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UNRAVELING INTERACTIVE EFFECT OF ZINC AND PHOSPHORUS APPLICATION ON GROWTH, YIELD, AND QUALITY ATTRIBUTES OF ONION (*ALLIUM CEPA* L.)

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Abstract

The onion is a crucial vegetable that is widely utilized in households. The onion bulb boasts a rich composition of vitamins, minerals, and carbohydrates. However, an imbalanced fertilization, particularly concerning phosphorus (P) and zinc (Zn), poses a significant challenge to sustainable onion production and quality. Notably, these two nutrients exhibit an antagonistic effect within the plant. This study aims to unravel interactive effects of P and Zn, seeking optimal levels to enhance onion yield and quality traits. Therefore, the current study was conducted to check the interactive effect of three Zn doses (5, 10, and 15 kg Zn ha^{-1}) and five P doses (75, 100, 125, 150, and 175 kg P ha^{-1}) on the onion growth, yield and quality traits. Results indicated that the combined application of 10 kg Zn ha^{-1} with 150 kg P ha^{-1} yielded superior outcomes, including increased leaf length (39.3 cm), plant height (58.3 cm), leaf width (1.54 cm), leaf density (8.89 $plant^{-1}$), number of rings (10.3 rings $bulb^{-1}$), and onion yield (26.5 ton ha^{-1}). Furthermore, simultaneous application demonstrated the highest Zn and P concentrations in leaves (0.31 mg kg^{-1} and 2.06 mg kg^{-1}, respectively) and bulbs (0.33 mg kg^{-1} and 2.34 mg kg^{-1}, respectively). Furthermore, application of Zn and P also significantly affected bulbs skin color and foliage color. The findings of this study conclude that the simultaneous application of 10 kg Zn ha^{-1} and 150 kg P ha^{-1} is the best management practice for onion cultivation to achieve higher growth, yield, and quality traits in onions.

Key words: Onion, Antagonistic effect, Micronutrients, Imbalanced fertilization, Bulb skin color

Introduction

Onion is a winter vegetable crop that plays a pivotal role in the daily diet (Teshika *et al.,* 2019). It contains sulphur compound alkyl propyl disulfide, which is responsible for onion pungency. Onion bulbs offer variety of benefits including cancer prevention, anti-inflammatory, anti-diabetic, hypolipidemic, antimicrobial, anti-hypertensive, antioxidant production, and immune-protective (Lin *et al.,* 2016; Zhu *et al.,* 2018; Asemani *et al.,* 2019; Shahrajabian *et al.,* 2020). Onion bulbs also have major curative features, including reducing stomach warming during digestion and regulating blood pressure and lipids (Yang *et al.,* 2018). Onion bulbs are also an excellent dietary source of phenolic content, total flavonoids, anthocyanin, and proteins (Metrani *et al.,* 2020). It is also a rich source of vitamins A and C, sulfur-containing amino acids, and minerals like P, Ca, Mn, and Fe (Priya *et al.,* 2015; Shahrajabian *et al.,* 2020; Sagar *et al.,* 2022). Onion bulbs are also used in various cuisines and recipes as a condiment, spice, and salad in combination with fresh vegetables and are an important ingredient in paste and pickles (Edith *et al.,* 2018; Piechowiak *et al.,* 2020). However, there is a declining trend in onion growth, yield, and quality traits due to imbalanced fertilization, depleting soil fertility, and repeated cultivation of the exhaustive nature of crops. In addition, onion has a shallow and unbranched root system, hence effect of imbalanced nutrition is more obvious and evident (Rizk *et al.,* 2012; Aziz *et al.,* 2020).

