]. These variations provide the genetic basis and the basis for the creation of new varieties that are naturally more P-efficient and more climate-resilient [68-69]. At both P levels, lentil germplasm lines, such as IC 560135, IG 334, IG 560157, and IG 568229, have been found to have high biomass yields, indicating that they are efficient. These lentil germplasm lines are highly valued because, under a wider range of P levels, they produce more biomass. Many researchers have considered that the biomass or dry matter produced under P stress conditions is a vital feature of P efficiency germplasm evaluation [70-71].

The IPL 406 and P 3233, IG 560183 and IC 560135, I-G-Y 50, and IG 69568 lentil germplasm lines showed similar P efficiency and production in our present study, while the P deficit medium showed greater differences as seen in Tables S1 and S2 and Table 3. Plants prefer to regulate biomass partitioning as an essential mechanism in the case of P stress conditions and attempt to infuse more photosynthates into actively growing plant components such as younger leaves and root tissues [61, 72-73]. By increasing the rate of growth of root cortical aerenchyma, leading to decreases in total root respiration and at the cost of the total root [74-75], the root diameter under P stress in plants is increased. Crops under extreme conditions try, as a spontaneous reaction, to increase the root surface area, to try to absorb more nutrients and water to resolve the harsh events of nature [76]. As in the S1 Table, the P efficient germplasm based on scoring also had maximum root dry matter. The stress environment of P significantly increases higher root hair density and root length [77-78], resulting in greater access to available P in deeper soil layers. However, under the P deficit medium, root hairs increase; under the high P medium, growth does not decrease [79]. It was observed under the P deficit medium that the root: shoot ratio increased compared to adequate P media in lentil germplasm. (Table 2). Wheat grown in the P deficit condition under the hydroponic method showed an increased root length [80] and the same in barley under field conditions [81].

In order to see the relationship between P deficit and adequate media, the connection between root characteristics, biomass-related characteristics, and partitioning characteristics was further studied. A positive and significant correlation between root traits, biomass, and partitioning characteristics was indicated by correlation analysis (Fig.6). These correlations may be associated with increased production from the roots of plant hormone cytokinins, which play a crucial role in biomass partitioning [82-83]. This ultimately leads to increased P uptake and its assimilation, leading to greater biomass and grain yield production. PRL was positively and significantly correlated with TRL, TRT, and TSA under both P adequate and deficit means. Selection based on root traits such as TRL, TRT, and TSA for P efficiency will be highly rewarding at the seedling stage. A negative and significant association with all other root traits was shown by the RAD under P deficit medium. It points out that RAD is a key characteristic and can play a key role in distinguishing the availability of P from the root characteristics [84].

In P stress environments, P efficient mungbean genotypes showed higher root volume (RV) and root surface area (RSA) [85]. In plants, the rate of nutrient absorption is directly correlated with the root surface area [86-87]. Higher root lengths and surface area in crop plants, coupled with vigorous root growth, ensure the effective absorption of macro and micronutrients at an early stage [88]. In addition to this, known facts [89-90] are the role and association of root architectural features such as root number and total root length in improving crop biomass and grain yield. Early vigorous root growth not only supports higher biomass production at a preliminary phase in stressful environments, but also ensures good grain yield and productivity.

PCON and PUPE:

The productivity of crop plants depends on P uptake and assimilation, but successful uptake is more important in P deficiency or weak soils where P is not applied or P is much lower, and because of the soil fixation process, a lot of P is not available if applied. In resource-rich countries where adequate or higher doses of P are used, key factors include both P uptake and utilization [91]. In P efficiency breeding, germplasm classification is the first stage. If the material is derived from contrasting germplasm lines, selection for P would be rewarding [92]. PUPE is the ability of the crop to take P (either fixed form or available form) from the soil and PUTE is the efficiency of the crop that uses P to convert it into biomass and grain yield. The sum of PUPE and PUTE is known as PUE [93-95]. In many genotypes of wheat[96-97], rice[98-99], maize[100], brassica[101], chickpea[102], soybean[103], lentil[58], mungbean[59 and 85], and pigeonpea[104], genetic variability for improved P acquisition and use has been reported in the case of P-stressed conditions. Different parameters for estimating P efficiency have been proposed by various researchers, such as the ratio of dry matter produced at deficit and adequate conditions per applied unit of P[105] to total P uptake by the crop[106] and the ratio of higher biologically active P(Pi) to total P taken by the plant[48, 107-108]. Researchers were compelled to classify germplasm lines based on P efficiency and to grow highly productive PUE crop plants because of raising the cost of P fertilisers, small rock phosphate supplies, low P use by farmers, and other geopolitical factors. The key strategy for the production of P efficient crops is successful use of P efficient germplasm, genes, and QTLs targeting PUE enhancement in agriculture [109]. Various methods for grouping germplasm lines have been used by researchers for P efficiency. In the present study, germplasm lines were grouped according to different methods and, when different methods were used, germplasm lines were divided into different groups [110-112]. Germplasm lines were divided into three classes in our study (Tables 4 and 6; Figures 2 and 3). Just one IG-Y-50 germplasm line scored 13 out of 15 in the P deficit medium, and was considered to be effective (E). Based on a score of 08, three genotypes, L 4698, IG 936 and IG 560257, were found to be inefficient (Table 6).

