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Phosphorus and Zinc Fertilization Influence Crop Growth Rates and Total Biomass of Coarse vs. Fine Types Rice Cultivars

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Abstract: Under the rice–wheat cropping system (RWS), the continuous cropping of rice (*Oryza sativa* L.) and wheat (*Triticum aestivum* L.) deplete soil fertility, and reduce crop growth and total rice biomass. In RWS, both phosphorus (P) and zinc (Zn) deficiencies are considered important nutritional constraints for reducing rice crop growth rates (CGR) and total biomass/biological yield (BY). The objective of this experiment was to investigate the impact of phosphorus (0, 40, 80, 120 kg P ha^{-1}) and zinc rates (0, 5, 10, 15 kg Zn ha^{-1}) on CGR and BY of three rice genotypes [fine (Bamati-385) versus coarse (Fakhre-e-Malakand and Pukhraj)] in Northwestern Pakistan during summer 2011 (Y1) and 2012 (Y2). The results revealed that higher CGR at various growth stages and total BY was obtained with the integrated use of higher phosphorus (80 and 120 kg P ha^{-1}) and zinc rates (10 and 15 kg Zn ha^{-1}). The lower CGR and BY were recorded when P and Zn were not applied (control) or when P and Zn were applied alone. In the case of rice genotypes, the highest CGR and BY were recorded for the hybrid rice (Pukhraj) than the other two genotypes. The CGR was increased to the highest level at the heading stage as compared to tillering and physiological maturity. The increase in CGR had a positive impact on the total BY of rice cultivars. The increase in BY had a positive relationship with grain yield and grower's income. It was concluded from the study that the combined application of higher P and Zn rates to the coarse rice genotypes (Fakhre-e-Malakand and Pukhraj) could increase CGR, total BY, crop productivity and profitability.

Keywords: *Oryza sativa* L.; genotypes; phosphorus; zinc; crop growth rate; BY

1. Introduction

Rice (*Oryza sativa* L.) is the staple food of mankind and provides 35%~60% of the dietary calories consumed by 3 billion people, making it—without question—the most important crop worldwide [1]. The demand for increasing rice production is particularly urgent, because the population of traditional rice-producing countries will require 70% more rice by the year 2025 [2,3]. Hence, world rice production must increase by approximately 1% annually to meet the growing demand [4].

Phosphorus (P) and zinc (Zn) deficiency are two of the most important nutritional constraints to rice growth across the globe [2,5–7]. Phosphorus and zinc deficiency not only decrease the productivity and quality of the current rice crop [2,5] but also have a negative impact on the productivity of the subsequent wheat crop under the rice–wheat cropping system (RWS) [8,9]. Zinc is absorbed by plants as cations (Zn^{2+}) and P is taken up by plants as phosphate anions ($H_2PO_4^{-1}$ or HPO_4^{-2}). These cations and anions attract each other, which facilitates the formation of chemical bonds that can form within the soil or the plant. If excess P binds a large quantity of Zn normally available to the plant, the result can be a P-induced Zn deficiency [9]. This generally results in reduced shoot Zn concentration and reduced rice growth [6,10].

Fertilizers are a costly input, such that their use limits the profitability of rice farming for high-input or low-input systems, and the use of fertilizers for these two rice nutrients is notoriously inefficient [11]. Regarding the interaction of Zn and P, numerous studies have been carried out and all confirm this point, that Zn and P imbalance in the plant, as a result of excessive accumulation of P, causes Zn imposed deficiency [12–16]. Next to N and P deficiency, Zn deficiency is now considered the most widespread nutrient disorder in lowland rice [17,18]. High soil pH appears to be the main factor associated with the widespread Zn deficiency in the calcareous soils of the Indo-Gangetic plains of India and Pakistan [19,20]. The yield of rice is an integrated result of various processes, including canopy photosynthesis, conversion of assimilates to biomass and partitioning of assimilates to grains [6,7,21–23].

Studies on Zn and P interaction and their impact on rice crop growth rates (CGR) and total biomass/biological yield (BY) have not been reported, even under RWS. The main objective of this experiment was to investigate whether there is any difference in the CGR and BY of rice genotypes at various P and Zn rates.

2. Materials and Methods

2.1. Site Description

A field experiment was conducted to investigate the impact of phosphorus (0, 40, 80, 120 kg P ha^{-1}) and zinc rates (0, 5, 10, 15 kg Zn ha^{-1}) on the crop growth rate (CGR) and total biomass/biological yield (BY) of three rice (*Oryza sativa* L.) genotypes [fine (Bamati-385) versus coarse (Fakhre-e-Malakand and Pukhraj)] under RWS. The experiment was conducted at Batkhela, Malakand Agency on farmer's field in Northwest Pakistan during 2011 (Y1) and 2012 (Y2). Batkhela is located at 34°37′0″ N and 71°58′17″ E in DMS (Degrees Minutes Seconds) or 34.6167 and 71.9714 (in decimal degrees). The soil of the experimental site is clay loam, slightly alkaline in reaction (pH = 7.3), non-saline (ECe = 1.02 dS m^{-1}), moderately calcareous in nature ($CaCO_3$ = 7.18%), low in soil fertility containing less organic matter (0.71%), extractable P (5.24 mg kg^{-1}) and Zn (0.93 mg kg^{-1}) [9,24]. Weather data for RWS during the two years, e.g., 2011–2012 (Y1) and 2012–2013 (Y2) were different [9].