Phosphorus (P) is a significant constraint on agricultural productivity, primarily because of its limited mobility in the soil solution, this characteristic leads to low phosphorus use efficiency within current cropping systems (Mardamootoo *et al.,* 2021; Khan *et al.,* 2022). A sufficient supply of P is required for crop plants due to its vital role in energy transformation during photosynthesis and respiration, and being a structural component of nucleic acids (Khan *et al.,* 2014). Its deficiency leads to stunted plant growth and development and yield losses (Balemi *et al.,* 2012). Several previous studies have reported that higher onion growth, yield, and quality traits were recorded with the application of optimum P fertilization compared to limited P availability (El-Hamady, 2017; Tekeste *et al.,* 2018; Qazi *et al.,* 2020). Zinc is the most important micronutrient that plays a significant role in enzyme

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activation, photo-assimilates translocation and auxin metabolism, and ultimately higher crop growth, developmental and physiological and productivity of onion (Zeidan *et al.,* 2010; Ballabh & Rana, 2012). The synthesis of chlorophyll pigment and carbohydrates is also an imperative function of Zn (Borowiak *et al.,* 2015; Hussain *et al.,* 2023). It is also crucial for optimum plant growth and development due to the activation of growth-promoting regulators and enzymes (Rai *et al.,* 2021) and improving nitrogen accumulation in plants (Selvakumar *et al.,* 2018; Song & Kim, 2020), hence its deficiency leads to severe damage in plants. Previous studies have reported higher growth, yield, and quality traits of onion with Zn fertilization (Ballabh *et al.,* 2013; Almendros *et al.,* 2015; Bhat *et al.,* 2018; Miah *et al.,* 2020).

Similarly, soil pH is a major factor that can determine the availability of Zn in the soil. However, Zn is also adsorbed on carbonate surfaces and hydroxides, thereby reduced Zn availability to plants (Brummer *et al.,* 1983; Prasad *et al.,* 2016). The application of Zn has a positive (synergistic effect) with N and K but a negative interaction (antagonistic effect) with P, Ca, Fe, and Cu (Prasad *et al.,* 2016). The antagonistic effect is primarily associated with the interference of P, Ca, Fe, and Cu in the absorption of Zn on root surfaces or/and its translocation from root to shoot in plants. With the application of P, a significant decrease in Zn availability in soil, Zn uptake by roots, and its translocation from roots to other plant tissues is proof of the antagonistic effect of P with Zn (Vafaei & Sarraf, 2014; Adnan, 2016; Thangasamy, 2016; Smith *et al*., 2017).

Due to the calcareous nature of Pakistani soils, fertilizer P forms complexes with calcium (Ca), and becomes unavailable for crop plants especially in alkaline calcareous soils (Smith & Schindler, 2009). About 80-90% of Pakistani soils are considered P deficient. In addition to that, research has shown that a very small portion (about 5-20%) of applied P fertilizers is absorbed by crop plants and a major portion becomes unavailable to the crop plants due to insoluble P complex formation (Mehta *et al.,* 2014), which resulted in low P use efficiency. The major source of P fertilizer is Di-ammonium phosphate which is costly resulting in a higher cost of production at farm levels (Trolove *et al.,* 2003; Khan *et al.,* 2014]. Micronutrient deficiency is also a major constraint that led to a decrease in crop production and nutritional quality worldwide (Zulfiqar *et al.,* 2020). The elevated adsorption of Zn on soil particles and poor soil Zn bioavailability due to the calcareous nature and higher pH of Pakistani soils have led to about 50% Zn deficient soils and crop productivity (Hussain *et al.,* 2011). To achieve higher productivity of onion, the combined application of micro and macronutrients has a great role in the fertilization program (Dang *et al.,* 1990; Prusty *et al.,* 2020).

However, no such in-depth research has been conducted to evaluate the interactive effect of P and Zn on the growth, yield, and quality traits of onions in semiarid regions. For this, we hypothesized that the optimum level of P and Zn may reduce the extent of the antagonistic effect between P and Zn and improve onion growth, yield, and quality traits. Therefore, the present research work was conducted to study the antagonistic effect of P and Zn on onion growth, yield, and quality traits, and to optimize P and Zn application rates in the onion crop.

Materials and Methods

Study area and climate: This research was conducted at the Local Farm (30.05 N, 72.35 E) of a progressive farmer in District Vehari, South Punjab, Pakistan during the growing period of winter seasons 2020-2021. The study area was characterized as an irrigated and semi-arid region. The weather data, including mean maximum temperature and minimum temperature, and total rainfall during the growing season of onion crop was collected from the Weather Research Station, Vehari District, South Punjab, Pakistan (Fig. 1). The lowest and highest recorded temperatures were 5°C and 20°C, respectively, with total rainfall of 55.6 mm observed during the growing season. The growing degree days (GDDs) accumulated for the onion crop were 3648°C.