Many researchers have only classified germplasm in low P-medium [110-112]. However, this grouping, when grown in sufficient P-mediums, failed to respond effectively to the response. Although germplasm will be efficient at low P-mediums, under adequate P-mediums, it may not be possible to achieve sufficient biomass to produce yield. A clearer picture will therefore be provided by the classification of genotypes in an adequate P supply medium. As a result, the germplasms were grouped under adequate P-mediums and the response was given in Table 5. The germplasm IC 560135 obtained the maximum score (14 out of 15) under the adequate P medium and was judged to be the most effective. The germplasm IC 268238 with a minimum score (07 out of 15) was described as the most inefficient. In both P-mediums, we need germplasm which performs best, so any score obtained by germplasm has been added and the grouping has been achieved. To our surprise, the majority of the germplasm lines were classified in the same class, with a few minor exceptions. Two IC 560135 and IG-Y-50 germplasm lines achieved the maximum score (26, 24 out of 30, respectively) and are the most effective. The

two IC 268238 and ILWL15 germplasm lines defined by the minimum score, i.e. 16 and 17, respectively, were inefficient, indicating that both P-mediums played a vital role in the classification of the germplasm lines (Table 7).

For better clarification, both Fageria[113] and Kosar and his colleagues[114] have classified genotypes into four classes. The graphical display of genotypes in the four classes I ER ii) ENR iii) IR (iv) INR is included in this classification. Due to higher dry biomass production, two IC560135 and IG-Y-50 lentil germplasm lines were rated as ER under the P deficit medium, but the IG-Y-50 entry slipped into the ENR class with an adequate P medium (Fig 2). A P deficit medium in the ENR category and an adequate P medium in the IR category were observed in the commercial cultivar IPL-406. In the IR class, another IC 268238 lentil germplasm was grouped at P deficit medium, whereas it slipped under adequate P availability in the INR class. PUPE and biomass are vital classification targets. To construct two graphs, PUPE and biomass were used. Under the P deficit medium, IG 560183 was listed as ENR for PUPE at P adequate medium, whereas it was grouped as ER for PUTE under the P deficit medium (Figure 3). Therefore, in order to distinguish the genotypes of lentils, it is also very important to classify them into an adequate P medium.

This technique does not discriminate between the very narrow range between the PUPE and dry matter ER and INR groups, e.g. genotypes L 4649, IPL321 and ILL 10821 (at P deficit) and ILL 10821, L5126 and IG 129185 (at an adequate P medium), the input being close to or on the boundary line between the efficient and inefficient axes (Figure 2). By classifying germplasm into nine categories [115], the next technique overcomes these minor variations (Fig 4). But it was only used under conditions of P deficiency in several crops [110-112]. We used both adequate and deficit P levels in this study to classify genotypes of lentils. In the case of P deficit medium for P uptake efficiency, Germplasm IC 560135 was discovered as HDM-MP, while it was grouped as HDM-HPP under P adequate medium (Fig. 4). In the case of germplasm, IG 560183 and IG 130033 were in the P deficit medium in the MDM-MP class, while P jumped to the HDM-HP class in the adequate medium. This approach was further used to group genotypes for the effectiveness of P utilisation. For both P media, Germplasm line IC 560135 was identified as HDM-MPP (Fig 5). At P deficit, the germplasm line IG 136607 was observed as HDM-HP while it was identified as MDM-MP at P adequate medium. The germplasms IG 560157, IG 568229, and IG 130033 were grouped as HDM-HP at P adequate medium under MDM-MP at P deficit medium.

In the case of other approaches, various indices such as SSI, STI, MPI, GMP, and TOL have been used to understand the degree of tolerance in lentil genotypes. These indices have been used in several crops to measure drought stress. However, given its widespread use, including P stress, it also provides a simple and easy method for the identification of biomass-based tolerant, productive, climate-smart, and contrasting genotypes [116]. The above indices indicated that the tolerance levels of the genotypes ILWL-95, L 4076, IC 268238, and IG 560185 were high. The multiple or mean score index (MSI) indicated that P efficient is the genotype IC 560135 and P inefficient is ILWL-15. The multiple or mean scoring index saves breeder time from the first selection to further screening of selected plants and provides a basis for accurate comparisons of germplasm lines that would be appropriate for exposing the secret underlying crop productivity in high-stress environments[117].

