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Grain Yield, Dry Weight and Phosphorus Accumulation and Translocation in Two Rice (*Oryza sativa* L.) Varieties as Affected by Salt-Alkali and Phosphorus

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Abstract: Salt-alkali is the main threat to global crop production. The functioning of phosphorus (P) in alleviating damage to crops from saline-alkaline stress may be dependent on the variety of crop but there is little published research on the topic. This pot experiment was conducted to study if P has any effect on rice (*Oryza sativa* L.) yield, dry matter and P accumulation and translocation in salt-alkaline soils. Plant dry weight and P content at heading and harvest stages of two contrasting saline-alkaline tolerant (Dongdao-4) and sensitive (Tongyu-315) rice varieties were examined under two saline-alkaline (light versus severe) soils and five P supplements (P0, P50, P100, P150 and P200 kg ha^{-1}). The results were: in light saline-alkaline soil, the optimal P levels were found for P150 for Dongdao-4 and for P100 for Tongyu-315 with the greatest grain dry weight and P content. Two rice varieties obtained relatively higher dry weight and P accumulation and translocation in P0. In severe saline-alkaline soil, however, dry weight and P accumulation and translocation, 1000-grain weight, seed-setting rate and grain yield significantly decreased, but effectively increased with P application for Dongdao-4. Tongyu-315 showed lower sensitivity to P nutrition. Thus, a more tolerant variety could have a stronger capacity to absorb and translocate P for grain filling, especially in severe salt-alkaline soils. This should be helpful for consideration in rice breeding and deciding a reasonable P application in saline-alkaline soil.

Keywords: saline-alkaline tolerance; phosphorus application; optimal phosphorus; 1000-grain weight; seed-setting rate

1. Introduction

Soil salinity is one of the major abiotic stresses on agricultural production throughout the world. There are approximately 9 × 10^8 ha saline soils around the world and 2.33 × 10^6 ha severe saline-alkaline soils in the Songnen plain in Northeast China [1,2]. With high salt concentration and high pH, soil salinity seriously reduces crop growth and grain yield through induced osmotic stress, ionic toxicity and difficulty in P uptake [3,4].

Phosphorus deficiency and salinity were believed to be two independent factors to crop P uptake, plant growth and yield [5,6]. Root P absorption has always been restrained by the competition of Na^+,

Cl^-, $CO_3{}^{2-}$ and other salt ions, or changed into insoluble phosphate by the combination of exchangeable Ca^{2+} in saline-alkaline conditions [7,8]. Thus, saline-alkaline stress occurs generally when there is plant P deficiency. Restricted P diffusion and movement make it difficult for crops to absorb P in saline-alkaline soil [9,10]. The ionic imbalance, stomatal closure and reactive oxygen induced by saline-alkaline stress can seriously damage plant photosynthesis and carbohydrate synthesis, and then suppress plant biomass and P accumulation and translocation [11]. Mittler and Blumwald [12] regard the mixed stress environment of salt-alkali and P deficiency as a new type of abiotic stress, which might require new adaptation strategies for crops to be able regulate them. The characteristics of plant growth, dry weight (DW) and P accumulation and translocation from vegetable parts to grains during crop maturity also vary with different crop varieties, growth stages, saline-alkaline soil conditions and P supplementation [13,14].

Crops generally have different strategies in regulating ionic-selective absorption and metabolic balance in salinity [15,16]. Aslam et al. [17] found lower shoot Na^+ and Cl^- but higher P and Zn^{2+} in salt-tolerant tice varieties than in sensitive ones. Tolerant varieties can effectively decrease the absorption of Na^+ and Cl^- and remobilize toxic ions into vacuoles to promote root development and nutrient uptake [18]. Tian et al. [19] found that tolerant rice varieties accumulated significantly higher biomasses and yields at maturity under saline-alkaline stress. With P absorption supressed, some varieties can maintain a stronger ability to gain greater plant biomass and grain yield with a relatively lower tissue P content [20]. The DW and nutritional translocation can partly increase with dynamic carbohydrate accumulation in grain under stress conditions [21,22].

Phosphorus plays an important role in crop growth and harvest. It has been thought that P application can effectively alleviate the adverse effects of salinity on crops [23,24]. A higher root biomass and leaf K^+ and P content was found in tomatoes under salt stress after P application, which increased the intracellular osmotic potential, maintained photosynthesis and carbohydrate synthesis, and then improved P translocation to the fruit part [25]. The yield components of rice, such as panicle number, seed-setting rate and grain weight significantly increased with P fertilization [26]. As a result, an over-dose of P fertilization is occurring in traditional-agricultural farmlands especially in saline-alkaline soil in order to gain the "ideal" grain yields. However, it turns out that excessive P application leads to partly decreased crop yield, even enormous resource waste, serious environmental pollution, and many other problems [27,28]. Dewit [29] believed that all yield components could be obtained using an optimal P level, and the dry weight translocation from vegetable parts to grains would then be the greatest. However, an optimal P level in normal soil may not be optimal in saline-alkaline soil for a given crop variety. This needs more research. An optimal P fertilization depends on the soil conditions and crop varieties.

The relationships between rice development, P accumulation and translocation with P application and saline-alkaline stress are not clear. To study these relationships, the saline-alkaline-tolerant variety Dongdao-4 and the saline-alkaline-sensitive variety Tongyu-315 were used to examine grain yield, DW and P accumulation and translocation with P application in different saline-alkaline soils. The main purposes of this study are to determine: (a) How does rice development, yield, P accumulation and translocation respond to different saline-alkaline stress and P treatments? (b) Is "the greater the application of P, the higher the saline-alkaline tolerance and yield for rice varieties" accurate?

2. Materials and Methods

2.1. Plant Growth and Experimental Set-Up

Two rice varieties (Dongdao-4, saline-alkaline-tolerant, and Tongyu-315, saline-alkaline-sensitive) with similar flowering dates were chosen in this pot experiment. Dongdao-4 is from the Northeast Institute of Geography and Agroecology, Chinese Academy of Sciences, Changchun, Jilin, China, while Tongyu-315 is from the Tonghua Academy of Agricultural Sciences, Meihekou, Jilin, China. The pot experiment was conducted in May-September 2015 in a glasshouse at the Da' an-Sodic Land Experiment Station, located in Da'an county, Jilin (45°35′58″–45°36′28″N, 123°50′27″–123°51′31″E), a typical saline-alkaline region in the Songnen Plain, Northeast China.

Fully developed rice seeds were germinated in distilled water for 5 days and then sown on disks on the 20 April 2015. Six uniform seedlings were transplanted into two holes in a plastic pot (34 cm diameter × 29 cm depth) that was filled with 18 kg soil media (see below) on the 30 May and grown in a glasshouse (day/night temperature; 32/17 °C, 5 cm running water layer in each pot). Two uniform seedlings remained in a hole after 7 days of transplantation. Two types of saline-alkaline soils (light saline-alkaline soil, LSA, versus severe saline-alkaline soil, SSA) from 0 to 20 cm depth of rice fields were air-dried and then passed through a 5 mm sieve. The basic soil chemical properties are listed in Table 1.

Table 1. Physical and chemical properties of two soil types.

Soil Type	pH	EC μS cm^{-1}	ENa^+ cmol kg^{-1}	CEC cmol kg^{-1}	Organic Matter %	Total N mg kg^{-1}	Available N mg kg^{-1}	Total P mg kg^{-1}	Available P mg kg^{-1}
LSA	8.27	271.0	1.75	18.00	1.77	740.4	153.9	384.0	35.15
SSA	9.09	395.7	3.19	14.81	1.18	615.1	88.9	344.2	28.60

LSA, light saline-alkaline soil; SSA, severe saline-alkaline soil. pH and electrical conductivity (EC) were determined under soil: water = 1:5; Exchangeable sodium (ENa^+) was determined with NH_4OAC and NaOH exchange method; Cation exchange capacity (CEC) was determined with the NH_4OAC exchange method; Organic matter was determined with the potassium dichromate method; Total N was determined with the Kjeldahl method; total P, available -N and -P were determined with the NaOH fusion, alkaline hydrolysis diffusion method, and $NaHCO_3$ extraction method, respectively.

Five phosphorus fertilization levels were administered in each soil type: P0 kg ha^{-1} (0 g pot^{-1}), P50 kg ha^{-1} (2.5 g pot^{-1}), P100 kg ha^{-1} (5 g pot^{-1}), P150 kg ha^{-1} (7.5 g pot^{-1}), and P200 kg ha^{-1} (10 g pot^{-1}). The phosphorus fertilizer used was triple super phosphate. The same nitrogen (N) and potassium (K) fertilization rates were applied: 180 kg N ha^{-1} (2.5 g N pot^{-1} as urea) and 80 kg K ha^{-1} (1 g K pot^{-1} as potassium sulphate). Four days before transplanting the rice, 40% N, 100% P and 70% K were applied as base fertilizer on the 26 May, 30% N as a topdressing for tillering on the 14th June (15 days after transplanting), and then the remaining 30% N and 30% K were applied as topdressings for booting on the 14 July (45 days after transplanting). In a total of 120 pots (2 rice varieties × 2 soil types × 5 P levels × 2 stages × 3 replicates), the experiment was of a completely randomized design.