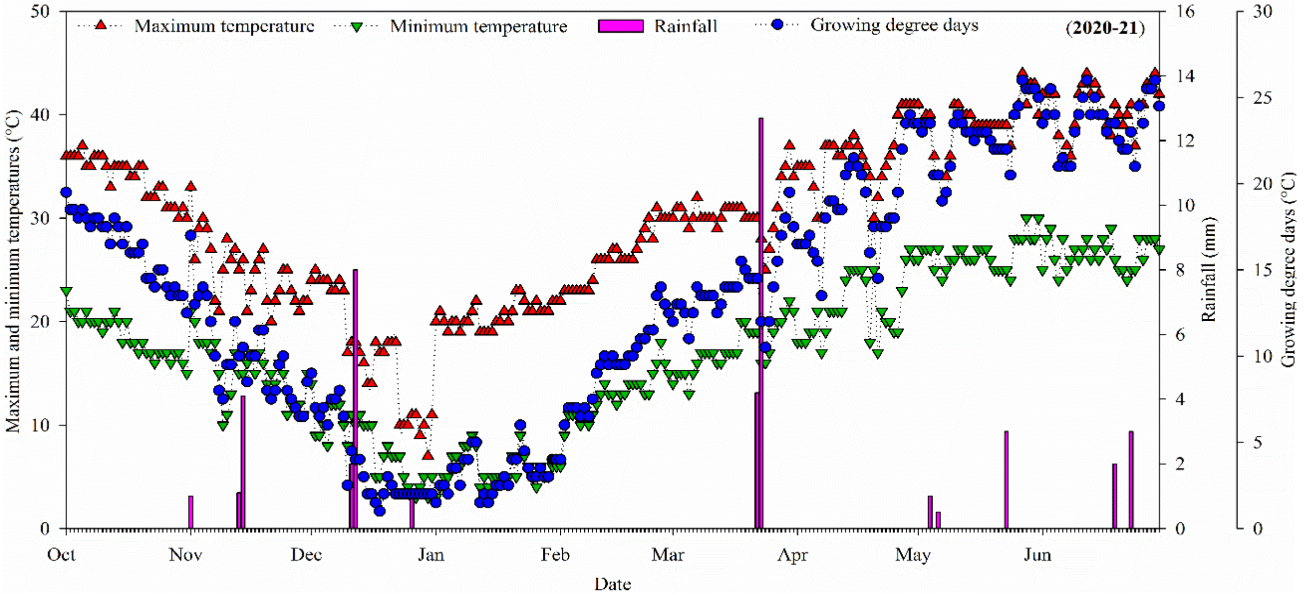

Fig. 1. Weather data including the maximum and minimum temperatures and rainfall and growing degree days during the growing period 2020-21 of the experimental site.

Experimental design and treatments: The present field experiment was laid out in a randomized complete block design with a split-plot arrangement having 3 replications. The unit plot size was 5 m × 3 m with row spacing of 30 cm and spacing of 8 cm between the seedlings. Treatments were consisted of three rates of Zn (Zn_1=5, Zn_2=10 and Zn_3=15 kg ha^{-1}) and five rates of P (P_1=75, P_2=100, P_3=125, P_4=150, and P_5=175 kg ha^{-1}). The source of Zn and P was Naya Zinc plus (27%) and Single Super Phosphate (18%), respectively.