Conclusion

In many agroecosystems, the supply of phosphorus is significantly decreasing due to soil erosion, soil fixation, and more than 50 percent of global cultivated land and most cultivated areas in Africa have been affected. In the low-input agriculture of poor nations, rigorous phosphorous fertilisation is not a common practise. Because of insufficient phosphate deposit supplies, high P fertiliser prices and additional environmental issues, this approach is not feasible in the long term. Higher P-efficiency crops will not only reduce production costs, but also increase food security in developing countries. The development of P-efficient crop plants mainly relies on the identification and classification of germplasm for the efficiency of phosphorus use. In order to graphically differentiate genotypes based on different parameters in both deficit P and adequate media, various methods have been compared.

Methods

Plant materials and plant growth conditions

Screening of 40 lentil genotypes for sufficient P (concentration of 250 μM KH_2PO_4) or P-deficit (concentration of 3 μM KH_2PO_4) root features, including 25 exotic germplasm lines, six advanced breeding lines (ABL), five germplasm lines of Indian origin, and five varieties of commercially released (Table 1). The experiment was hosted at NICRA (National Climate Resilient Agriculture Initiative) in a managed environment facility at the Indian Agricultural Research Institute (IARI), New Delhi, India between November 2018 and October 2019. The chamber temperature (air) was 23/18 °C, and the relative air humidity was maintained by about 45 per cent (± 2 °C) day by night, respectively. The intensity of light was maintained between 450 to 1300 $\mu\text{mol m}^{-2} \text{s}^{-1}$. Lentil seeds were sterilised and cleaned on the surface by 0.1% HgCl_2 (w/v) over three and a half minutes with double-distilled water before they were placed for germination. Uniform seedlings without root injuries transferred to the Hoagland solution at 2 stage of cotyledonary leaf. The nutrient solution contains macro and micronutrients in compliance with [47,118].

In order to determine adequate and deficient levels of P, an experiment was conducted in the preliminary based on chlorophyll content, biomass and other visual symptoms. Two levels P have been maintained using KH_2PO_4 (adequate, P 250 μM and deficit, P 3 μM). The pH of the nutrient solution is adjusted to 6.0 by adding 1 M KOH or 1 M HCl solution. A 2-inch thermocol sheet (Renu Wear[®]) with 5 x 5 cm hole is used to maintain plant and row to rows the distance from plant to plant in order to better facilitate the growing of seedlings. This item covers and fits into plastic containers measuring 30 X 45 X 15 cm with a capacity of 10 L of solution (Plastic trays procured from Bio-Link Pvt. Ltd. New Delhi). For screening, a container with eight genotypes in 3 replicates accommodates 24 seedlings. The aquarium air pump (SOBOTM, 5W, 2-way air pump) has oxidised the solution on a regular basis and needs to change the solution every third day. ICAR-NBPGR and ICAR-IARI New Delhi have the plant materials. It must be collected in compliance with the rules and regulations of the National Biodiversity Agency (NBA) Govt. of India.

Root measurements

To record root parameter data, twenty-four-day old seedlings grown with adequate and deficient P media were used. The intact root system was harvested from each plant and carefully spread, without overlapping roots, over a scanning tray. An Epson professional (EPSON[™], model: V700) root scanner was used to check the roots. TIFF-format grayscale quality images were analysed by WinRhizo[™] (Pro version 2016; Regent Instrument Inc.,

Quebec, Canada). Setup parameters: image resolution of 400 dpi, manual dark root on white background, scanner calibration, 8 bit depth, image resolution of 4395 x 6125 pixels, 0 mm focal length. Roots are distributed in a 30 x 40 x 2 cm acrylic tray with a volume of water of 700 ml. Manually, the debris was separated from the sample root by suspending it in a beaker containing water. The trash-free, cleaner roots were used for study and scanning. The root characteristics were total root length (TRL), primary root length (PRL), total surface area (TSA), root average diameter (RAD), total root volume (TRV), total root tips (TRT), root crossings (RC), and root forks (RF). With the help of a steel measuring scale (EISCO-GROZ™), PRL was measured manually.

Biomass measurements

The hot air oven was used to dry root and shoot parts at 60°C to obtain dry weights. Using precision digital weighing balance (Citizen™, Model: CX 265), root dry weight (RDW) (g / plant) and shoot dry weight (SDW) (g / plant) were recorded. The proportion of RDW data to SDW is known as the root to shoot ratio (RSR). By adding the plant's RDW and SDW, the total dry weight (TDW) (g / plant) was calculated.

Phosphorus estimation of plants

The fine powder was generated from root and shoot samples that were dried. A ratio 9:4 of HNO₃: HClO₄ di-acid mixture was used to obtain a clear solution of 0.1 gm of fine powder after digestion [118]. The whole solution was filtered by the Whatman No.1 philtre paper and a volume of up to 50 ml was achieved. To measure phosphorus (P) [48], the calorimetric method was used. Into a 50 ml volumetric flask, the 2 ml sample being digested was pipetted. 10 ml of solution B (Table S1) was added to this and then up to 50 ml of ddH₂O was added to the volume. The solution mixture needed to stand for half an hour to develop a blue colour. After this, a double beam UV spectrophotometer at 660 nm was used to analyse the solution absorbance. Some blanks were also prepared using double distilled water instead of the digested sample. By using the standard P solution graph, the P concentration (PCON) (mg P / g) dry weight was determined. Combining PUPE and PUTE produces the PUE. As per reference [119], P uptake efficiency (PUPE) (mg P / plant) and P utilisation efficiency (PUTE) (g dry weight / mg P) were measured.