2.2. Experimental Sampling and Measurement

Root, shoot and/or grain parts were collected and washed in distilled water at the heading stage (63 days after transplantation) and the maturity stage (105 days after transplantation). The dry weight of each plant part was determined after destroying enzyme activity at 105 °C for 2 h and then oven-dried at 80 °C to a constant weight. The total sample was shredded and a sub-sample was digested completely by H_2SO_4 and H_2O_2 for total P measurement [28]. Plant P concentrations were measured with the Mo-Sb Spectrochrometry method by a Smart Chem 300 elemental analyser (Advanced Monolithic Systems, Graz, Italy). The 1000-grain weight, seed-setting rate (SR) and tissue DW and P translocation at maturity were also measured.

Parameters were calculated as follows [13,30]:

P content (mg pot^{-1}) = DW of sub-sample (g) × P concentration (mg g^{-1})
Seed-setting rate (SR, %) = Number of filled grains/ total grains
Dry weight translocation (DWT, g pot^{-1}) = total DW at heading − (shoot + root) DW at maturity.
Contribution of DW accumulation to grains (CDWAG, %) = (DWT/grain DW) × 100.
Harvest index (HI) = grain DW/total aboveground DW at maturity.
Phosphorus translocation (PT, mg pot^{-1}) = total P content at heading − (shoot + root) P content at maturity.

Contribution of phosphorus accumulation to grains (CPAG, %) = (PT/grain P content at maturity) × 100.

Phosphorus harvest index (PHI) = grain P content at maturity/total P content of above ground DW at maturity.

2.3. Statistical Analysis

Data (means ± SE, n = 3) were subjected to the analysis of variance (ANOVA) and then determined by the Tukey significance test at $p < 0.05$ to determine varietal differences between treatments. Stepwise backward regression was used to evaluate relationships between rice dry weight and tissue P content of varieties and saline-alkaline soils. Statistical analyses were carried out using the SPSS 20.0 (SPSS, Chicago, IL, USA).

3. Results

3.1. DW Production

Shoot, root and total DW of rice were significantly different among varieties, saline-alkaline soils and P levels at the heading stage (Table 2). In LSA soil, Dongdao-4 had the highest shoot DW in P150 (78.69 g) and the lowest shoot DW in P50 (61.56 g). Root DW of Dongdao-4 was higher in P0 and P150 (about 11.50 g) than in other P levels. Tongyu-315 had a similar root DW with approximately 11.50 g among P levels. Plant growth of the two rice varieties was seriously restrained by SSA stress but differently affected by P treatment. Dongdao-4 had increasing shoot DW from 42.13 g (P0) to 61.57 g (P200) and root DW from 6.40 g (P0) to 7.77 g (P150) with P application. DW of Tongyu-315 changed less among the five P levels.

Table 2. Plant dry weight at rice heading stage under five P treatments in two saline-alkaline soils.

P Level	Soils	Shoot (DW g pot^{-1})		Root (DW g pot^{-1})		Total (DW g pot^{-1})	
		Dongdao-4	Tongyu-315	Dongdao-4	Tongyu-315	Dongdao-4	Tongyu-315
P0	LSA	70.04 ± 1.08 b, x, α	67.97 ± 1.58 ab, x, α	11.94 ± 0.13 a, x, α	10.78 ± 0.41 a, x, α	81.98 ± 1.16 b, x, α	78.75 ± 1.88 a, x, α
	SSA	42.13 ± 1.22 c, y, α	39.52 ± 1.2 8ab, y, α	6.40 ± 0.20 bc, y, α	4.92 ± 0.15 b, y, β	48.53 ± 1.40 c, y, α	44.44 ± 1.42 ab, y, α
P50	LSA	61.56 ± 1.34 d, x, α	62.88 ± 1.14 b, x, α	9.33 ± 0.21 b, x, β	11.78 ± 0.32 a, x, α	70.89 ± 1.55 d, x, α	74.66 ± 1.33 a, x, α
	SSA	50.62 ± 1.43 b, y, α	37.49 ± 1.33 ab, y, β	7.33 ± 0.16 ab, y, α	6.11 ± 0.37 a, y, β	57.95 ± 1.59 b, y, α	43.60 ± 1.67 ab, y, β
P100	LSA	64.06±0.57 cd, x, β	67.77 ± 1.01 ab, x, α	9.63 ± 0.35 b, x, β	11.09 ± 0.11 a, x, α	73.69 ± 0.86 cd, x, β	78.86 ± 1.03 a, x, α
	SSA	54.22 ± 0.95 b, y, α	33.28 ± 0.54 b, y, β	7.65 ± 0.30 a, y, α	4.53 ± 0.06 a, y, β	61.88 ± 1.12 ab, y, α	37.81 ± 0.57 b, y, β
P150	LSA	78.69 ± 1.62 a, x, α	69.09 ± 0.58 a, x, β	11.06 ± 0.30 a, x, α	11.27 ± 0.51 a, x, α	89.75 ± 1.52 a, x, α	80.36 ± 1.07 a, x, β
	SSA	55.69±1.18 b, y, α	38.49 ± 2.98 ab, y, β	7.77 ± 0.10 a, y, α	4.53 ± 0.23 a, y, β	63.46 ± 1.08 ab, y, α	43.02 ± 2.77 ab, y, β
P200	LSA	67.77 ± 0.74 bc, x, α	66.13 ± 1.2 6ab, x, α	8.92 ± 0.29 b, x, β	12.09 ± 0.17 a, x, α	76.70 ± 0.99 bc, x, α	78.22 ± 1.10 a, x, α
	SSA	61.57 ± 1.05 a, y, α	41.58 ± 1.40 a, y, β	6.29 ± 0.20 c, y, α	4.37 ± 0.14 a, y, β	67.86 ± 1.25 a, y, α	45.96 ± 1.49 a, y, β

LSA, light saline-alkaline soil; SSA, severe saline-alkaline soil; P0, 0 kg P ha^{-1}; P50, 50 kg P ha^{-1}; P100, 100 kg P ha^{-1}; P150, 150 kg P ha^{-1}; P200, 200 kg P ha^{-1}. Values (means ± SE, n = 3) followed by different letters designate significant differences ($p < 0.05$) between P levels in the same column for a given rice variety and a given soil (a, b, c, d); between soils in the same column for a given variety and a given P level (x, y); and between rice varieties in the same row for a given P level and a given soil (α, β), respectively.

When it came to the harvest stage, rice varieties showed lower shoot and root DW than that in the heading stage under LSA soil (Table 3). The plant DW was similar among the two varieties at low P levels (P50 and P100) but distinctly different at high P levels (P100–P200) in the two soils. Dongdao-4 had the highest shoot, grain and root DW in P150 in LSA soil (68.90 g, 78.04 g and 10.81 g, respectively). The total plant DW also increased from 91.32 g to 137.70 g with P0 to P200 in SSA soil. Tongyu-315 obtained the highest grain and total plant DW in P100 with 76.08 g and 150.21 g in LSA soil, 44.18 g and 97.27 g in SSA soils, respectively.

Table 3. Plant dry weight at rice harvest stage under five P treatments in two saline-alkaline soils.

P Level	Soils	Shoot (DW g pot^{-1})		Grain (DW g pot^{-1})		Root (DW g pot^{-1})		Total (DW g pot^{-1})	
		Dongdao-4	Tongyu-315	Dongdao-4	Tongyu-315	Dongdao-4	Tongyu-315	Dongdao-4	Tongyu-315
P0	LSA	60.87 ± 0.48 b, x, α	59.99 ± 1.28 c, x, α	70.35 ± 2.00 bc, x, α	69.24 ± 1.34 bc, x, α	9.31 ± 0.33 b, x, α	9.58 ± 0.28 a, x, α	140.54 ± 2.73 bc, x, α	138.81 ± 1.42 b, x, α
	SSA	48.10 ± 0.46 c, y, α	46.84 ± 0.82 b, y, α	38.22 ± 1.33 d, y, α	35.11 ± 0.39 cd, y, α	5.00 ± 0.15 c, y, α	5.44 ± 0.19 bc, y, α	91.32 ± 1.33 d, y, α	87.39 ± 0.61 b, y, α
P50	LSA	58.16 ± 0.96 c, x, α	55.24 ± 1.31 c, x, α	63.20 ± 2.00 d, x, α	64.29 ± 0.99 c, x, α	7.83 ± 0.17 c, x, α	8.17 ± 0.17 b, x, α	129.19 ± 3.11 d, x, α	127.70 ± 2.27 c, x, α
	SSA	47.96 ± 1.41 c, y, α	47.80 ± 1.39 ab, y, α	32.90 ± 0.77 e, y, α	31.75 ± 0.44 d, y, α	4.16 ± 0.13 d, y, β	5.97 ± 0.19 b, y, α	85.02 ± 2.15 e, y, α	85.51±1.21 b, y, α
P100	LSA	55.61 ± 0.83 d, x, β	65.55 ± 0.49 ab, x, α	66.03±0.69 cd, x, β	76.08 ± 0.93 a, x, α	10.34 ± 0.28 ab, x, α	8.58 ± 0.14 ab, x, β	131.98 ± 0.37 cd, x, β	150.21 ± 0.89 a, x, α
	SSA	46.50 ± 1.08 c, y, α	46.11 ± 0.37 b, y, α	46.24 ± 0.81 c, y, α	44.18 ± 1.04 a, y, α	4.90 ± 0.08 c, y, β	6.97 ± 0.15 a, y, α	97.64 ± 0.51 c, y, α	97.27 ± 1.32 a, y, α
P150	LSA	68.90 ± 1.62 a, x, α	67.80 ± 1.76 a, x, α	78.04 ± 0.78 a, x, α	72.34 ± 1.47 ab, x, β	10.84 ± 0.09 a, x, α	8.90 ± 0.19 ab, x, β	157.79 ± 2.43 a, x, α	149.04 ± 0.83 a, x, β
	SSA	59.34±1.33 b, y, α	46.42 ± 1.55 b, y, β	57.92 ± 0.97 b, y, α	39.59 ± 0.80 b, y, β	7.31 ± 0.17 b, y, α	5.87 ± 0.13 b, y, β	124.57 ± 0.74 b, y, α	91.88 ± 1.84 ab, y, β
P200	LSA	65.89 ± 0.84 a, x, α	64.31 ± 0.91 b, x, α	74.50 ± 1.14 ab, x, α	71.27 ± 0.95 ab, x, α	10.01 ± 0.23 ab, x, α	8.59 ± 0.27 ab, x, β	150.39 ± 1.77 ab, x, α	144.18 ± 1.85 ab, x, α
	SSA	65.61 ± 0.69 a, x, α	50.35 ± 1.27 a, y, β	64.15 ± 0.85 a, y, α	37.27 ± 1.00 bc, y, β	7.94 ± 0.12 a, y, α	4.79 ± 0.24 c, y, β	137.70 ± 0.46 a, y, α	92.40 ± 2.29 ab, y, β