Experimental procedures: Nursery of the onion was sown on October 20, 2020 by using the cultivar NARC-2005 (high yielding onion cultivar, developed by the National Agriculture Research Centre in Pakistan) at the rate of 6 kg per acre, and transplanted to the field after a month. Before transplanting the seedlings, the experimental field was plowed 30 cm deep and harrowed by using a tractor having cultivator. Large clods were broken down to ensure the fine land bed preparation. The plots were leveled; ridges were made at a spacing of 30 cm. The nursery bed was irrigated one day before uprooting the seedlings to facilitate the uprooting and subsequent good field establishment of onion seedlings. Then seedlings were planted on both sides of the ridges by maintaining an 8 cm distance between the seedlings. Irrigations and drainage channels were made for conveyance and drainage of excess water. All the P doses were applied at the time of field preparation. The Zn doses were applied 10 days after transplanting of the nursery. The onion crop was irrigated based on dominant agro-climatic conditions and by using stage-basis irrigation scheduling approach. Overall, ten irrigations, each of 75 mm water were applied to the onion crop throughout the growing season. To control thrips, chlorphenapyre 200 ml per acre was used. Pre-emergence herbicide pendimethalin was applied to control weed emergence. Subsequently, infestation of later weeds including Cyperus rotundus and Cynodon dactylon were controlled manually. Other recommended agronomic practices like gap filling, weeding, plant protection, etc. were kept uniform for all treatments. When 70% of plants showed neck fall, onion bulbs were harvested on June, 20 2021.

Measurements and analytical procedures

Growth and yield traits of onion: The length of three leaves per plant (from upper, medium, and lower) of the tagged ten plants was measured at maturity by using a ruler, and the average leaf length was determined. Similarly, plant height of fully developed ten plants was measured with the help of a scale, and mean plant height was calculated. By using a ruler, the leaf width of fully developed ten tagged plants was measured and the average leaf width was determined. To measure the leaf density, a simple technique where up to 3 leaves, 4-5 leaves, and 6 or more leaves indicated as low, medium, and high leaf density, respectively was used. Five mature dry bulbs were taken from each plot separately and then the number of rings was counted by cutting each bulb into separate layers and then the average of the ring was taken. Total bulbs were taken from each plot measured the yield and converted into tons per hectare.

Quality traits of onion: With the help of an onion descriptor, the skin color of harvested bulbs from each plot was estimated and their mean was determined. The foliage color of the fully developed ten plants from each plot was recorded by observing each plant and comparing it with the color chart. The color chart is an essential to determine particular color of onion and ensure consistent quality and marketability. Color chart is a reliable tool to categorize onions into different grades, positively reflects their market value (Hanci & Gokce, 2018). Yellow and red onions are considered best colors for cooking and salad respectively. Zn content in onion leaves and bulbs was measured through an Atomic Absorption Spectrometer (Perkin Elme-PinAAcle 900F). In the method, a 0.5 mg onion sample was taken and a 10 mL solution of Perchloric acid and Nitric acid 1:2 ratio was added to each sample the mixture was heated at 120°C temperatures on a hot plate for one hour later the temperature was increased to 300°C until the color of solution disappeared. Then, solution was filtered and its volume was made 25 mL by using distilled water. The filtrate was used to determine Zn through an Atomic Absorption Spectrometer. Moreover, P contents in onion leaves and bulbs were measured through a Spectrophotometer (Perkin Elmer Lambda 25 UV/Visible Spectrophotometer) by using ammonium-vanado-molybdate methods (Zia *et al.,* 2017).

Statistical analysis: Data collected including different growth, yield, and quality traits was statistically analyzed by using analysis of variance (ANOVA) technique (Steel *et al*., 1997). Furthermore, treatment means of different traits of onion were further compared by using the least significant difference (LSD) at a 5% probability level. Sigma plot v.15 was also used for the regression analysis and graphical representation of the data. By using statistical package readxl, cor, and corplot of the R software, the association of growth, yield, and quality traits with each other was assessed.