2.2. Experimentation

The experiment was conducted in a randomized complete block design with a split-plot arrangement using three replications. Combination of factor-A, three rice genotypes [fine (Bamati-385) versus coarse (Fakhre-e-Malakand and Pukhraj)] and factor-B, four P rates (0, 40, 80, 120 kg P ha^{-1}) were allotted to main plots, while factor-C, the four Zn rates (0, 5, 10, 15 kg Zn ha^{-1}) were allotted to subplots. A sub-plot size of 12 m^2 (3 m × 4 m) having 300 hills per subplot, and hill to hill distance of 20 cm apart was used. A uniform dose of 120 kg N ha^{-1} as urea and 60 kg K_2O ha^{-1} [SOP (sulphate of potash) or MOP (muriate of potash)] was applied to all treatments. All potassium, P (triple super phosphate) and Zn (zinc sulphate) were applied at the time of transplanting, while nitrogen was applied in two equal splits, i.e., 50% each at transplanting and 30 days after transplanting. The amount of sulfur was maintained constantly in the Zn applied plots by adding additional sulfur using SOP. All subplots were separated by about 30 cm ridges to stop the movement of water/nutrients among different treatments. Water to each treatment was separately applied from the water channel and the crop was grown under flooded condition almost the whole growing period [24].

Data were calculated on CGR at three different growth stages (tillering, heading and physiological maturity) and total BY at harvesting. At tillering, heading and physiological maturity five hills within each treatment were harvested. Leaf, stems and panicles were separated, dried and weighed by an electronic balance to record data on dry weight of leaf, stem, and panicles (no panicles were observed at tillering). Dry weight hill^{-1} at each growth stage was calculated as sum of the dry weights of the plant components [24]. The CGR is defined as dry matter accumulation per unit ground area per unit time was determined at various growth stages (transplanting to tillering, tillering to heading, and heading to physiological maturity) according to the procedures used by [25].

$$CGR = W_2 - W_1/(\mathrm{GA})\ (t_2 - t_1) \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (\mathrm{g\ m^{-2}\ day^{-1}})$$

where

W_1 = Dry weight (g) m^{-2} at the beginning of interval;
W_2 = Dry weight (g) m^{-2} at the end of the interval;
$t_2 - t_1$ = The time interval between the two consecutive samplings;
GA = Ground area occupied by plants at each sampling.

At harvest maturity, four meters square area within each treatment was harvested, the material was sun-dried up to constant weight and weighed, and then was converted into BY (kg ha^{-1}).

2.3. Statistical Analysis

Data were subjected to analysis of variance (Table 1) according to the methods described for randomized complete block design with split plot arrangement combined over the years [26] and means between treatments were compared using least significant difference (LSD) test ($p \leq 0.05$).

Table 1. Mean square and significance level for crop growth rates (CGR) and biomass/biological yield (BY) of rice genotypes (G) as affected by phosphorus (P) and zinc (Zn) application.

Source of Variance	DF	CGR T-T		CGR T-H		CGR H-PM		BY	
		MS	Sig.	MS	Sig.	MS	Sig.	MS	Sig.
Years (Y)	1	75.8	**	7410	***	245.4	ns	56,603,277	ns
Rep. (within years)	4	–	–	–	–	–	–	–	–
Genotypes	2	70.0	***	9169	***	2636	***	44,688,057	***
Y × G	2	8.69	**	1139	***	1676	***	3,416,454	ns
Phosphorus (P)	3	58.5	***	4646	***	596.0	***	85,343,094	***
Y × P	3	4.20	ns	217	ns	52.43	ns	9,035,611	ns
P × G	6	3.00	*	65.9	***	92.01	ns	28,039,619	***
Y × P × G	6	6.71	***	11.1	ns	25.56	ns	1,125,688	ns
Pooled Error-I	44	1.18	–	11.5	–	46.16	–	3,999,861	–
Zinc (Zn)	3	7.56	***	202	***	166.2	*	23,002,115	***
Y × Zn	3	1.70	ns	1.53	ns	12.19	ns	356,618	ns
Zn × G	6	0.94	ns	4.28	ns	6.53	ns	2,206,022	ns
Y × Zn × G	6	0.49	ns	39.5	***	21.26	ns	1,123,908	ns
P × Zn	9	1.02	ns	10.2	ns	60.06	ns	2,855,133	ns
Y × P × Zn	9	2.18	**	7.68	ns	41.47	ns	985,953	ns
P × Zn × G	18	1.82	***	14.1	*	39.70	ns	5,048,345	**
Y × P × Zn × G	18	1.39	**	13.5	*	58.82	ns	1,417,858	ns
Pooled Error-II	144	0.67	–	7.85	–	42.91	–	2,149,826	–
Total	287	–	–	–	–	–	–	–	–
CV main plots (%)		15.1		8.6		19.4		11.0	
CV sub plots (%)		11.4		7.1		18.0		8.0	

Where: MS stands for mean square, Sig. for significance, ns for non-significant, while *, ** and *** stands for significant at 5, 1 and 0.1% level of probability, respectively. T-T = transplanting to tillering, T-H = tillering to heading, and H-PM = heading to physiological maturity.