LSA, light saline-alkaline soil; SSA, severe saline-alkaline soil; P0, 0 kg P ha^{-1}; P50, 50 kg P ha^{-1}; P100, 100 kg P ha^{-1}; P150, 150 kg P ha^{-1}; P200, 200 kg P ha^{-1}. Values (means ± SE, n = 3) followed by different letters designate significant differences ($p < 0.05$) between P levels in the same column for a given rice variety and a given soil (a, b, c, d, e); between soils in the same column for a given variety and a given P level (x, y); and between rice varieties in the same row for a given P level and a given soil (α, β), respectively.

3.2. P Accumulation

The P accumulation between varieties, saline-alkaline soils and P levels was also greatly different at the rice heading stage (Table 4).

There was higher total P content in P0 (202.70 mg of Dongdao-4 and 236.66 mg of Tongyu-315) and P150 (237.10 mg of Dongdao-4 and 238.20 mg of Tongyu-315) for two rice varieties in LSA soil. Tongyu-315 had significantly higher P content than Dongdao-4 in all plant parts and P levels in LSA soil. When it came to SSA soil, plant P content was significantly reduced, especially at the P0 level. However, with P levels increasing from P0 to P200, Dongdao-4 markedly increased its shoot P content from 108.02 mg to 165.17 mg and maintained a greater root P content (approximately 18 mg) in SSA soil. The P content of Tongyu-315 changed less with P levels.

Compared to the rice heading stage, shoot P content greatly decreased while grain, root and total P content significantly increased at maturity, especially in the grain parts (Table 5). Dongdao-4 had much higher grain and total P content than Tongyu-315 at five P levels in the two soils. It also obtained higher shoot P content than Tongyu-315 at higher P levels (P100–P200) in SSA soil. There was not much difference of shoot and root P content between P levels in LSA soil. The greatest grain of P content was found at P150 with 267.19 mg for Dongdao-4 and at P100 with 186.26 mg for Tongyu-315 in LSA soil. In SSA soil, however, the greatest grain in P content occurred at P200 with 222.77 mg for Dongdao-4 and at P100 with 101.83 mg for Tongyu-315. The total P content of the two varieties was also the highest at the same P level. Shoot and root P content was higher in SSA than in LSA soil for Dongdao-4, but it was the opposite for Tongyu-315.

Table 4. Plant P accumulation at rice heading stage under five P treatments in two saline-alkaline soils.

P Level	Soils	Shoot P (mg P pot^{-1})		Root P (mg P pot^{-1})		Total P (mg P pot^{-1})	
		Dongdao-4	**Tongyu-315**	**Dongdao-4**	**Tongyu-315**	**Dongdao-4**	**Tongyu-315**
P0	LSA	186.42 ± 2.49 b, x, β	216.76 ± 3.16 ab, x, α	16.27 ± 1.27 ab, x, α	19.89 ± 0.45 ab, x, α	202.70 ± 2.44 b, x, β	236.66 ± 2.92 a, x, α
	SSA	108.02 ± 1.04 d, y, β	128.17 ± 3.64 ab, y, α	18.61 ± 0.42 a, x, α	11.62 ± 0.45 a, y, β	126.63 ± 0.62 c, y, β	139.79 ± 3.21 ab, y, α
P50	LSA	127.41 ± 1.85 c, x, β	182.60 ± 1.29 c, x, α	15.22 ± 0.90 ab, x, β	23.81 ± 1.46 a, x, α	142.63 ± 1.62 c, x, β	206.41 ± 0.23 b, x, α
	SSA	128.48 ± 3.40 c, x, α	125.19 ± 2.35 ab, y, α	16.09 ± 0.53 a, x, α	11.46 ± 0.65 a, y, β	144.56 ± 2.89 b, x, α	136.65 ± 2.96 ab, y, α
P100	LSA	123.12 ± 1.88 c, x, β	206.02 ± 2.25 b, x, α	16.83 ± 0.84 ab, x, β	20.78 ± 1.11 ab, x, α	139.96 ± 1.96 c, x, β	226.80 ± 2.14 a, x, α
	SSA	131.95 ± 3.21 c, x, α	115.36 ± 3.07 b, y, β	19.56 ± 1.53 a, x, α	9.69 ± 0.66 ab, y, β	151.51 ± 4.72 b, x, α	125.05 ± 3.73 b, y, β
P150	LSA	218.90 ± 6.61 a, x, α	219.59 ± 3.51 a, x, α	18.20 ± 0.20 a, x, α	18.61 ± 1.18 b, x, α	237.10 ± 6.75 a, x, α	238.20 ± 4.67 a, x, α
	SSA	150.70 ± 0.81 b, y, α	133.31 ± 8.35 ab, y, α	20.46 ± 1.37 a, x, α	10.97 ± 0.79 a, y, β	171.15 ± 1.91 a, y, α	144.29 ± 7.77 ab, y, β
P200	LSA	177.82 ± 5.57 b, x, β	211.92 ± 2.28 ab, x, α	14.09 ± 0.43 b, x, β	19.50 ± 0.58 ab, x, α	191.92 ± 5.44 b, x, β	231.41 ± 2.87 a, x, α
	SSA	165.17 ± 0.92 a, x, α	142.51 ± 1.21 a, y, β	16.81 ± 0.65 a, y, α	7.38 ± 0.14 b, y, β	181.98 ± 0.31 a, x, α	149.89 ± 1.25 a, y, β

LSA, light saline-alkaline soil; SSA, severe saline-alkaline soil; P0, 0 kg P ha^{-1}; P50, 50 kg P ha^{-1}; P100, 100 kg P ha^{-1}; P150, 150 kg P ha^{-1}; P200, 200 kg P ha^{-1}. Values (means ± SE, n = 3) followed by different letters designate significant differences ($p < 0.05$) between P levels in the same column for a given rice variety and a given soil (a, b, c, d); between soils in the same column for a given variety and a given P level (x, y); and between rice varieties in the same row for a given P level and a given soil (α, β), respectively.

Table 5. Plant P accumulation at rice harvest stage under five P treatments in two saline-alkaline soils.