Results

Growth and yield traits of onion: Results of the interactive effects of P and Zn showed that all the studied traits of onion were found significant at $p \leq 0.05$ due to the combined addition of P and Zn (Tables 1, 2). Onion showed higher leaf length (39.3 cm), plant height (58.3 cm), whole round leaf width (1.54 cm), and leaf density (8.89 $plant^{-1}$) with the combined application of Zn 10 kg ha^{-1} and P 150 kg ha^{-1} (treatment Z_2P_4). However, mean leaf length, plant height, whole round leaf width, and leaf density were 35.4 cm, 52.2 cm, 1.39 cm, and 8.05, respectively. Moreover, onion produced a higher number of rings (10.3 rings $bulb^{-1}$) and onion yield (26.5 ton ha^{-1}) with the combined application of Zn 10 kg ha^{-1} and P 150 kg ha^{-1}. However, mean number of rings per bulb and onion yield was 8.97 and 24.1 ton ha^{-1}, respectively (Tables 1, 2). Results also indicated that growth and yield traits of onion were increased linearly by increasing Zn and P levels however, it was decreased by the application of higher dose of Zn 15 kg ha^{-1} and P 175 kg ha^{-1}. In this context, combined application of Zn 10 kg ha^{-1} with P 150 kg ha^{-1} is a best treatment combination of Zn and P for improving growth and yield traits of onion. Moreover, the results of the regression analysis showed that the onion yield showed a positive and moderately strong correlation with the whole leaf width and number of rings per bulb with R^2 values of 0.58 and 0.51, respectively (Fig. 2a and b). Similarly, the onion yield also showed a positive and moderately strong correlation with the Zn and P concentrations in leaves of the onion with R^2 values of 0.54 and 0.57, respectively (Fig. 2c and d).

Table 1. Interactive effect of Zn and P application on growth and yield traits of the onion.

Treatments	Leaf length (cm)	Plant height (cm)	Whole leaf width (cm)
Zn_1P_1	34.2 ± 0.69	46.3 ± 2.52	1.05 ± 0.19
Zn_1P_2	34.7 ± 0.42	50.3 ± 0.58	1.35 ± 0.01
Zn_1P_3	32.8 ± 1.83	51.6 ± 0.58	1.39 ± 0.01
Zn_1P_4	34.2 ± 0.69	49.3 ± 1.15	1.46 ± 0.04
Zn_1P_5	33.8 ± 0.84	52.6 ± 1.53	1.43 ± 0.02
Zn_2P_1	36.0 ± 1.00	51.0 ± 1.00	0.98 ± 0.20
Zn_2P_2	35.1 ± 1.02	50.6 ± 1.15	1.44 ± 0.02
Zn_2P_3	35.7 ± 1.53	54.3 ± 2.08	1.53 ± 0.02
Zn_2P_4	39.3 ± 1.95	58.3 ± 1.53	1.54 ± 0.02
Zn_2P_5	36.0 ± 0.33	57.0 ± 2.65	1.47 ± 0.02
Zn_3P_1	35.1 ± 0.51	50.3 ± 0.58	1.32 ± 0.03
Zn_3P_2	34.7 ± 1.02	51.6 ± 0.58	1.39 ± 0.01
Zn_3P_3	37.2 ± 0.69	53.0 ± 1.00	1.50 ± 0.03
Zn_3P_4	35.4 ± 1.31	52.0 ± 1.00	1.52 ± 0.03
Zn_3P_5	36.8 ± 0.19	55.6 ± 3.79	1.5 ± 0.03
Mean	35.4	52.2	1.39
Significance level	$p<0.003$	$p<0.02$	$p<0.007$
LSD ($p\leq0.05$)	3.47	3.29	0.23
CV	5.99	6.50	5.48

Values are given as means ±standard error of the means (n = 3). Means with in columns sharing different letters vary significantly at $p\leq0.05$; LSD = Least significance difference, CV=Coefficient of variance; Zn=Zinc; P=Phosphorus; Zn_1=5, Zn_2=10, and Zn_3=15 kg ha^{-1}, P_1=75, P_2=100, P_3=125, P_4=150, and P_5=175 kg ha^{-1}

Table 2. Interactive effect of Zn and P application on growth and yield traits of the onion.