3. Results

3.1. Crop Growth Rate from Transplanting to Tillering

Crop growth rate (CGR) (g m^{-2} day^{-1}) at the early growth stage (tillering) was significantly affected by P and Zn rates, genotypes and years (Table 1). The interactions Y × G, P × G and P × Zn × G were also significant for CGR (Table 1). Years mean data indicated that the highest CGR (7.92 g m^{-2} day^{-1}) was associated with 120 kg P ha^{-1}, being at par with 80 kg P ha^{-1} (7.77 g m^{-2} day^{-1}), and minimum CGR (5.96 g m^{-2} day^{-1}) was calculated for P control plots (Table 2). In the case of Zn rates, maximum CGR (7.41 g m^{-2} day^{-1}) was recorded with 15 kg Zn ha^{-1} being statistically identical with 5 and 10 kg Zn ha^{-1}, and the Zn control plots had reduced CGR to a minimum level (6.69 g m^{-2} day^{-1}). Among the three rice genotypes, maximum CGR (8.12 g m^{-2} day^{-1}) was recorded for Pukhraj, followed by F-Malakand (6.84 g m^{-2} day^{-1}), while minimum CGR (6.50 g m^{-2} day^{-1}) was recorded for fine genotype (B-385).

The Y × G interaction (Table 2) indicated that CGR for all three genotypes was higher in Y2 than in Y1. The Y2 had higher CGR (7.67 g m^{-2} day^{-1}) as compared with Y1 (6.64 g m^{-2} day^{-1}). The P × G interaction indicated that CGR of all three rice genotypes was increased while increasing the P level (Figure 1) and the increase was higher for the two coarse genotypes (Pukhraj and F-Malakand) than fine genotype (B-385). The three-way interaction among P × Zn × G indicated that the CGR for all three rice genotypes was increased while increasing P and Zn rates (Figure 2), and both coarse genotypes (Pukhraj and F-Malakand) had higher CGR than fine genotype (B-385) at all P and Zn rates.

Table 2. Crop growth rate (g m^{-2} day^{-1}) from transplanting to tillering of rice genotypes as affected by phosphorus and zinc application.

	Years		
Phosphorus (kg ha^{-1})	**2011**	**2012**	**Mean**
0	5.74	6.18	5.96 c
40	6.55	7.39	6.97 b
80	7.14	8.41	7.77 a
120	7.15	8.69	7.92 a
$LSD_{0.05}$	0.46	0.59	0.36
Zinc (kg ha^{-1})			
0	6.36	7.03	6.69 b
5	6.70	7.65	7.18 a
10	6.80	7.88	7.34 a
15	6.71	8.12	7.41 a
$LSD_{0.05}$	ns	0.38	0.27
Genotypes			
B-385 (fine)	5.91	7.09	6.50 c
F-Malakand (coarse)	6.07	7.61	6.84 b
Pukhraj (coarse)	7.94	8.30	8.12 a
$LSD_{0.05}$	0.40	0.51	0.32
Years mean	6.64 b	7.67 a	

Means of the same category followed by different letters are significantly different at 5% level of probability using LSD test. Significant interactions are P × G * (Figure 1) and P × Zn × G *** (Figure 3). Where ns = non-significant data., while * and *** stands for significant data at 5 and 0.1% level of probability, respectively.

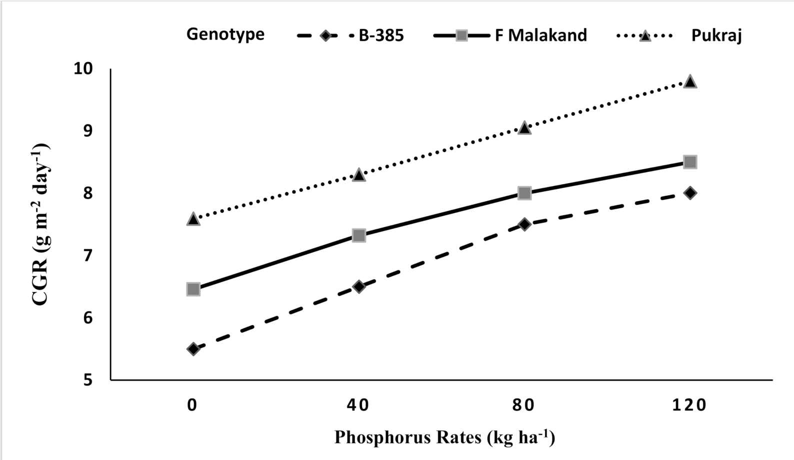

Figure 1. Crop growth rate (g m^{-2} day^{-1}) from transplanting to tillering of rice as affected by phosphorus into genotype (P × G) interaction.