P Level	Soils	Shoot P (mg P pot^{-1})		Grain P (mg P pot^{-1})		Root P (mg P pot^{-1})		Total P (mg P pot^{-1})	
		Dongdao-4	Tongyu-315	Dongdao-4	Tongyu-315	Dongdao-4	Tongyu-315	Dongdao-4	Tongyu-315
P0	LSA	44.81 ± 1.63 b, x, α	45.69 ± 2.60 b, x, α	247.63 ± 5.33 ab, x, α	151.90 ± 5.66 c, x, β	21.72 ± 1.95 a, x, β	33.79 ± 0.18 bc, x, α	314.16 ± 8.86 abc, x, α	231.38 ± 3.70 d, x, β
	SSA	52.93 ± 2.97 ab, x, α	33.92 ± 1.38 b, y, β	131.24 ± 7.75 d, y, α	82.24 ± 0.46 b, y, β	48.08 ± 0.81 a, y, α	30.41 ± 0.82 bc, y, β	232.25 ± 8.31 bc, y, α	146.57 ± 2.19 c, y, β
P50	LSA	47.29 ± 1.24 b, x, α	50.76 ± 2.26 ab, x, α	220.24 ± 8.85 b, x, α	152.38 ± 3.83 c, x, β	22.90 ± 1.22 a, x, β	36.92 ± 1.37 ab, x, α	290.43 ± 10.79 c, x, α	240.07 ± 0.63 cd, x, β
	SSA	59.45 ± 1.40 a, y, α	40.70 ± 0.84 ab, y, β	112.49 ± 2.59 d, y, α	77.86 ± 1.37 b, y, β	35.84 ± 2.04 bc, y, α	35.19 ± 1.26 ab, x, α	207.77 ± 5.50 c, y, α	153.76 ± 0.96 bc, y, β
P100	LSA	42.84 ± 0.50 b, x, β	55.37 ± 1.61 a, x, α	231.08 ± 7.42 b, x, α	186.26 ± 1.92 a, x, β	19.78 ± 1.14 a, x, β	28.65 ± 0.58 d, x, α	293.70 ± 8.60 bc, x, α	270.29 ± 4.09 a, x, α
	SSA	45.62 ± 2.95 b, x, α	35.56 ± 1.39 ab, y, β	157.07 ± 0.41 c, y, α	101.83 ± 4.64 a, y, β	31.32 ± 1.46 c, y, α	39.05 ± 3.21 a, y, α	234.00 ± 4.42 b, y, α	176.44 ± 0.96 a, y, β
P150	LSA	56.05 ± 2.37 a, x, α	54.57 ± 0.56 a, x, α	267.19 ± 3.81 a, x, α	169.70 ± 3.42 ab, x, β	19.64 ± 1.59 a, x, β	38.49 ± 0.72 a, x, α	342.88 ± 6.69 a, x, α	262.76 ± 3.04 ab, x, β
	SSA	57.53 ± 0.97 a, x, α	38.44 ± 2.37 ab, y,β	200.57 ± 4.79 b, y, α	97.71 ± 2.57 a, y, β	42.18 ± 0.84 ab, y, α	28.52 ± 1.92 bc, y, β	300.27 ± 4.45 a, y, α	164.67 ± 3.00 ab, y, β
P200	LSA	50.03 ± 1.80 ab, x, α	53.64 ± 1.44 ab, x, α	261.86 ± 2.50 a, x, α	166.20 ± 2.11 bc, x, β	17.22 ± 1.66 a, x, β	30.65 ± 1.12 cd, x, α	329.11 ± 3.60 ab, x, α	250.50 ± 4.13 bc, x, β
	SSA	54.15 ± 2.09 ab, x, α	43.55 ± 3.03 a, y, β	222.77 ± 1.80 a, y, α	90.28 ± 3.12 ab, y, β	24.08 ± 2.09 d, x, α	26.03 ± 0.30 c, y, α	301.00 ± 2.23 a, y, α	159.85 ± 4.16 b, y, β

Abbreviations: LSA, light saline-alkaline soil; SSA, severe saline-alkaline soil; P0, 0 kg P ha^{-1}; P50, 50 kg P ha^{-1}; P100, 100 kg P ha^{-1}; P150, 150 kg P ha^{-1}; P200, 200 kg P ha^{-1}. Values (means ± SE, n = 3) followed by different letters designate significant differences ($p < 0.05$) between P levels in the same column for a given rice variety and a given soil (a, b, c, d); between soils in the same column for a given variety and a given P level (x, y); and between rice varieties in the same row for a given P level and a given soil (α, β), respectively.

3.3. Relationship between DW and P Content at Maturity

The relationship between plant DW and P content was analysed. Significantly ($p < 0.01$) positive correlations were found between the DWs and P content of grain and total plant of the two rice varieties in both saline-alkaline soils (Figure 1a–d). However, two rice varieties showed different results in correlations with the root part (Figure 1e,f). The relation of root biomass and root P content was negative for Dongdao-4 without being statistically significant in two soils, but were notably ($p < 0.01$) positive for Tongyu-315 in SSA soil.

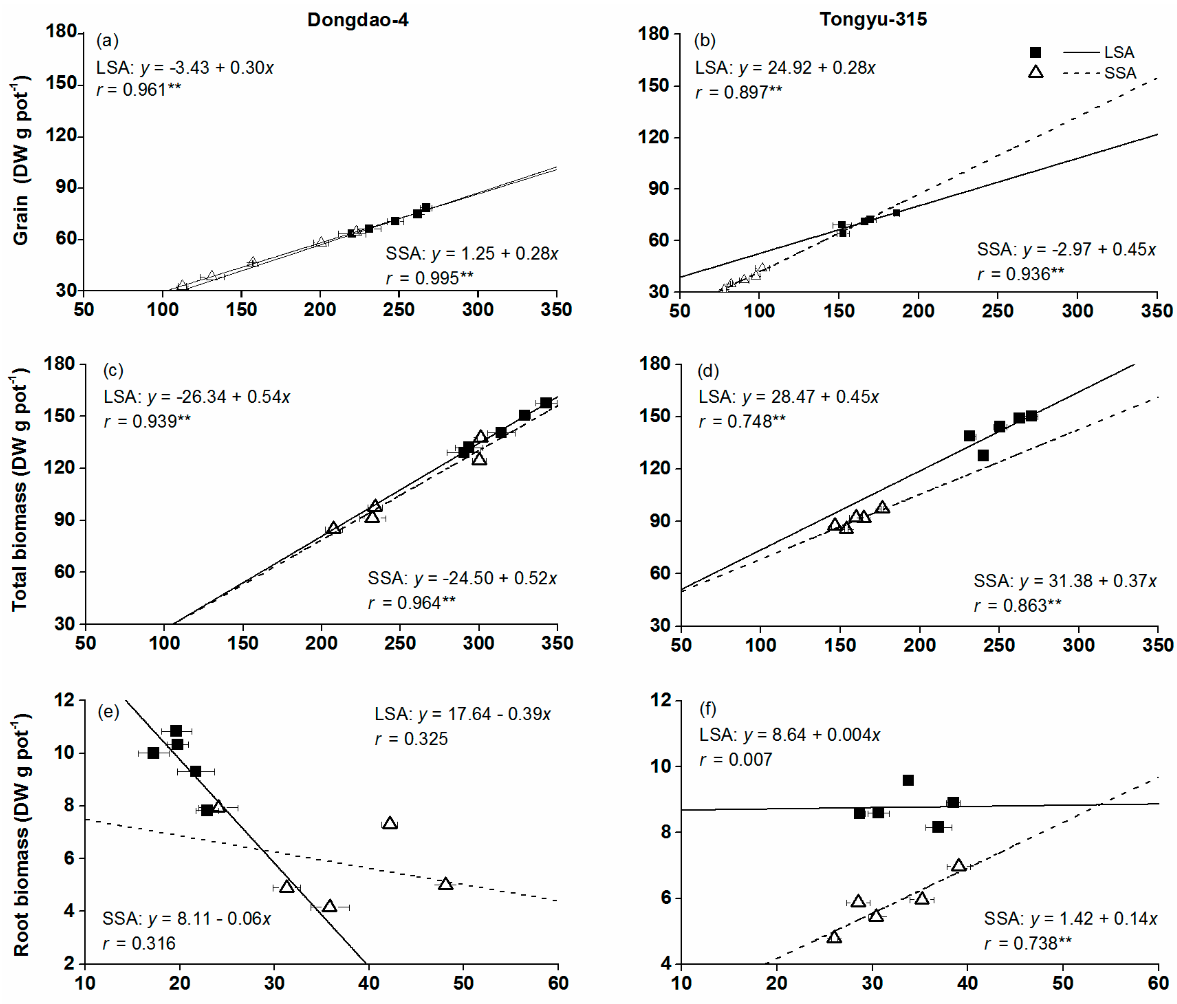

Figure 1. Relationships between biomass production and plant P content of Dongdao-4 and Tongyu-315 with five P levels in two saline-alkaline soils after harvest. Abbreviations: LSA, light saline-alkaline soil; SSA, severe saline-alkaline soil; regressions are shown for light saline-alkaline soil (solid symbols and lines) and severe saline-alkaline soil (open symbols and dashed lines). r, Pearson correlation coefficients; Data are means ± SE ($n = 15$); ** indicates significant difference at $p < 0.01$.

3.4. The 1000-Grain Weight and SR

The 1000-grain weight and SR of the two varieties were found to be lower in SSA soil than in LSA soil, especially for the SR of Tongyu-315 (Figure 2). Dongdao-4 had significantly greater 1000-grain weight and SR than Tongyu-315 for a given soil and given P level. It gained the greatest 1000-grain weight in P200 with 27.76 g and 26.78 g in LSA and SSA soil, respectively (Figure 2a). For the SR of Dongdao-4, it remained at a similar value with approximately 91% at five P levels in LSA soil, but significantly increased from 77.77% to 87.82% with P0 to P200 in SSA soil (Figure 2b).

Different from Dongdao-4, Tongyu-315 had the highest 1000-grain weight and SR at the P100 level in two saline-alkaline soils, but the 1000-grain weight was similar among P levels with approximately 20.5 g in two soils. The SR of Tongyu-315 was above 80% in LSA soil, but it markedly decreased to approximately 60% at all P levels in SSA soil (except the value of 73.54% in P100).