The following formula measures the P stress factor (PSF) [120].

$$PSF (\%) = \frac{SDM (ad.) - SDM (def.)}{SDM (ad.)} \times 100$$

Where

SDM (shoot dry matter), Total Dry weight (TDW), ad. (Adequate; 250 µm KH₂PO₄), def. (deficit; 3 µm KH₂PO₄)

Techniques of Classification.

Technique 1.

Lentil genotypes were classified into 3 groups [110-112].

1. (E)-Efficient: (The genotype mean $> \mu + SD$)
2. (M)-Medium: (The genotype mean between $\mu - SD$ to $\mu + SD$)
- (I)-Inefficient: (The genotype mean $< \mu - SD$).

Efficient (E) to 3, medium (M) to 2, and inefficient (I) score 1 are determined for the respective parameters, and the total score is calculated by applying the individual score to the different genotype parameters.

Technique 2.

This technique classified the lentil genotypes into 4 groups [113-114].

1. ER: Efficient and Responsive genotypes for phosphorus
2. ENR: Efficient and Non-Responsive genotypes for phosphorus
- IR: Inefficient but Responsive genotypes for phosphorus
1. INR: Inefficient and non-responsive genotypes for phosphorus

The entries are referred to as effective, which must have a dry weight higher than the dry weight average. The responsive one shows a PUE higher than the usual PUE, and vice versa.

Technique 3.

This is a graphical technique in which the graph is drawn with dry matter and P uptake, i.e. x and y-axis, respectively. Every axis is divided into three parts: low($> \mu + SD$), medium($\mu - SD$ to $\mu + SD$) and high($< \mu + SD$)[115].

Lentil genotypes were classified into nine groups.

1. LDM-LP: Low dry matter and low phosphorus
2. LDM-MD: Low dry matter and medium phosphorus
3. LDM-HP: Low dry matter and high phosphorus
4. MDM-LP: Medium-dry matter and low phosphorus
5. MDM-MP: Medium-dry matter and medium phosphorus
6. MDM-HP: Medium-dry matter and high phosphorus
7. HDM-LP: High dry matter and low phosphorus
8. HDM-MP: High dry matter and medium phosphorus
9. HDM-HP: High dry matter and high phosphorus

Technique 4.

This is an index technique used in abiotic stress situations such as drought. The indices of phosphorous stress tolerance were calculated using the following formulas based on dry matter (DM).

1. SSI: Stress Susceptibility Index = $(1 - D/C)/(1 - xD/xC)$ [121].
2. TOL: Tolerance Index = $C - D$ [122].
3. MP: Mean Productivity Index = $(C + D)/2$ [122].
4. GMP: Geometric Mean Productivity Index $GMP = \sqrt{C \times D}$ [123].
5. STI: Stress Tolerance Index $STI = (C \times D)/(xC)$ [123].
6. MSI : Mean Score Index $MSI = SSI + TOL + MP + GMP + STI / 5$ [116].

C-Controlled treatment

D-Stressed treatment

In formula C, D is biomass or dry matter of plant (DM) in control (C) and stress (D) treatment.

The xC, xD are mean values for biomass / dry matter genotypes of the aboveground portion of the plant (DM) under control (C) and stressed (D) treatment.

Interpretation of these index values are for SSI and TOL lower the index value means higher tolerance levels. In case of MP, GMP and STI higher the index value means higher tolerance level [116].

List Of Abbreviations

Name	Descriptions
P	Phosphorus
QTL	Quantitative Trait Loci
PUE	Phosphorus Use Efficiency
PUPE	Phosphorus Uptake Efficiency
PUTE	Phosphorus Utilization Efficiency
NPK	Nitrogen, Phosphorus , Potash
PCON	Phosphorus Concentration
ABL	Advanced Breeding Lines
TIFF	Tagged Image File Format
PRL	Primary Root Length
TRL	Total Root Length
TSA	Total Surface Area
RAD	Root Average Diameter
TRV	Total Root Volume
TRT	Total Root Tips
TRC	Total Root Crossings
TRF	Total Root Forks
RDW	Root Dry Weight
SDW	Shoot Dry Weight
TDW	Total Dry Weight
RSR	Root Shoot Ratio
PSF	Phosphorus Stress Factor
UV	Ultra Violet
E	Efficient
M	Medium
I	Inefficient
ER	Efficient but Responsive genotype
ENR	Efficient but Non-Responsive genotype
IR	Inefficient but Responsive genotype
INR	Inefficient but non-responsive genotype