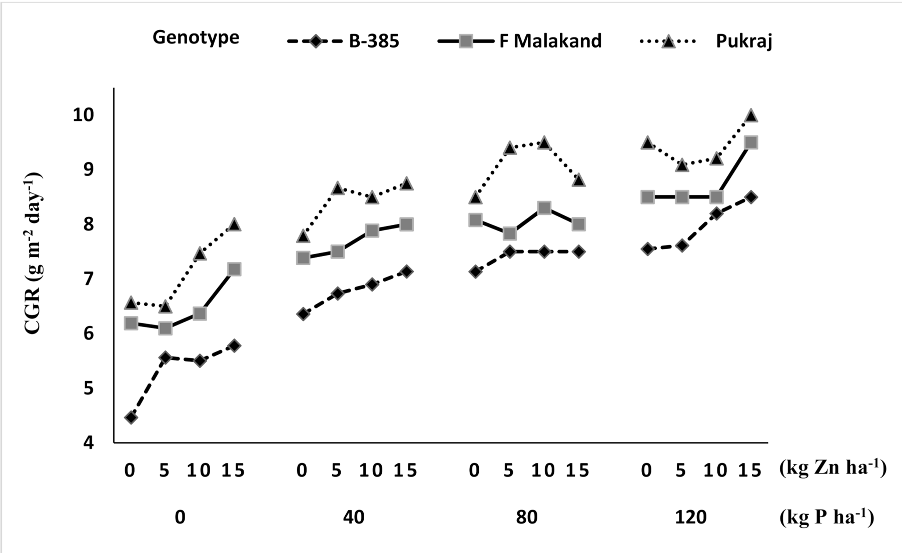

Figure 2. Crop growth rate (g m^{-2} day^{-1}) from transplanting to tillering of rice as affected by phosphorus into zinc into genotype (P × Zn × G) interaction.

3.2. Crop Growth Rate from Tillering to Heading

The crop growth rate from tillering to heading was significantly affected P and Zn rates, genotypes and years (Table 1). The interactions Y × G, P × G and P × Zn × G were also significant (Table 1). The highest CGR (46.9 g m^{-2} day^{-1}) was recorded for 120 kg P ha^{-1}, while minimum CGR (28.7 g m^{-2} day^{-1}) was observed for P control plots (Table 3). In the case of Zn rates, maximum CGR (41.3 g m^{-2} day^{-1}) was recorded for 15 kg Zn ha^{-1}, and the Zn control plots had the minimum CGR value of 37.6 g m^{-2} day^{-1} (Table 3). Among the three rice genotypes, maximum CGR (49.8 g m^{-2} day^{-1}) was recorded for Pukhraj, followed by F-Malakand (38.5 g m^{-2} day^{-1}), and the minimum CGR (30.4 g m^{-2} day^{-1}) was recorded for B-385 (Table 3).

In the case of Y × G interaction (Table 3), an increase in CGR for all three rice genotypes was noticed in Y2 over Y1. The CGR of coarse genotypes was more than the fine genotype (Table 3). The Y2 had higher CGR (44.6 g m^{-2} day^{-1}) as compared with Y1 (34.5 g m^{-2} day^{-1}). The increase in P level had increased the CGR in all three cultivars but the response of the Pukhraj was more to the higher P level than the other two genotypes (Figure 3). The three-way interaction among P × Zn × G (Figure 4) indicated that Pukhraj (the hybrid rice) had a higher CGR at each P level along with the highest rate of

15 kg Zn ha^{-1}. The two local genotypes of rice (F-Malakand and B-385) had higher CGR at each P level when applied in combination with 10 kg Zn ha^{-1} (Figure 4).

Table 3. Crop growth rate (g m^{-2} day^{-1}) from tillering to heading of rice genotypes as affected by phosphorus and zinc application.

	Years		
Phosphorus (kg ha^{-1})	**2011**	**2012**	**Mean**
0	25.9	31.4	28.7 d
40	33.6	43.7	38.7 c
80	38.4	49.7	44.0 b
120	40.0	53.7	46.9 a
$LSD_{0.05}$	1.45	1.84	0.99
Zinc (kg ha^{-1})			
0	32.7	42.6	37.6 d
5	33.7	43.8	38.8 c
10	35.5	45.5	40.5 b
15	36.0	46.6	41.3 a
$LSD_{0.05}$	1.36	1.27	0.79
Genotypes			
B-385 (fine)	28.2	32.5	30.4 c
F-Malakand (coarse)	34.3	42.7	38.5 b
Pukhraj (coarse)	40.9	58.7	49.8 a
$LSD_{0.05}$	1.26	1.60	1.14
Years mean	34.5 b	44.6 a	

Means of the same category followed by different letters are significantly different at 5% level of probability using least significant difference (LSD) test. Significant interactions are P × G * (Figure 3) and P × Zn × G *** (Figure 4). Where ns = non-significant data, while * and *** stands for significant data at 5 and 0.1% level of probability, respectively.