Treatments	Leaf length (cm)	Plant height (cm)	Whole leaf width (cm)
Zn_1P_1	8.30 ± 0.58	7.66 ± 0.58	19.7 ± 2.57
Zn_1P_2	6.50 ± 0.51	8.33 ± 0.58	22.1 ± 1.53
Zn_1P_3	7.30 ± 0.58	8.66 ± 0.58	22.4 ± 1.14
Zn_1P_4	6.70 ± 0.69	9.00 ± 1.00	25.9 ± 1.48
Zn_1P_5	8.60 ± 0.58	8.66 ± 0.58	24.3 ± 0.34
Zn_2P_1	9.00 ± 0.67	9.00 ± 1.00	22.2 ± 1.15
Zn_2P_2	8.40 ± 0.51	8.66 ± 0.58	23.6 ± 1.15
Zn_2P_3	8.77 ± 0.84	9.66 ± 0.58	25.7 ± 0.20
Zn_2P_4	8.89 ± 0.69	10.3 ± 0.58	26.5 ± 0.88
Zn_2P_5	8.55 ± 0.51	9.33 ± 0.58	25.6 ± 1.27
Zn_3P_1	7.77 ± 0.39	8.33 ± 0.58	23.3 ± 0.93
Zn_3P_2	8.11 ± 0.84	8.66 ± 0.58	25.3 ± 0.20
Zn_3P_3	8.30 ± 0.34	9.33 ± 0.58	25.4 ± 0.19
Zn_3P_4	8.11 ± 0.85	9.33 ± 0.58	26.2 ± 1.47
Zn_3P_5	7.55 ± 0.51	9.66 ± 0.58	22.7 ± 2.77
Mean	8.05	8.97	24.1
Significance level	$p<0.004$	$p<0.05$	$p<0.001$
LSD ($p\leq0.05$)	2.11	1.68	2.10
CV	8.50	6.10	7.10

Values are given as means ±standard error of the means (n = 3). Means with in columns sharing different letters vary significantly at $p \leq 0.05$; LSD = Least significance difference, CV=Coefficient of variance; Zn=Zinc; P=Phosphorus; Zn_1=5, Zn_2=10, and Zn_3=15 kg ha^{-1}, P_1=75, P_2=100, P_3=125, P_4=150, and P_5=175 kg ha^{-1}

Quality traits of onion: The result regarding the interactive effect of P and Zn showed that all the studied quality traits (bulb skin color, foliage color, and Zn and P concentration in leaves and bulbs) of onion were found significant at $p\leq0.05$ (Tables 3, 4). Treatment combinations including Zn_1P_1, Zn_1P_2, and Zn_2P_1 showed brown bulb skin color and the Zn_1P_3, and Zn_3P_1 showed light brown bulb color of onion. Moreover, treatment combinations Zn_2P_2, and Zn_3P_1 showed dark brown, and Zn_1P_4, Zn_1P_5, Zn_2P_3, Zn_2P_4 Zn_2P_5, Zn_3P_2, Zn_3P_3, Zn_3P_4, and Zn_3P_5 showed red bulb skin color of onion. The dominant color of onion bulbs was red, which found in the treatment combinations, where phosphorus application was gradually increased during the current study (Table 3). Similarly, treatment combinations Zn_1P_4, Zn_1P_5, Zn_2P_1, Zn_2P_2, Zn_2P_3, Zn_2P_4, Zn_2P_5, Zn_3P_2, Zn_3P_3, Zn_3P_4, and Zn_3P_5 showed bullish green foliage color, and light green foliage of onion was observed by Zn_1P_1, Zn_1P_2, Zn_1P_3, Zn_2P_1, and Zn_3P_1 (Table 3).

Onion crops showed the maximum Zn concentration in leaves (0.31 mg kg^{-1}) and bulbs (0.33 mg kg^{-1}) with the combined application of Zn 10 kg ha^{-1} and P 150 kg ha^{-1} (Table 4). The mean Zn concentrations in leaves and bulbs were 0.23 mg kg^{-1} and 0.24 mg kg^{-1}, respectively. Similar to Zn concentration, onion crops showed the maximum P concentration in leaves (2.06 mg kg^{-1}) and bulbs (2.34 mg kg^{-1}) with the combined application of Zn 10 kg ha^{-1} and P 150 kg ha^{-1} (Table 4). The means of P concentrations in leaves and bulb of onion were 1.49 mg kg^{-1} and 1.77 mg kg^{-1}, respectively. Results also indicated that the quality traits of onion were increased linearly by increasing Zn and P levels however, it was decreased by the application of a higher dose of Zn 15 kg ha^{-1} and P 175 kg ha^{-1}. In this context, the combined application of Zn 10 kg ha^{-1} with P 150 kg ha^{-1} is the best treatment combination of Zn and P for improving Zn and P concentrations in leaves and bulbs of onion. The regression analysis revealed that the Zn concentration in the leaves showed a positive and highly strong correlation with the Zn concentration in the onion bulbs with a R^2 value of 0.82 (Fig. 3a). Similarly, it was observed that the P concentration in the leaves was a positive and highly strong correlation with the P concentration in the onion bulbs with a R^2 value of 0.93 (Fig. 3b).