LDM-LP	Low dry matter and low phosphorus
LDM-MD	Low dry matter and medium phosphorus
LDM-HP	Low dry matter and high phosphorus
MDM-LP	Medium-dry matter and low phosphorus
MDM-MP	Medium-dry matter and medium phosphorus
MDM-HP	Medium-dry matter and high phosphorus
HDM-LP	High dry matter and low phosphorus
HDM-MP	High dry matter and medium phosphorus
HDM-HP	High dry matter and high phosphorus
SSI	Stress Susceptibility Index
TOL	Tolerance Index
MP	Mean Productivity Index
GMP	Geometric Mean Productivity Index
STI	Stress Tolerance Index
MSI	Mean Score Index
ANOVA	Analysis Of Variance
df	Degrees of freedom

Declarations

S.No.	Description of declarations	
1.	Ethics approval and consent to participate	Not applicable
2	Consent for publication	Not applicable
3	Availability of data and materials	On fair request, the datasets used and/or analysed during the current study are available from the corresponding author. The ICAR-NBPGR and ICAR-IARI New Delhi materials are available. It can be obtained as per the National Biodiversity Authority (NBA) rules and regulations under the Government of India.
4	Competing interests	The authors note that they do not have any conflicting interests
5	Funding	No unique research grant was issued.
6	Authors' contributions	<p>Conceptualization: MSA, HKD</p> <p>Formal analysis: MSA, NR, AK</p> <p>Funding acquisition: SU, SK , AS</p> <p>Investigation: MSA, NR, VR, RP, GPM</p> <p>Methodology: VR, HKD, RP, MP, DS</p> <p>Project administration: MSA, NR, GPM</p> <p>Resources: GC, RM, SU, AS, SK</p> <p>Supervision: HKD, VR, DS</p> <p>Validation: MP, VR, RM, AK</p> <p>Visualization: MSA, HKD</p>
7	Acknowledgements	The authors are grateful for providing the requisite NICRA facilities for the smooth conduct of research to Dr. A. K. Singh, Head, Genetics Division and Joint Research Director, IARI, New Delhi, Dr. C. Viswanathan, Head, Plant Physiology Division, IARI, New Delhi.
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Tables

Table 1. The list of genotypes of lentils used in the experiment, with their species, nature, and source / origin.

S. No	Name	Species	Nature of material	Source of material
1	HM-1	<i>Lens culinaris</i> subsp. <i>culinaris</i>	Commercially released variety	HAU Hisar, India
2	L 4649	"	Advanced Breeding line	IARI, New Delhi India
3	IG 69568	"	Exotic germplasm	ICARDA, Morocco
4	IC 321808	"	Indian Germplasm	NBPGR, New Delhi India
5	IC 560135	"	Indian Germplasm	NBPGR, New Delhi India
6	IG 136607	"	Exotic germplasm	ICARDA, Morocco
7	IG-Y- 50	"	Advanced Breeding line	IARI, New Delhi India
8	IG 134349	"	Exotic germplasm	ICARDA, Morocco
9	LL 699	"	Advanced Breeding line	PAU Ludhiana India
10	IC 268238	"	Indian Germplasm	NBPGR, New Delhi India
11	ILWL-95	<i>Lens culinaris</i> subsp. <i>orientalis</i>	Wild lentil	ICARDA, Morocco
12	ILWL-15	<i>Lens culinaris</i> subsp. <i>odemensis</i>	Wild lentil	ICARDA, Morocco
13	IG 73798	<i>Lens culinaris</i> subsp. <i>culinaris</i>	Exotic germplasm	ICARDA, Morocco
14	EC 78472	"	Exotic germplasm	ICARDA, Morocco
15	L5126	"	Advanced Breeding line	IARI, New Delhi India
16	Fasciated mutant	"	Advanced Breeding line	IARI, New Delhi India
17	L 4618	"	Advanced Breeding line	IARI, New Delhi India
18	IC 560181	"	Indian Germplasm	NBPGR, New Delhi India
19	IG 129185	"	Exotic germplasm	ICARDA, Morocco
20	IG 49	"	Exotic germplasm	ICARDA, Morocco
21	IG 112078	"	Exotic germplasm	IARI, New Delhi India
22	IG 73920	"	Exotic germplasm	ICARDA, Morocco
23	P 3233	"	Exotic germplasm	ICARDA, Morocco
24	IG 560183	"	Exotic germplasm	IARI, New Delhi India
25	IPL 406	"	Commercially released variety	IIPR, Kanpur India