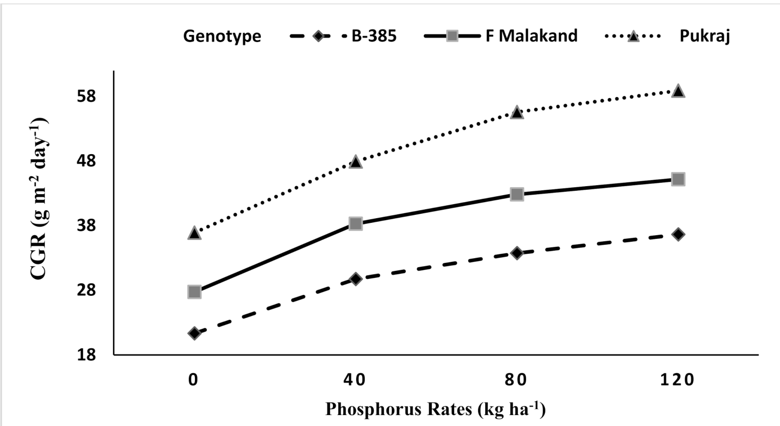

Figure 3. Crop growth rate (g m^{-2} day^{-1}) from tillering to heading of rice as affected by phosphorus into genotype (P × G) interaction.

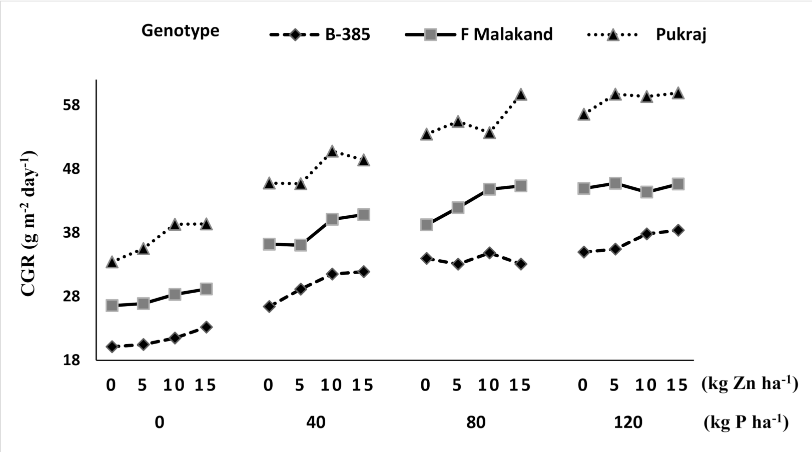

Figure 4. Crop growth rate (g m^{-2} day^{-1}) from tillering to heading of rice as affected by phosphorus into zinc into genotypes (P × Zn × G) interaction.

3.3. Crop Growth Rate from Heading to Physiological Maturity

The P and Zn rates and genotypes had significantly affected CGRs from heading to physiological maturity (Table 1). Years and all interactions except Y × G had no significant effect on the CGR (Table 1). The highest CGR (14.71 g m^{-2} day^{-1}) was recorded with the application of 120 kg P ha^{-1} which was statistically identical with 40 and 80 kg P ha^{-1}, and the minimum CGR (8.60 g m^{-2} day^{-1}) was observed for P control plots (Table 4). In the case of Zn rates, the maximum CGR (14.73 g m^{-2} day^{-1}) was recorded with 15 kg Zn ha^{-1} being at par with 10 kg Zn ha^{-1} (13.25 g m^{-2} day^{-1}), and the minimum CGR (11.09 g m^{-2} day^{-1}) was recorded for zinc control plots (Table 4). Among the three rice genotypes, maximum CGR (13.57 g m^{-2} day^{-1}) was recorded for Pukhraj, followed by F-Malakand (11.85 g m^{-2} day^{-1}), while minimum CGR (8.25 g m^{-2} day^{-1}) was recorded for B-385 (Table 4).

Table 4. Crop growth rate (g m^{-2} day^{-1}) from heading to physiological maturity of rice genotypes as affected by phosphorus and zinc application.

	Years		
Phosphorus (kg ha^{-1})	**2011**	**2012**	**Mean**
0	10.72	6.47	8.60 b
40	14.11	13.88	13.99 a
80	14.92	13.58	14.25 a
120	15.49	13.93	14.71 a
$LSD_{0.05}$	ns	4.47	2.28
Zinc (kg ha^{-1})			
0	12.53	9.65	11.09 c
5	12.99	11.97	12.48 bc
10	13.94	12.57	13.25 ab
15	15.78	13.68	14.73 a
$LSD_{0.05}$	ns	3.38	2.16
Genotypes			
B-385 (fine)	6.99	9.50	8.25 c
F-Malakand (coarse)	10.13	13.57	11.85 b
Pukhraj (coarse)	14.31	12.83	13.57 a
$LSD_{0.05}$	2.47	3.35	1.98
Years mean	13.81	11.96	

Means of the same category followed by different letters are significantly different at 5% level of probability using LSD test. Where ns = non-significant data.