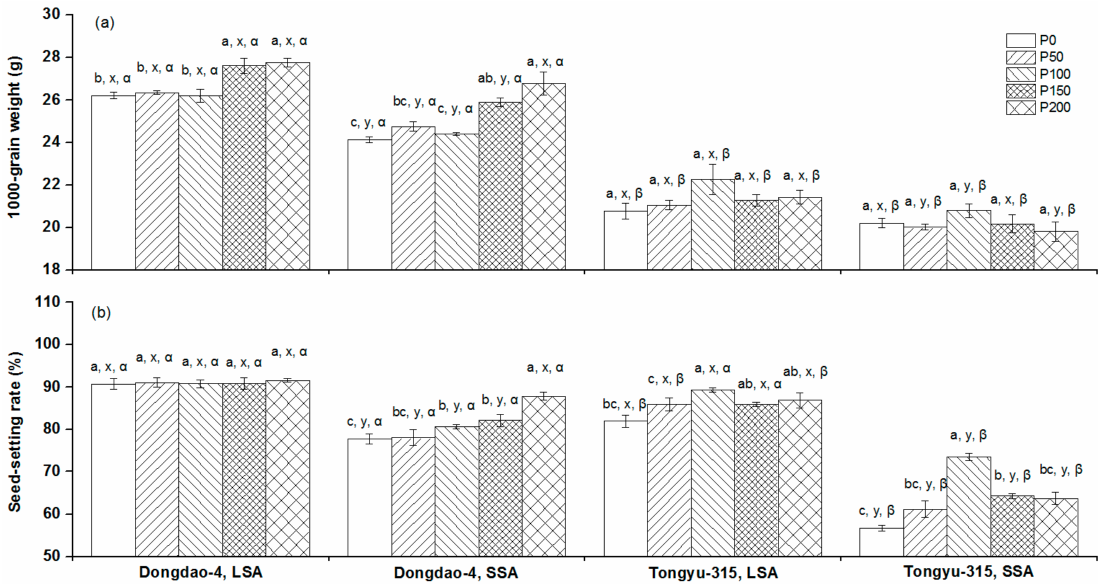

Figure 2. 1000-grain weight and seed-setting rate of two rice varieties (Dongdao-4 and Tongyu-315) under five P treatments in two saline-alkaline soils. Abbreviations: LSA, light saline-alkaline soil; SSA, severe saline-alkaline soil; P0, 0 kg P ha^{-1}; P50, 50 kg P ha^{-1}; P100, 100 kg P ha^{-1}; P150, 150 kg P ha^{-1}; P200, 200 kg P ha^{-1}. Values (means ± SE, n = 3) followed by different letters designate significant differences ($p < 0.05$) between P levels for a given rice variety and a given soil (a, b, c); between soils for a given variety and a given P level (x, y); and between rice varieties for a given P level and a given soil (α, β), respectively.

3.5. DW Translocation

The responses of DWT and CDWAG to P levels were similar for a given rice variety and a given saline-alkaline soil (Figure 3a,b). They showed positive values in LSA soil but dramatically turned to negative in SSA soil for the two rice varieties (except the values at P50 and P100 of Dongdao-4). The highest DWT and CDWAG of Dongdao-4 in LSA soil was found at P0 with 11.8 g pot^{-1} and 16.8%, and the lowest at P200, with 0.8 g pot^{-1} and 1.1%, respectively. For Tongyu-315 in LSA soil, these two parameters were similar at P0 and P50 and much higher than those at high P levels (P100, P150 and P200). In SSA soil, Dongdao-4 had significantly higher DWT and CDWAG than Tongyu-315 for a given P level. These two parameters of Tongyu-315 reached a marked trough at the P100 level in SSA soil with −15.28 g pot^{-1} (DWT) and −34.55% (CDWAG). The differences of HI among the two varieties and five P levels were not significant, with approximately 0.53 in LSA soil (Figure 3c). In SSA soil, however, both rice varieties showed notably lower HI for a given P level especially in P0 and P50 (approximately 0.42). With P levels increased from P100 to P200, stability was maintained with approximately 0.49 for Dongdao-4 but decreased to 0.43 for Tongyu-315.

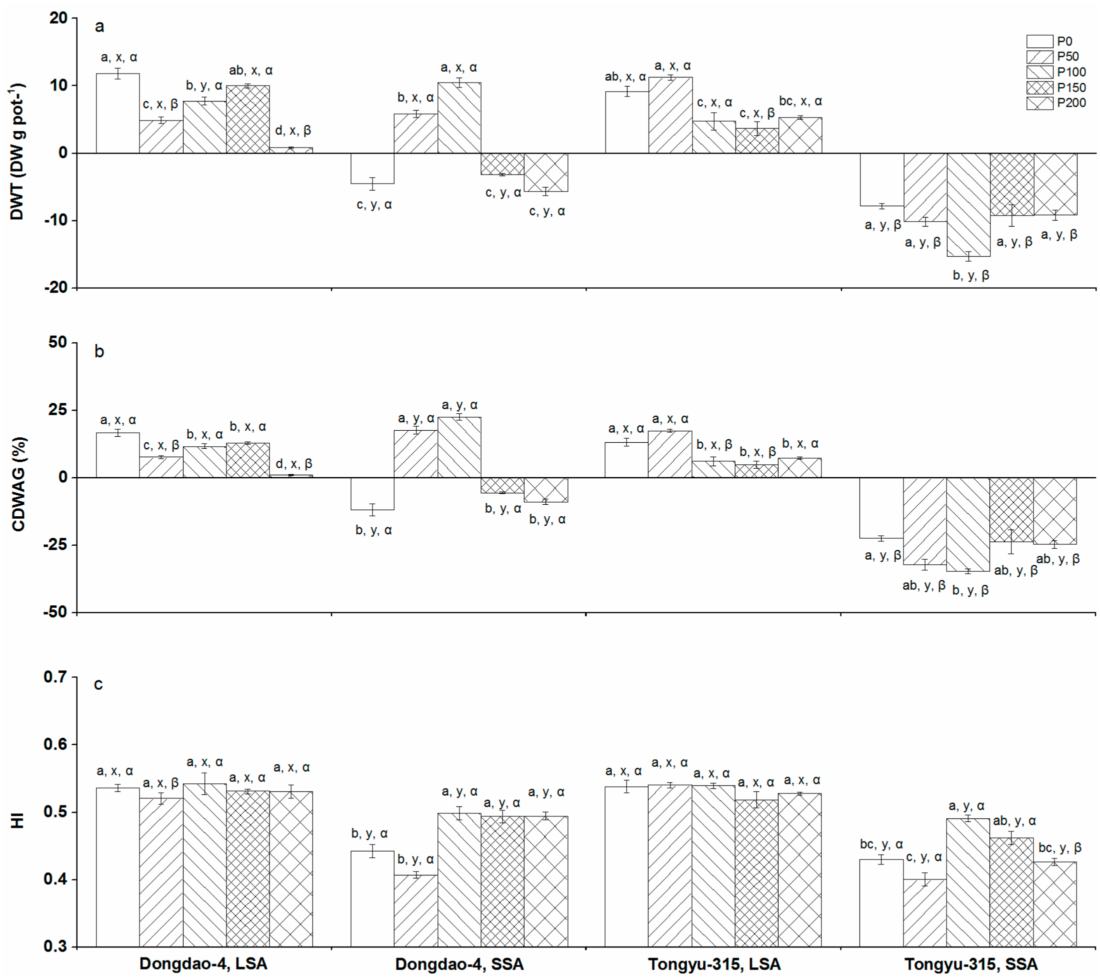

Figure 3. Dry weight translocation of two rice varieties (Dongdao-4 and Tongyu-315) under five P treatments in two saline-alkaline soils. Abbreviations: DWT, Dry weight translocation; CDWAG, Contribution of dry weight accumulation to grains; HI, Harvest index; LSA, light saline-alkaline soil; SSA, severe saline-alkaline soil; P0, 0 kg P ha^{-1}; P50, 50 kg P ha^{-1}; P100, 100 kg P ha^{-1}; P150, 150 kg P ha^{-1}; P200, 200 kg P ha^{-1}. Values (means ± SE, n = 3) followed by different letters designate significant differences (p < 0.05) between P levels for a given rice variety and a given soil (a, b, c); between soils for a given variety and a given P level (x, y); and between rice varieties for a given P level and a given soil (α, β), respectively.

3.6. P Translocation

For a given P level, the PT, CPAG and PHI of two rice varieties were found to be higher in LSA than in SSA soil (Figure 4). In LSA soil, Dongdao-4 had similarly lower PT (75 mg pot^{-1}) and CPAG (33%) at P50 and P100 levels, but it had the highest parameter at P150 with 161.41 mg pot^{-1} and 60.40%, respectively (Figure 4a,b). The PT and CPAG of Tongyu-315 in LSA soil were basically not affected by P application and remained approximately 120 mg pot^{-1} and 80%, respectively, except the lower PT at P50 (118.73 mg pot^{-1}) and higher CPAG at P0 (103.69%). In SSA soil, the PT, CPAG and PHI of Dongdao-4 at P0 were the least among the P levels with 25.62 mg pot^{-1}, 19.74% and 0.56, respectively. Their parameters were also much lower than those of Tongyu-315 at P0 in the same soil type. While PT and CPAG of Dongdao-4 in P200 were respectively four and two times greater than those at P0. The PT and CPAG of T315 were found to be lowest at the P100 level in SSA soil. Although there was no significant difference among P levels for PHI of the two varieties, Dongdao-4 had a markedly higher value than Tongyu-315 for each given P level in LSA soil (approximately 77%

of Dongdao-4 vs. 65% of Tongyu-315) (Figure 4c). The highest PHI of Dongdao-4 was found at P200 with 0.74 in SSA soil. This was much higher than that of Tongyu-315 at the same P level. The PHI of Tongyu-315 was similar among P levels in SSA soil, at approximately 57% (except the value at P50).