26	IG 560206	"	Exotic germplasm	ICARDA, Morocco
27	L 4076	"	Commercially released variety	IARI, New Delhi India
28	IG 134656	"	Exotic germplasm	ICARDA, Morocco
29	IG 560185	"	Exotic germplasm	ICARDA, Morocco
30	L 4698	"	Advanced Breeding line	IARI, New Delhi India
31	PL 97	"	Commercially released variety	GBPUAT, Pantnagar India
32	P 2208	"	Exotic germplasm	ICARDA, Morocco
33	ILL 10821	"	Exotic germplasm	ICARDA, Morocco
34	IG 936	"	Exotic germplasm	ICARDA Morocco
35	IPL 321	"	Commercially released variety	IIPR, Kanpur India
36	P 2116	"	Exotic germplasm	ICARDA, Morocco
37	IG 334	"	Exotic germplasm	ICARDA, Morocco
38	IG 560157	"	Exotic germplasm	ICARDA, Morocco
39	IG 568229	"	Exotic germplasm	ICARDA, Morocco
40	IG 130033	"	Exotic germplasm	ICARDA, Morocco

Table 2: Analysis of variance (ANOVA), coefficient of variation (CV) and broad sense heritability for the studied traits under adequate phosphorus (250 μ M KH₂PO₄ concentration) and phosphorous deficit (3 μ M KH₂PO₄ concentration) media.

Variables	Mean squares			CV (%)	Heritability
	Genotype (G)	Phosphorus (P)	G × P		
df	39	1	39		
PRL	149.65*** (0.000)	8166.6*** (0.000)	32.16*** (0.000)	9.55	0.78
TRL	73380.95*** (0.000)	948285.45*** (0.000)	6689.77*** (0.000)	12.52	0.66
TPA	122.59*** (0.000)	3240.59*** (0.000)	147.91*** (0.000)	16.61	0.60
TSA	1111.42*** (0.000)	18998.35*** (0.000)	1007.38*** (0.000)	14.84	0.79
TRV	0.0096*** (0.000)	0.745*** (0.000)	0.0046*** (0.000)	6.24	0.73
RAD	0.1402*** (0.000)	1.342*** (0.000)	0.1105*** (0.000)	15.30	0.78
TRT	353772*** (0.000)	31547.9.4*** (0.000)	185661.11*** (0.000)	9.46	0.64
TRF	341762.78*** (0.000)	5752058.43*** (0.000)	304417.83*** (0.000)	11.70	0.54
TRC	26049.54*** (0.000)	537706.66*** (0.000)	38340.99*** (0.000)	11.36	0.53
TDW	0.0493*** (0.000)	1.633*** (0.000)	0.0277*** (0.000)	11.97	0.41
SDW	0.0413*** (0.000)	1.414*** (0.000)	0.0208*** (0.000)	14.29	0.46
RDW	0.0011*** (0.000)	0.0058*** (0.000)	0.0011*** (0.000)	13.31	0.54
RSR	0.2049*** (0.000)	3.659*** (0.000)	0.151*** (0.000)	23.05	0.69
PCON	5.093*** (0.000)	896*** (0.000)	6.05*** (0.000)	10.29	0.73
PUPE	1.07*** (0.000)	127.70*** (0.000)	1.039*** (0.000)	17.84	0.23
PUTE	2.21*** (0.000)	41.27*** (0.000)	2.14*** (0.000)	38.94	0.12

*, ** and *** significant at $P < 0.05$, $P < 0.01$ and $P < 0.001$ respectively; p-values were given in parentheses behind mean squares.

Table 3 Candidate trait variability among 40 lentil genotypes grown under Adequate ($250 \mu\text{M KH}_2\text{PO}_4$ concentration) and P deficit ($3 \mu\text{M KH}_2\text{PO}_4$ concentration)

Traits	P Levels								% reduction in mean values
	Adequate (250 μM KH ₂ PO ₄)				Deficit (3 μM KH ₂ PO ₄)				
	Mean	Range	SE	SD	Mean	Range	SE	SD	
Root Traits									
PRL	22.95	(13.67-35.33)	0.75	4.79	34.61	(22.33-50.67)	0.96	6.13	-33.33
TRL	413.91	(120.57-673.77)	19.38	122.62	288.19	(60.68-563.68)	17.07	107.95	43.62
PA	19.95	(5.07-33.51)	1.24	7.87	12.60	(3.23-29.51)	0.838	5.30	58.33
TSA	54.58	(14.25-106.33)	3.33	21.05	36.78	(10.32-90.46)	2.56	16.21	48.39
RAD	0.349	(0.28-0.52)	0.006	0.043	0.46	(0.37-0.65)	0.008	0.053	-24.13
TRV	0.581	(0.15-1.08)	0.032	0.204	0.43	(0.11-1.13)	0.032	0.205	35.11
TRT	555.233	(140-1937)	56.211	355.51	325.933	(34.33-1072.67)	36.54	231.13	70.33
TRF	759.400	(133-2002.33)	58.94	372.80	499.77	(72.33-1221)	43.70	276.42	51.94
TRC	211.401	(39-505.67)	18.79	118.86	116.73	15-447)	13.54	85.64	81.10
Biomass related Traits									
TDW	0.314	(0.06-0.84)	0.022	0.142	0.147	(0.04-0.34)	0.010	0.066	113.61
SDW	0.2627	(0.04-0.76)	0.020	0.127	0.108	(0.03-0.26)	0.0099	0.060	143.24
RDW	0.052	(0.01-0.12)	0.003	0.021	0.0407	(0.01-0.08)	0.0024	0.015	27.76
RSR	0.228	(0.1-1.29)	0.028	0.179	0.486	(0.12-1.08)	0.045	0.290	-51.49
Uptake and utilization traits									
P CON	5.58	(2.72-8.66)	0.224	1.42	1.718	(0.14-6.08)	0.205	1.30	224.80
PUPE	1.74	(0.23-3.66)	0.125	0.79	0.28	(0.01-1.29)	0.043	0.275	521.43
PUTE	0.193	(0.12-0.37)	0.009	0.06	0.95	(0.05-8.02)	0.193	1.22	-79.68