In the interaction between Y × G (Table 4) indicated that the CGR of F-Malakand and B-385 was higher in Y2 than Y1, in the case of hybrid rice (Pukhraj) the CGR was higher in Y1 than in Y2.

3.4. Total Rice Biomass/Biological Yield at Harvest

Total Biomass yield (BY) at harvest was significantly affected by P and Zn rates, and genotypes (Table 1). Years and all interactions except P × G and P × Zn × G were found non-significant for BY (Table 1). The highest BY (19,114 kg ha^{-1}) was obtained with 120 kg P ha^{-1} being at par with 80 kg P ha^{-1} (18,938 kg ha^{-1}), and minimum BY (16,726 kg ha^{-1}) was recorded for P control plots (Table 5). In the case of Zn rates, maximum BY (18,835 kg ha^{-1}) was obtained with 10 kg Zn ha^{-1} being at par with 15 kg Zn ha^{-1} (18,523 kg ha^{-1}), and the minimum BY (17,566 kg ha^{-1}) was recorded for zinc control plots (Table 5). The interaction of Y × Zn (Table 5) indicated that the BY was higher at all Zn rates in Y2 than Y1. Among the three rice genotypes, maximum BY (19,785 kg ha^{-1}) was recorded for Pukhraj, followed by F-Malakand (19,125 kg ha^{-1}), and minimum BY (15,762 kg ha^{-1}) was recorded for B-385 (Table 5).

The interaction of P × G revealed that an increase in P rates up to 80 kg ha^{-1} increased BY of Pukhraj and B-385 (Figure 5). The BY of F-Malakand was decreased with an increasing P level up to 80 kg ha^{-1}, but a further increase in P level increased BY of F-Malakand (Figure 5). The three-way interaction among P × Zn × G indicated that Pukhraj had the highest BY at 80 kg P + 10 kg Zn ha^{-1} (Figure 6), while in the case of two local cultivars (F-Malakand and B-385), a higher BY was obtained at 120 kg P + 15 kg Zn ha^{-1} (Figure 6).

Table 5. Biomass/biological yield (kg ha^{-1}) of rice genotypes as affected by phosphorus and zinc application.

	Years		
Phosphorus (kg ha^{-1})	**2011**	**2012**	**Mean**
0	16,555	16,898	16,726 c
40	17,997	18,239	18,118 b
80	18,303	19,573	18,938 a
120	18,268	19,960	19,114 a
$LSD_{0.05}$	1030	922	672
Zinc (kg ha^{-1})			
0	17,114	18,018	17,566 b
5	17,453	18,493	17,973 b
10	18,383	19,286	18,835 a
15	18,174	18,872	18,523 a
$LSD_{0.05}$	678	700	483
Genotypes			
B-385 (fine)	15,148	16,376	15,762 c
F-Malakand (coarse)	18,884	19,366	19,125 b
Pukhraj (coarse)	19,310	20,259	19,785 a
$LSD_{0.05}$	892	799	582
Years mean	17,781	18,667	

Means of the same category followed by different letters are significantly different at 5% level of probability using LSD test. Significant interactions for BY are P × G * (Figure 5) and P × Zn × G *** (Figure 6). Where ns = non-significant data, while * and *** stands for significant data at 5 and 0.1% level of probability, respectively.

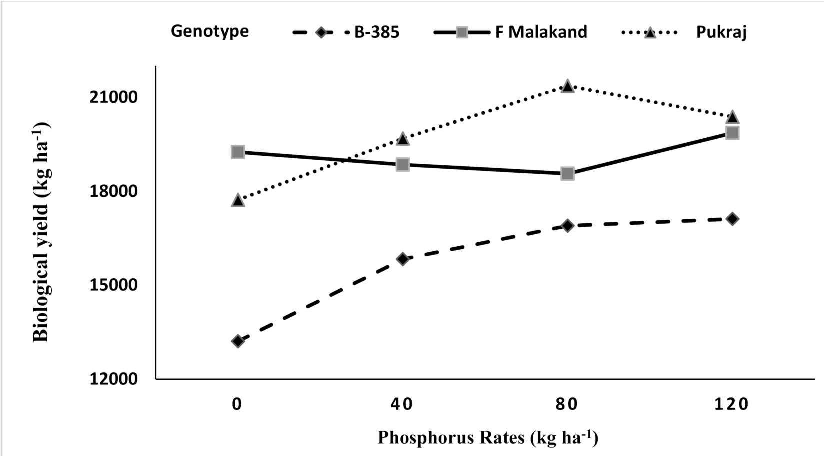

Figure 5. Biological yield (kg ha^{-1}) of rice as affected by phosphorus into genotypes (P × G) interaction.