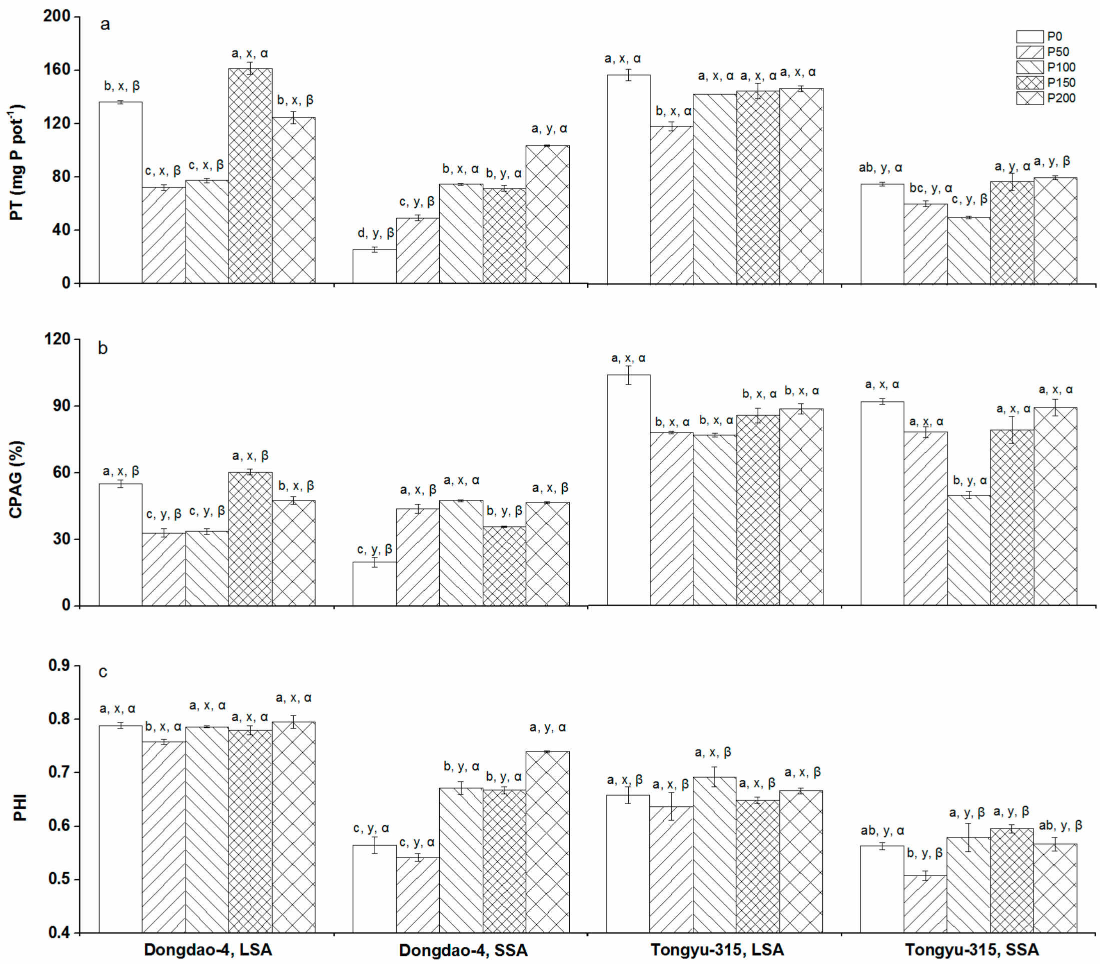

Figure 4. P translocation of two rice varieties (Dongdao-4 and Tongyu-315) under five P treatments in two saline-alkaline soils. Abbreviations: PT, P translocation; CPAG, Contribution of P accumulation to grains; PHI, P harvest index; LSA, light saline-alkaline soil; SSA, severe saline-alkaline soil; P0, 0 kg P ha^{-1}; P50, 50 kg P ha^{-1}; P100, 100 kg P ha^{-1}; P150, 150 kg P ha^{-1}; P200, 200 kg P ha^{-1}. Values (means ± SE, n = 3) followed by different letters designate significant differences ($p < 0.05$) between P levels for a given rice variety and a given soil (a, b, c); between soils for a given variety and a given P level (x, y); and between rice varieties for a given P level and a given soil (α, β), respectively.

4. Discussion

4.1. DW and P Accumulation

As the second major contributor to nutrition, P plays an important role in plant cell division, starch and sucrose biosynthesis, biomass accumulation and grain filling. Generally, plant P concentration maintains a relatively stable level and changes less for the cell metabolic balance. There has been found a tight positive correlation between rice biomass and plant P content, and the characteristics of rice tiller number, biomass and P uptake were found in same QTLs (quantitative trait locus) [31]. Thus, higher plant biomass possibly compares with the higher P content.

Soil P uptake is conducted by the phosphate transporter in the cell membrane of the crop root and then transported to above ground. There are mainly two types of P transporters: the high-affinity transport system and the low-affinity transport system [32,33]. The high-affinity transport system is specifically induced by P deficiency and seriously inhibited by P re-application, while the low-affinity transport system is constitutively expressed without being affected by different varieties and nutritional conditions [34,35]. In the P deficient condition, a rice plant will make lots of genetic, morphological and physiological changes to improve P uptake, such as the expression of high-affinity transport system, enlarged root biomass and superficial area, increased root/shoot ratio and so on [36]. Hu and Chu [37] found that increased root biomass, root length and upregulated high-affinity P transporters were the main strategies for rice to cope with the P deficiency. Moreover, P uptake can be effectively improved by some root acid phosphatases and organic acids [38]. In this experiment, two rice varieties showed higher DW and P content at P0 than at other P levels in LSA soil, with the results especially significant for the Dongdao4 overall growth stage. With P application increasing, probably the expression of the high-affinity P transport system was inhibited but the low-affinity P transport system was maintained. Thus, the slightly reduced DW and P content at P50 and even at P100 occurred in the two rice varieties, which has seldom been reported in previous studies.

The difference of crop biomass and P content between varieties is less than that between soil conditions. The crop development and P uptake is easily restrained by saline stress [39]. It is due to the restrictions from high Na^+ concentration and osmotic potential in saline soil solution, which make it difficult for the root to absorb water and useful inorganic ions [40]. Blocked leaf photosynthesis and carbohydrate synthesis also lead to the decreased DW and P content in rice seedlings [41]. In addition, the high-affinity transport system is seriously restricted and little energy can be used in P uptake in SSA soil. Thus, the salinity stress may have a more serious effect on the plant in P deficient conditions [42–44]. Similar results were also been found in the SSA soil, where DW and P content of Dongdao-4 showed least at the P0 level. Then they significantly increased with P application, indicating that he saline-alkaline tolerance of Dongdao-4 might be improved. A lot of research has shown the importance of P supplementation in improving the plant development under salinity [45,46]. Elgharably [23] found that 60 mg kg^{-1} P significantly increased wheat biomass and P accumulation under salt stress by reducing the Cl^- and Na^+ uptake in the root and increasing root biomass. P fertilizer promoted sucrose accumulation in the plant by effectively improving cellular water status and photosynthetic stability [47]. P can promote water and nutritional uptake by accelerating root growth, increasing the root/shoot ratio, secreting organic acids and other mechanisms [48,49]. Thus, root development plays a vital role in crop stress tolerance. In SSA conditions, root DW and P accumulation and grain yield of Dongdao-4 significantly increased with P application from P0 to P200. The root and grain DW and P content of Tongyu-315 reached a peak at P100. This indicated that P was more effective in alleviating the adverse effects of the SSA stress for Dongdao-4 than for Tongyu-315. Qadir and Schubert [50] believe that, given enough inorganic P compounds of $H_2PO_4^-$ and HPO_4^{2-}, the intracellular pH balance can be maintained and the SSA tolerance of crops can be improved. The markedly higher P content in plant stem, grain and root of Dongdao-4 at heading and maturity stages may be helpful in alleviating damage from SSA stress.

4.2. Optimal P Application

The optimal P levels are largely different among rice varieties and saline-alkaline soils [14]. Mahmood and Ali [51] determined 120 kg hm^{-2} P for the highest grain yield of direct-seeded rice varieties. Adequate P supplementation can also generally increase the root biomass, tilling number and cellular metabolism to promote rice precocity and high grain yield [52]. Excessive P application can significantly reduce the rice root, stem and tilling production [17]. In this experiment, Dongdao-4 had the greatest plant DW, grain weight and P content at P150 in LSA soil and at P200 in SSA soil. Probably the crop needs more P absorption to compensate for the negative internal effects induced by SSA soil. Tongyu-315 had the largest grain weight and P content at P100 in the two saline-alkaline soils. Decreased 1000 grain weight and SR was also found at higher P levels (P150 and P200) for Tongyu-315.