Table 4. Grouping lentil genotypes into efficient (E), medium (M) and inefficient (I) class under adequate P supply based on their index scores of different parameters. (Adequate P KH_2PO_4 of 250 μM)

S. No	Name	SDW	RDW	RSR	PUPE	PUTE	Total of 15
1	HM-1	M	M	M	M	I	9
2	L 4649	M	E	M	M	M	11
3	IG 69568	M	M	M	M	I	9
4	IC 321808	M	M	M	M	M	10
5	IC 560135	E	E	M	E	E	14
6	IG 136607	M	M	M	M	M	10
7	IG-Y- 50	M	E	M	M	M	11
8	IG 134349	M	M	M	M	M	10
9	LL 699	M	E	M	E	M	12
10	IC 268238	I	I	M	I	M	07
11	ILWL-95	I	I	M	I	E	08
12	ILWL-15	I	I	M	I	E	08
13	IG 73798	M	M	M	M	M	10
14	EC 78472	M	M	M	E	M	11
15	L5126	M	M	M	M	M	10
16	Fasciated mutant	M	M	M	M	M	10
17	L 4618	M	M	M	M	M	10
18	IC 560181	M	M	M	M	M	10
19	IG 129185	M	M	M	M	M	10
20	IG 49	M	M	M	M	I	09
21	IG 112078	M	M	M	M	M	10
22	IG 73920	M	M	M	M	M	10
23	P 3233	M	M	M	E	I	10
24	IG 560183	E	M	M	M	E	12
25	IPL 406	M	I	M	M	M	09
26	IG 560206	M	M	M	M	E	11
27	L 4076	M	M	E	I	E	11
28	IG 134656	M	M	M	M	M	10
29	IG 560185	M	M	M	M	M	10
30	L 4698	M	M	M	M	M	10

31	PL 97	M	M	M	M	M	10
32	P 2208	I	M	M	I	M	08
33	ILL 10821	M	M	M	M	M	10
34	IG 936	M	M	M	M	M	10
35	IPL 321	M	M	M	M	M	10
36	P 2116	M	M	M	M	M	10
37	IG 334	E	E	M	E	M	13
38	IG 560157	E	M	M	E	M	12
39	IG 568229	E	E	M	E	M	13
40	IG 130033	M	E	M	M	M	11

Table 5. Grouping lentil genotypes into efficient (E), medium (M) and inefficient (I) class under deficit P supply based on their index scores of different parameters. (Deficit P KH_2PO_4 of 3 μM).

S. No	Name	SDW	RDW	RSR	PUPE	PUTE	Total
1	HM-1	I	M	E	M	M	10
2	L 4649	M	E	M	M	M	11
3	IG 69568	M	M	M	M	M	10
4	IC 321808	M	E	E	M	M	12
5	IC 560135	E	M	M	E	M	12
6	IG 136607	E	M	M	M	M	11
7	IG-Y- 50	E	E	M	E	M	13
8	IG 134349	M	M	I	M	M	09
9	LL 699	E	M	M	M	M	11
10	IC 268238	I	M	E	M	I	09
11	ILWL-95	M	M	E	M	M	11
12	ILWL-15	I	I	M	M	E	09
13	IG 73798	M	M	M	M	M	10
14	EC 78472	M	M	M	M	M	10
15	L5126	M	I	M	M	M	09
16	Fasciated mutant	I	M	E	M	M	10
17	L 4618	I	M	M	M	M	09
18	IC 560181	I	M	E	M	M	10
19	IG 129185	M	E	E	M	M	12
20	IG 49	M	E	E	M	M	12
21	IG 112078	M	M	M	M	M	10
22	IG 73920	M	M	M	M	M	10
23	P 3233	M	M	M	E	M	11
24	IG 560183	M	M	M	E	M	11
25	IPL 406	M	E	M	E	M	12
26	IG 560206	I	M	M	M	M	09
27	L 4076	M	M	M	M	M	10
28	IG 134656	M	M	M	M	M	10
29	IG 560185	E	M	M	M	M	11
30	L 4698	I	I	M	M	M	08