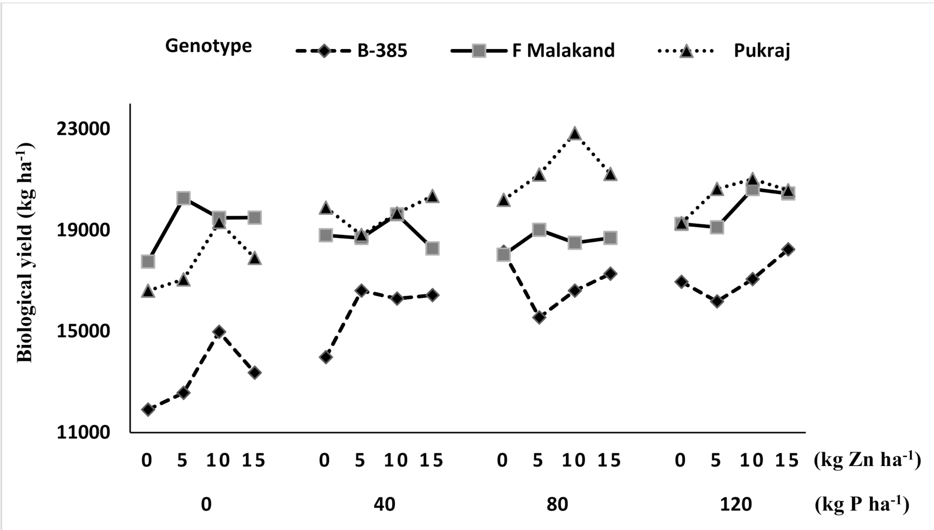

Figure 6. Biological yield (kg ha^{-1}) of rice as affected by phosphorus into zinc into genotypes (P × Zn × G) interaction.

4. Discussion

4.1. Crop Growth Rate at Different Growth Stages

The CGR depends on the amount of radiation intercepted by the crop and on the efficiency of conversion of intercepted radiation into dry matter. In this study, the CGR at different growth stages increased with the application of higher P rates (80 and 120 kg P ha^{-1}) and higher Zn rates (10 and 15 kg Zn ha^{-1}) and the increase was higher when both nutrients were applied in combination (P × Zn) than sole P or sole Zn application (Table 2, Table 3 andTable 4). The CGR decreased significantly ($p \leq 0.05$) at all three growth stages with the application of no (control) or lower P (0 and 40 kg P ha^{-1}) and Zn rates (0 and 5 kg Zn ha^{-1}). According to [27], the application of both P and Zn significantly increased total dry matter accumulation in rice. They reported the highest increase when both P and Zn were combined at their respective highest rates (100 and 10 ppm, respectively), the mean increase of shoots, roots and grains was 35, 39 and 25% higher over control (P0Zn0), respectively. The increase in CGR resulting from the combined application of P and Zn probably may be due to their beneficial effect on leaf area index [6], DMP [24], plants P and Zn contents [5] and higher yield and yield components [2]. The increase in dry matter accumulation with the application of P and Zn was also reported by other researchers [28–30]. According to [31], DM accumulation increased with an increased Zn level.

However, they reported maximum dry matter production with 40 kg Zn ha^{-1}. This contradiction might be due to differences in soil and environmental conditions as well as genotypes used. In our study, we confirmed that the increase in the CGR in rice crop with the application of higher P and Zn rates was attributed to their corresponding increase in the leaf area index [6]. This is because the increase in leaf area index probably increased the light interaction [32] that improved the CGR in this study.

The two coarse genotypes performed better than the fine genotype in terms of higher CGR (Table 2, Table 3 and Table 4) at different growth stages. According to [33], wide variability in photosynthetic rate (CGR) exits in rice genotypes. Earlier, [34] found that a high photosynthetic rate in crops is associated with higher productivity. The increase in the CGR in the course rice genotypes (Fakhre-e-Malakand and Pukhraj) over fine genotype (Basmati-385) was attributed to the higher leaf area index [6], increase in DMP into various plant parts [24] grain yield [2]. The increase in leaf area index and the corresponding increase in light interception [32] probably resulted i n higher CGR in rice. Our results are supported by [28] who reported differences in DM accumulation while growing different rice genotypes. This was expected since coarse genotypes take more nutrients (P and Zn) from soil [9], accumulate more Zn in plants [5] and partition more dry matter into various plant parts [24], thus resulting in a higher CGR. According to [35], DM production in six rice genotypes was significantly affected by P rates. An increase in DM accumulation or higher CGR is important because it is significantly associated with grain yield [2] and harvest index [8]. Hybrid rice genotypes had higher efficiency in DMP and, consequently, had higher grain yields than inbred lines [24,36].