This demonstrated that the salinity and excessive P both resulted in increased spikelet sterility and decreased seed setting in panicles at the rice booting and heading stage [53,54].

4.3. DW and P Translocation

Grain filling is mainly dependent on carbohydrate assimilation, and less on the dry weight translocation from vegetable parts [55]. The P translocation is much greater than the accumulation [13]. The DW and P translocation is easy to change by crop varieties, while most results were obtained on wheat [56,57]. In this experiment, the DW and P translocation of two rice varieties were different in the two saline-alkaline soils. Dongdao-4 had the higher DW and P translocation at P0 and P150 in LSA soil, which might come from its higher DW and P content at the rice heading stage. Dewit [29] found that higher-yield components in the optimal P fertilizer led to higher DW translocation to the seeds. Arduini et al. [55] concluded that the higher biomass in the wheat heading stage made it possible to translocate more DW to grain. Similarly, for Tongyu-315, there was relatively higher DW and P accumulation at P0 at the heading stage, contributing to higher DW and P translocation and grain yield at maturity. Panigrahy et al. [58] found that plants store P in vacuoles in a P sufficient condition but release P from vacuoles and translocate it to fresh parts and grains in a P deficient condition.

Plant biomass and nutrition accumulation and remobilization can easily be affected by stress [59,60]. Masoni et al. [13] found that increased DW translocation under stress conditions may be due to suppressed photosynthesis and reduced carbohydrates. Abdullah et al. [61] believe that salinity can severely reduce chlorophyllase activity and the photosynthetic capacity of the leaf, thereby suppressing the translocation of soluble sugar in the stems and branches. In this experiment, most of the DW translocations of the two rice varieties significantly decreased to negative in SSA soil, something which has never been mentioned by previous researchers. It can be explained as follows: a. increased sterility and chaff biomass took a greater proportion of the DW translocation to filled grain under SSA stress; b. shoot biomass kept increasing from rice heading to maturity stage in SSA soil. Przulj and Momcilovic [62] found that lower DW translocation to barley grain was correlated to higher shoot biomass accumulation and grain yield. In addition, stronger saline-alkaline tolerance can make crops acquire a higher 1000-grain weight, SR and HI especially with optimal P treatment. For Dongdao-4, for example, the greatest PT and CPAG were all found at the optimal P level (P200) in SSA soil.

5. Conclusions

The results of this experiment demonstrate the complex relationship between saline-alkaline and P application to DW and P accumulation and translocation of rice varieties. They have different optimal P levels for growth and grain yield in different soil conditions. For the saline-alkaline-tolerant rice variety, its stress-harmful effects can be effectively alleviated and grain yield can be greatly improved by increasing P application. For the saline-alkaline-sensitive rice variety, the optimal P level and tolerant ability may not be much affected by P application. The SSA stress seriously inhibits plant growth, P uptake, and DW and P translocation to grain, resulting in decreased 1000-grain weight, SR and yield of rice especially for the saline-alkaline-sensitive variety. Moreover, higher DW and P translocation of the tolerant variety may partly depend on its greater plant DW and P accumulation. Thus, various rice varieties and soil types should been considered in agricultural phosphate application. The mechanisms and reasons behind the rice DW and P translocation with saline-alkaline soil and P nutrition should be investigated further. More rice varieties should be used to test these conclusions.

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Author Contributions: All authors conceived and designed the experiments; Zhijie Tian and Jingpeng Li performed the experiments; Zhijie Tian, Xinhua He and Xueying Jia analyzed the data and wrote the paper. All authors have read and approved the final manuscript.

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References

1. Flowers, T.J.; Yeo, A.R. Breeding for salinity resistance in crop plants: Where next? *Aust. J. Plant Physiol.* **1995**, *22*, 875–884. [CrossRef]
2. Wang, C.Y.; Wu, Z.J.; Shi, Y.L.; Wang, R.Y. The resource of saline soil in the Northest China. *Chin. J. Soil Sci.* **2004**, *5*, 643–647. (In Chinese)
3. Dahiya, S.; Singh, M. Effect of salinity, alkalinity and iron application on the availability of iron, manganese, phosphorus and sodium in pea (*Pisum sativum* L.) crop. *Plant Soil* **1976**, *44*, 697–702. [CrossRef]
4. Lv, B.S.; Li, X.W.; Ma, H.Y.; Sun, Y.; Wei, L.X.; Jiang, C.J.; Liang, Z.W. Differences in growth and physiology of rice in response to different saline-alkaline stress factors. *Agron. J.* **2013**, *105*, 1119–1128. [CrossRef]
5. Fageria, N.K.; Barbosa, M.P. Dry-matter and grain yield, nutrient uptake, and phosphorus use-efficiency of lowland rice as influenced by phosphorus fertilization. *Commun. Soil Sci. Plan Anal.* **2007**, *38*, 1289–1297. [CrossRef]
6. Ramaekers, L.; Remans, R.; Rao, I.M.; Blair, M.W.; Vanderleyden, J. Strategies for improving phosphorus acquisition efficiency of crop plants. *Field Crops Res.* **2010**, *117*, 169–176. [CrossRef]
7. Hu, Y.; Schmidhalter, U. Drought and salinity: A comparison of their effects on mineral nutrition of plants. *J. Plant Nutr. Soil Sci.* **2005**, *168*, 541–549. [CrossRef]
8. Wang, J.L.; Shuman, L.M. Transformation of phosphate in rice (*Oryza sativa* L.) rhizosphere and its influence on phosphorus-nutrition of rice. *J. Plant Nutr.* **1994**, *17*, 1803–1815. [CrossRef]
9. Qadir, M.; Noble, A.D.; Oster, J.D.; Schubert, S.; Ghafoor, A. Driving forces for sodium removal during phytoremediation of calcareous sodic and saline-sodic soils: A review. *Soil Use Manag.* **2005**, *21*, 173–180. [CrossRef]
10. Sanaullah, M.; Rumpel, C.; Charrier, X.; Chabbi, A. How does drought stress influence the decomposition of plant litter with contrasting quality in a grassland ecosystem? *Plant Soil* **2012**, *352*, 277–288. [CrossRef]
11. Zhu, J.K. Plant salt tolerance. *Trends Plant Sci.* **2001**, *6*, 66–71. [CrossRef]
12. Mittler, R.; Blumwald, E. Genetic engineering for modern agriculture: Challenges and perspectives. *Ann. Rev. Plant Biol.* **2010**, *61*, 443–462. [CrossRef] [PubMed]
13. Masoni, A.; Ercoli, L.; Mariotti, M.; Arduini, I. Post-anthesis accumulation and remobilization of dry matter, nitrogen and phosphorus in durum wheat as affected by soil type. *Eur. J. Agron.* **2007**, *26*, 179–186. [CrossRef]
14. Grattan, S.R.; Grieve, C.M. Salinity mineral nutrient relations in horticultural crops. *Sci. Hortic Amst.* **1999**, *78*, 127–157. [CrossRef]
15. Sairam, R.; Tyagi, A. Physiology and molecular biology of salinity stress tolerance in plants. *Curr. Sci. India* **2004**, *86*, 407–421.
16. Shabbir, G.; Hussain, N.; Bhatti, M.; Ahmad, A.; Javed, M.; Shakir, M.A. Salt tolerance potential of some selected fine rice cultivars. *Field Stud.* **2001**, *1997*, 99.
17. Aslam, M.; Flowers, T.; Qureshi, R.; Yeo, A. Interaction of phosphate and salinity on the growth and yield of rice (*Oryza sativa* L.). *J. Agron. Crop Sci.* **1996**, *176*, 249–258. [CrossRef]
18. Flowers, T.J.; Flowers, S.A. Why does salinity pose such a difficult problem for plant breeders? *Agric. Water Manag.* **2005**, *78*, 15–24. [CrossRef]
19. Tian, Z.J.; Li, J.P.; Jia, X.Y.; Yang, F.; Wang, Z.C. Assimilation and translocation of dry matter and phosphorus in rice genotypes affected by salt-alkaline stress. *Sustainability* **2016**, *8*, 568. [CrossRef]
20. Richardson, A.E.; Simpson, R.J. Soil microorganisms mediating phosphorus availability. *Plant Physiol.* **2011**, *156*, 989–996. [CrossRef] [PubMed]
21. Fabre, D.; Siband, P.; Dingkuhn, M. Characterizing stress effects on rice grain development and filling using grain weight and size distribution. *Field Crops Res.* **2005**, *92*, 11–16. [CrossRef]
22. Tahir, I.S.A.; Nakata, N. Remobilization of nitrogen and carbohydrate from stems of bread wheat in response to heat stress during grain filling. *J. Agron. Crop Sci.* **2005**, *191*, 106–115. [CrossRef]