31	PL 97	M	M	M	M	M	10
32	P 2208	M	M	M	M	M	10
33	ILL 10821	M	M	M	M	M	10
34	IG 936	I	I	M	M	M	08
35	IPL 321	M	M	M	M	M	10
36	P 2116	E	E	M	M	M	12
37	IG 334	E	M	M	M	M	11
38	IG 560157	M	M	M	M	M	10
39	IG 568229	M	I	I	M	M	08
40	IG 130033	M	M	M	M	M	10

Table 6. Total score and score of lentil genotypes grown under hydroponic conditions at deficit and adequate P condition. (Adequate P; KH_2PO_4 concentration of 250 μm , P deficit; KH_2PO_4 concentration of 3 μm)

S. No	Name	Score at deficit P level/ out of 15 DF	Score at adequate P level/ out of 15 AD	Total Score/ out of 30
1	HM-1	10	9	19
2	L 4649	11	11	22
3	IG 69568	10	9	19
4	IC 321808	12	10	22
5	IC 560135	12	14	26
6	IG 136607	11	10	21
7	IG-Y- 50	13	11	24
8	IG 134349	9	10	19
9	LL 699	11	12	23
10	IC 268238	9	7	16
11	ILWL-95	11	8	19
12	ILWL-15	9	8	17
13	IG 73798	10	10	20
14	EC 78472	10	11	21
15	L5126	9	10	19
16	Fasciated mutant	10	10	20
17	L 4618	9	10	19
18	IC 560181	10	10	20
19	IG 129185	12	10	22
20	IG 49	12	9	21
21	IG 112078	10	10	20
22	IG 73920	10	10	20
23	P 3233	11	10	21
24	IG 560183	11	12	23
25	IPL 406	12	9	21
26	IG 560206	9	11	20
27	L 4076	10	11	21
28	IG 134656	10	10	20
29	IG 560185	11	10	21

30	L 4698	8	10	18
31	PL 97	10	10	20
32	P 2208	10	8	18
33	ILL 10821	10	10	20
34	IG 936	8	10	18
35	IPL 321	10	10	20
36	P 2116	12	10	22
37	IG 334	11	13	24
38	IG 560157	10	12	22
39	IG 568229	8	13	21
40	IG 130033	10	11	21

Figures

Figure 1

Graphical distribution of lentil genotypes on the basis of phosphorous stress factor (PSF) as a percentage increase in order based on their growth in P deficit and P adequate media.

Figure 1

Graphical distribution of lentil genotypes on the basis of phosphorous stress factor (PSF) as a percentage increase in order based on their growth in P deficit and P adequate media.

Figure 2

Graphical distribution of lentil genotypes into four groups for PUTE; (a) P deficit availability (KH_2PO_4 3 μM); (b) P adequate availability (KH_2PO_4 250 μM) .

Figure 2

Graphical distribution of lentil genotypes into four groups for PUTE; (a) P deficit availability (KH_2PO_4 3 μM); (b) P adequate availability (KH_2PO_4 250 μM) .

Figure 3

Graphical distribution of lentil genotypes into four groups for PUPE; (a) P deficit availability (KH_2PO_4 3 μM); (b) P adequate availability (KH_2PO_4 250 μM)

Figure 3

Graphical distribution of lentil genotypes into four groups for PUPE; (a) P deficit availability (KH_2PO_4 3 μM); (b) P adequate availability (KH_2PO_4 250 μM)

Figure 4

Graphical distribution and classification of lentil genotypes in nine groups ((a) P deficit availability (KH₂PO₄ 3 μM); (b) P adequate availability (KH₂PO₄ 250 μM) for PUTE.

Figure 4

Graphical distribution and classification of lentil genotypes in nine groups ((a) P deficit availability (KH_2PO_4 3 μM); (b) P adequate availability (KH_2PO_4 250 μM) for PUTE.

Figure 5

Graphical distribution and classification of genotypes of lentils into nine groups for PUPE (a) P deficit availability (KH_2PO_4 3 μM); (b) P adequate availability (KH_2PO_4 250 μM).

Figure 5

Graphical distribution and classification of genotypes of lentils into nine groups for PUPE (a) P deficit availability (KH_2PO_4 3 μM); (b) P adequate availability (KH_2PO_4 250 μM).

Figure 6

Pearson's Correlation coefficients upper diagonal (P adequate) and lower diagonal (P deficit) the circles boxed (significance at 95 % level) between the studied traits. (A: PRL, B: TRL, C: TPA, D: TSA, E: TRV, F: RAD, G: TRT, H: TRF, I: TRC, J: TDW, K: SDW, L: RDW, M: RSR, N: PCON, O: PUPE, and P: PUTE.)

Figure 6

Pearson's Correlation coefficients upper diagonal (P adequate) and lower diagonal (P deficit) the circles boxed (significance at 95 % level) between the studied traits. (A: PRL, B: TRL, C: TPA, D: TSA, E: TRV, F: RAD, G: TRT, H: TRF, I: TRC, J: TDW, K: SDW, L: RDW, M: RSR, N: PCON, O: PUPE, and P: PUTE.)

Supplementary Files

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