4.2. Biomass Yield

Yield is defined as the amount of specific substance produced (e.g., grain, straw, total dry matter) per unit area. The results of our current study revealed that the BY in rice genotypes increased with the application of higher P (80 and 120 kg P ha^{-1}) and higher Zn rates (10 and 15 kg Zn ha^{-1}). The increase in BY was more when both nutrients were applied in combination (P + Zn) than sole (P or Zn) applications (Table 5). The BY decreased tremendously with the application of lower P (0 and 40 kg P ha^{-1}) and lower Zn rates (0 and 5 kg Zn ha^{-1}). In this study, the CGR showed a positive relationship with total BY. Ref. [37] reported an increase of 80% in BY and 180% in grain yield of rice with the application of a higher P rate of 131 kg P ha^{-1} over P-control plots. Ref. [38] reported that P application increased grain yield of different rice genotypes and the differences in yield were attributed with an increase in panicle number and BY. Similarly, [39] reported that BY and grain yield of rice increased with the application of Zn in the soil. They reported maximum BY with the application of 5 mg Zn kg^{-1} of soil, which was about 33% greater than Zn-control plots, and maximum grain yield was achieved with the application of 20 mg Zn kg^{-1} of soil that was about 97% more than Zn-control plots. Likewise, [31] reported a significant effect of Zn fertilizer on grain, biomass and straw yields as well as the harvest of rice. According to [40], straw and paddy yield showed an increasing trend up to 9 kg Zn ha^{-1}. They reported the highest average paddy yield and yield components were recorded at 120 kg N + 90 kg P_2O_5 along with 9 kg Zn ha^{-1}.

Our results confirmed that both P and Zn application at higher rates in combination improved the leaf area index of rice [6], increased DMP into various plant parts [6], increased yield components and grain yield [2] hence the BY in rice was increased. Ref. [41] reported that Zn and P either alone or in combination showed a significantly positive effect on the grain and straw yield of rice. Similarly, [42] found that grain yield and BY in rice reached a maximum with the combined application of 33 kg P + 12 kg Zn ha^{-1}. Grain yield in cereals is related to BY and harvest index because the BY is a function of crop growth duration and CGR at successive growth stages [43]. In the present study, the total BY was more at heading (heading > physiological > tillering). Ref. [44] reported a reduction in shoot dry weight of upland rice from flowering to physiological maturity. The higher BY indicates more translocation of assimilates from the leaf, leaf sheaths and stems to the panicles during the grain filling period, resulting in higher grain yield [36]. The BY in this study decreased significantly ($p \leq 0.05$) with the application of no or lower P (0 and 40 kg P ha^{-1}) and Zn rates (0 and 5 kg Zn ha^{-1}). These results are in agreement with the results of [45] who reported that macro- as well as micronutrient deficiencies are the most important nutritional disorders that limit crop yields.

The coarse rice genotypes (Pukhraj and F-Malakand) in this study produced more BY than the fine genotype (B-385) as shown in Table 5. The increase in BY of coarse genotypes was attributed to the higher leaf area index [6], higher DMP into different plant parts [24] and the higher number of panicles hill^{-1}, more filled grains panicle^{-1} and heavy grains [2] than the fine genotype. Ref. [46] found very interesting results while comparing different maize genotypes. They reported that the hybrid maize (Pioneer-3025) with higher leaf area index (LAI) also produced higher total biomass than the two local varieties (Azam and Jalal). Likewise, [36] reported that the two hybrids (SL8 and Bigante) had higher grain and BY than the check genotype, IR72. Ref. [31] reported significant differences in yield and yield parameters of different rice genotypes. Significant differences in yields have been reported among crop species and genotypes of the same species in the absorption and utilization of nutrients including P [44,47]. Further increase in grain yield in cereals such as rice through breeding can only be accomplished with an increase in total BY. According to [48], grain yield improvement of lowland rice cultivars released by the International Rice Research Institute (IRRI) in the Philippines after 1980 was due to increases in biomass production. Reference [49,50] made comparisons among the improved semi-dwarf cultivars, and higher grain yield was achieved by increasing biomass production.

5. Conclusions

Phosphorus and zinc management is one of the most important strategies for improving growth and total biomass. Zinc into phosphorus interaction imbalance in the rice plant results in excessive phosphorus accumulation causing zinc-imposed deficiency, resulting in lower crop growth rate (CGR) and total biomass/biological yield (BY). The BY (19,114 kg ha^{-1}) ranked maximum with the highest rate of 120 kg P ha^{-1} and decreased to a minimum (16,726 kg ha^{-1}) in P control plots. Maximum BY (18,835 kg ha^{-1}) was obtained with 10 kg Zn ha^{-1} and the minimum BY (17,566 kg ha^{-1}) was recorded for Zn control plots. The results of our study confirmed that the integrated application of phosphorus and zinc at higher rates was more beneficial in terms of higher CGR and BY in all three genotypes under study. The sole application of P and Zn or no application (P and Zn not applied) reduced both CGR and BY. The higher CGR of rice hybrid (Pukhraj) was attributed to its higher leaf area index because of its long and wider leaves, and higher dry matter accumulation and partitioning. The CGR showed a positive relationship with total BY. The increase in BY had a positive impact on grain yield and grower's income.

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