23. Elgharably, A. Wheat response to combined application of nitrogen and phosphorus in a saline sandy loam soil. *Soil Sci. Plant Nutr.* **2011**, *57*, 396–402. [CrossRef]
24. Naheed, G.; Shahbaz, M.; Latif, A.; Rha, E.S. Alleviation of the adverse effects of salt stress on rice (*Oryza sativa* L.) by phosphorus applied through rooting medium: Growth and gas exchange characteristics. *Pak. J. Bot.* **2007**, *39*, 729–737.
25. Awad, A.; Edwards, D.; Campbell, L. Phosphorus enhancement of salt tolerance of tomato. *Crop Sci.* **1990**, *30*, 123–128. [CrossRef]
26. Usman, K. Effect of phosphorus and irrigation levels on yield, water productivity, phosphorus use efficiency and income of lowland rice in northwest Pakistan. *Rice Sci.* **2013**, *20*, 61–72. [CrossRef]
27. Alam, M.; Ali, M.; Amin, A.; Hasanuzzaman, M. Yield attributes, yield and harvest index of three irrigated rice varieties under different levels of phosphorus. *Adv. Biol. Res.* **2009**, *3*, 132–139.
28. Nieman, R.H.; Clark, R.A. Interactive effects of salinity and phosphorus nutrition on concentrations of phosphate and phosphate esters in mature photosynthesizing corn leaves. *Plant Physiol.* **1976**, *57*, 157–161. [CrossRef] [PubMed]
29. Dewit, C.T. Resource use efficiency in agriculture. *Agric. Syst.* **1992**, *40*, 125–151. [CrossRef]
30. Dordas, C. Dry matter, nitrogen and phosphorus accumulation, partitioning and remobilization as affected by N and P fertilization and source-sink relations. *Eur. J. Agron.* **2009**, *30*, 129–139. [CrossRef]
31. Wissuwa, M.; Yano, M.; Ae, N. Mapping of QTLs for phosphorus-deficiency tolerance in rice (*Oryza sativa* L.). *Theor. Appl. Genet.* **1998**, *97*, 777–783. [CrossRef]
32. Gao, J.P.; Chao, D.Y.; Lin, H.X. Toward understanding molecular mechanisms of abiotic stress responses in rice. *Rice* **2008**, *1*, 36–51. [CrossRef]
33. Lin, W.Y.; Lin, S.I.; Chiou, T.J. Molecular regulators of phosphate homeostasis in plants. *J. Exp. Bot.* **2009**, *60*, 1427–1438. [CrossRef] [PubMed]
34. Gordon-Weeks, R.; Tong, Y.; Davies, T.E.; Leggewie, G. Restricted spatial expression of a high-affinity phosphate transporter in potato roots. *J. Cell Sci.* **2003**, *116*, 3135–3144. [CrossRef] [PubMed]
35. Raghothama, K.G.; Karthikeyan, A.S. Phosphate acquisition. *Plant Soil* **2005**, *274*, 37–49. [CrossRef]
36. Yuan, H.; Liu, D. Signaling components involved in plant responses to phosphate starvation. *J. Integr. Plant Biol.* **2008**, *50*, 849–859. [CrossRef] [PubMed]
37. Hu, B.; Chu, C. Phosphate starvation signaling in rice. *Plant Signal. Behav.* **2011**, *6*, 927–929. [CrossRef] [PubMed]
38. Franco-Zorrilla, J.M.; Gonzalez, E.; Bustos, R.; Linhares, F.; Leyva, A.; Paz-Ares, J. The transcriptional control of plant responses to phosphate limitation. *J. Exp. Bot.* **2004**, *55*, 285–293. [CrossRef] [PubMed]
39. Sima, N.A.K.K.; Ahmad, S.T.; Alitabar, R.A.; Mottaghi, A.; Pessarakli, M. Interactive effects of salinity and phosphorus nutrition on physiological responses of two barley species. *J. Plant Nutr.* **2012**, *35*, 1411–1428. [CrossRef]
40. Mohammadi-Nejad, G.; Singh, R.; Arzani, A.; Rezaie, A.; Sabouri, H.; Gregorio, G. Evaluation of salinity tolerance in rice genotypes. *Int. J. Plant Prod.* **2010**, *4*, 199–207.
41. Jin, J.; Wang, G.H.; Liu, X.B.; Pan, X.W.; Herbert, S.J.; Tang, C.X. Interaction between phosphorus nutrition and drought on grain yield, and assimilation of phosphorus and nitrogen in two soybean cultivars differing in protein concentration in grains. *J. Plant Nutr.* **2006**, *29*, 1433–1449. [CrossRef]
42. Martinez, V.; Lächli, A. Phosphorus translocation in salt-stressed cotton. *Physiol. Plant.* **1991**, *83*, 627–632. [CrossRef]
43. Navarro, J.M.; Botella, M.A.; Cerdá, A.; Martinez, V. Phosphorus uptake and translocation in salt-stressed melon plants. *J. Plant Physiol.* **2001**, *158*, 375–381. [CrossRef]
44. Rogers, M.E.; Grieve, C.M.; Shannon, M.C. Plant growth and ion relations in lucerne (*Medicago sativa* L.) in response to the combined effects of NaCl and P. *Plant Soil* **2003**, *253*, 187–194. [CrossRef]
45. Gibson, T.S. Carbohydrate-metabolism and phosphorus salinity interactions in wheat (*Triticum-Aestivum* L.). *Plant Soil* **1988**, *111*, 25–35. [CrossRef]
46. Farooq, M.; Wahid, A.; Kobayashi, N.; Fujita, D.; Basra, S.M.A. Plant drought stress: Effects, mechanisms and management. *Agron. Sustain. Dev.* **2009**, *29*, 185–212. [CrossRef]
47. Sato, A.M.; Catuchi, T.A.; Ribeiro, R.V.; Souza, G.M. The use of network analysis to uncover homeostatic responses of a drought-tolerant sugarcane cultivar under severe water deficit and phosphorus supply. *Acta Physiol. Plant* **2010**, *32*, 1145–1151. [CrossRef]

48. Tran, H.T.; Hurley, B.A.; Plaxton, W.C. Feeding hungry plants: The role of purple acid phosphatases in phosphate nutrition. *Plant Sci.* **2010**, *179*, 14–27. [CrossRef]
49. Zribi, O.T.; Houmani, H.; Kouas, S.; Slama, I.; Ksouri, R.; Abdelly, C. Comparative study of the interactive effects of salinity and phosphorus availability in wild (*Hordeum maritimum*) and cultivated barley (*H-vulgare*). *J. Plant Growth Regul.* **2014**, *33*, 860–870. [CrossRef]
50. Qadir, M.; Schubert, S. Degradation processes and nutrient constraints in sodic soils. *Land Degrad. Dev.* **2002**, *13*, 275–294. [CrossRef]
51. Mahmood, I.A.; Ali, A. Response of direct seeded rice and wheat crops to phosphorus application with crop residue incorporation in saline-sodic soil. *Int. J. Agric. Biol.* **2015**, *17*, 1219–1224. [CrossRef]
52. Vance, C.P.; Uhde-Stone, C.; Allan, D.L. Phosphorus acquisition and use: critical adaptations by plants for securing a nonrenewable resource. *New Phytol.* **2003**, *157*, 423–447. [CrossRef]
53. Khatun, S.; Flowers, T. Effects of salinity on seed set in rice. *Plant Cell Environ.* **1995**, *18*, 61–67. [CrossRef]
54. Rao, P.S.; Mishra, B.; Gupta, S.; Rathore, A. Reproductive stage tolerance to salinity and alkalinity stresses in rice genotypes. *Plant Breed.* **2008**, *127*, 256–261. [CrossRef]
55. Arduini, I.; Masoni, A.; Ercoli, L.; Mariotti, M. Grain yield, and dry matter and nitrogen accumulation and remobilization in durum wheat as affected by variety and seeding rate. *Eur. J. Agron.* **2006**, *25*, 309–318. [CrossRef]
56. Fang, Y.; Xu, B.C.; Turner, N.C.; Li, F.M. Grain yield, dry matter accumulation and remobilization, and root respiration in winter wheat as affected by seeding rate and root pruning. *Eur. J. Agron.* **2010**, *33*, 257–266. [CrossRef]
57. Papakosta, D.K. Phosphorus accumulation and translocation in wheat as affected by cultivar and nitrogen fertilization. *J. Agron. Crop Sci.* **1994**, *173*, 260–270. [CrossRef]
58. Panigrahy, M.; Rao, D.N.; Sarla, N. Molecular mechanisms in response to phosphate starvation in rice. *Biotechnol. Adv.* **2009**, *27*, 389–397. [CrossRef] [PubMed]
59. Khan, M.A.; Abdullah, Z. Salinity–sodicity induced changes in reproductive physiology of rice (*Oryza sativa* L.) under dense soil conditions. *Environ. Exp. Bot.* **2003**, *49*, 145–157. [CrossRef]
60. Naheed, G.; Shahbaz, M.; Akram, N.A. Interactive effect of rooting medium application of phosphorus and NaCl on plant biomass and mineral nutrients of rice (*Oryza sativa* L.). *Pak. J. Bot.* **2008**, *40*, 1601–1608.
61. Abdullah, Z.; Khan, M.A.; Flowers, T. Causes of sterility in seed set of rice under salinity stress. *J. Agron. Crop Sci.* **2001**, *187*, 25–32. [CrossRef]
62. Przulj, N.; Momcilovic, V. Genetic variation for dry matter and nitrogen accumulation and translocation in two-rowed spring barley II. Nitrogen translocation. *Eur. J. Agron.* **2001**, *15*, 255–265. [CrossRef]