Correlation analysis: Leaf length showed a strong correlation with leaf density and a negative correlation with plant height, leaf width, number of rings per bulb, onion yield, Zn and P concentration in leaves and bulb of the onion crop (Fig. 4). Plant height has a strong correlation lead width, number of rings per bulb, onion yield, Zn and P concentration in leaves and bulbs and negative correlation with leaf density. Whole leaf width showed a negative correlation with leaf density and a weak correlation with plant height, number of rings per bulb, onion yield, Zn and P concentration in leaves and bulbs. Leaf density also showed a strong correlation with leaf length and a negative correlation with leaf width, number of rings per bulb, onion yield, and Zn and P concentration in leaves and bulbs. Moreover, number of rings per bulb of onion crop showed a weak positive correlation with leaf density of onion and a positive correlation with leaf width, onion yield, Zn and P concentration in leaves and bulbs. Onion yield showed a weak positive correlation with leaf density and a positive correlation with leaf width, number of rings per bulb, Zn and P concentration in leaves and bulbs. Zn and P concentration in leaves and bulbs showed a weak positive correlation with leaf density, and strong positive correlation with leaf width, number of rings per bulb, and onion yield (Fig. 4).

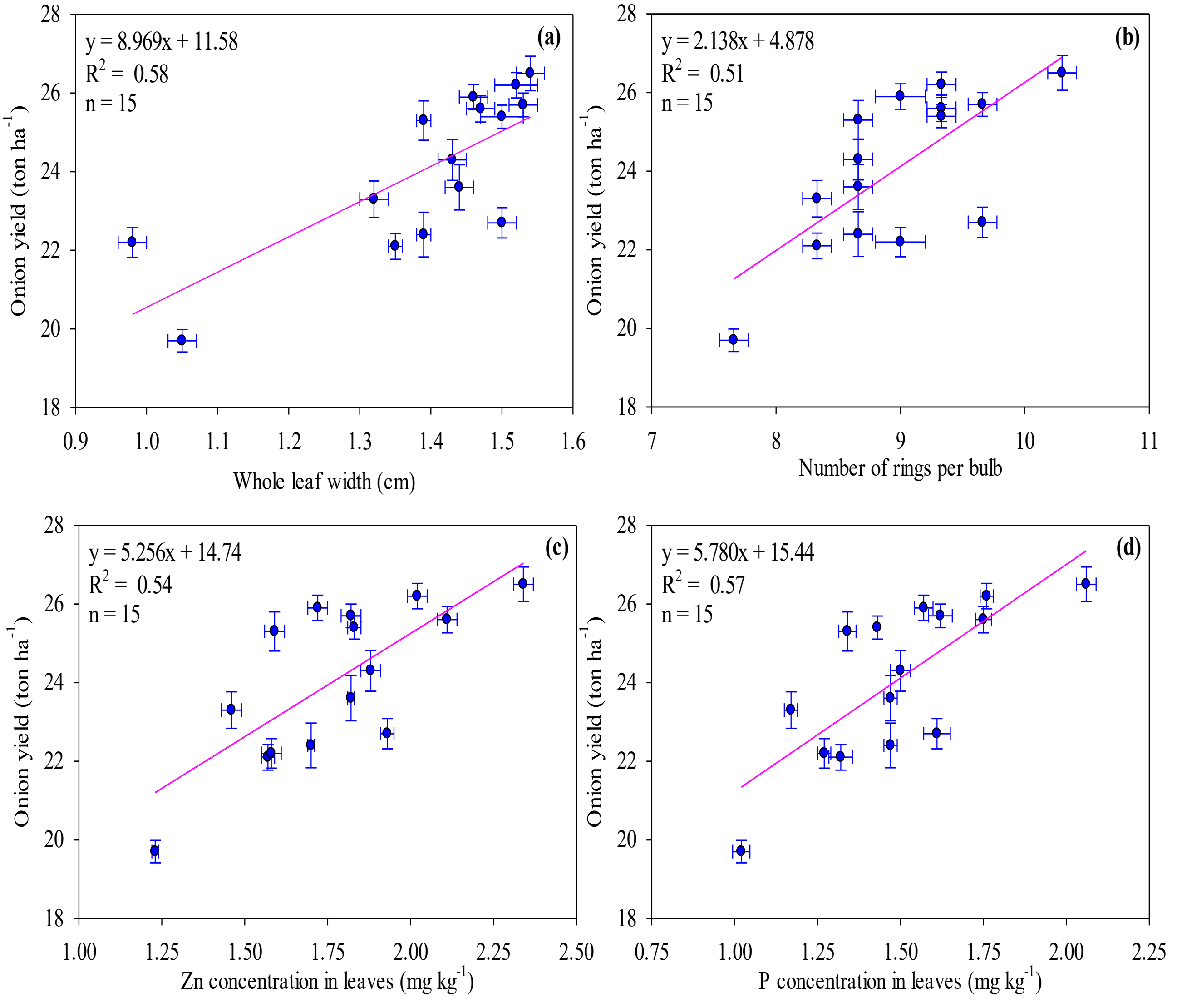

Fig. 2. The regression analysis of the onion yield with whole leaf width (a), number of rings per bulb (b), Zn concentration in leaves (c) and P concentration in leaves (d) under different Zn and P application rates. The vertical error bars show standard deviation for the x-axis, however the horizontal error bars represent standard deviation for the y-axis.

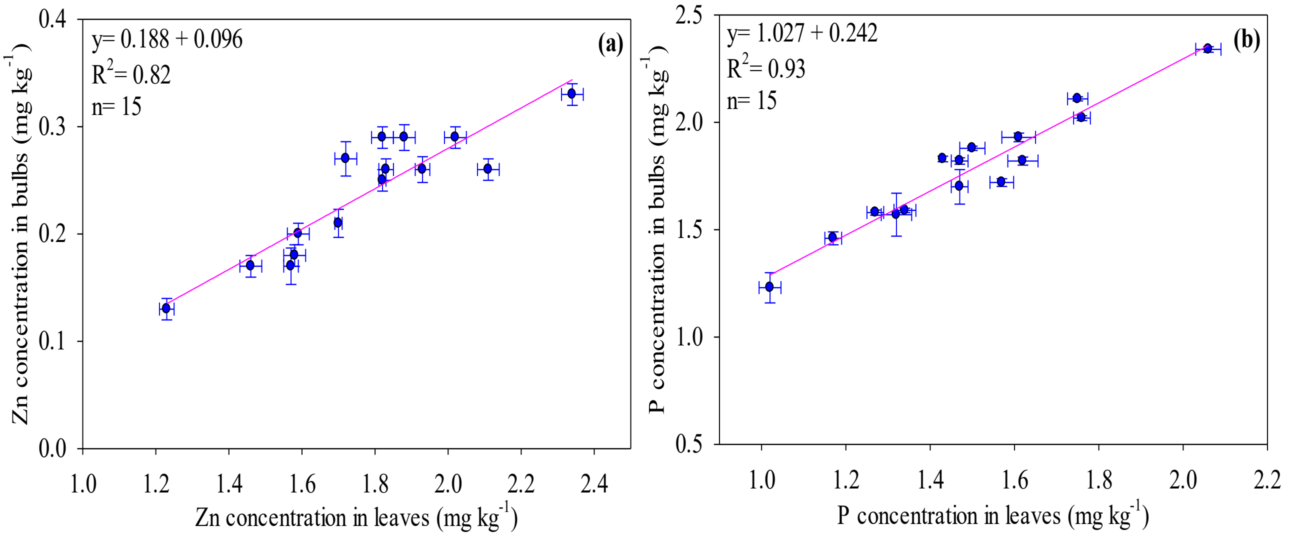

Fig. 3. The regression analysis of the Zn concentration in leaves with Zn concentration in bulbs (a), and P concentration in leaves with P concentration in bulbs (b) under different Zn and P application rates. The vertical error bars show standard deviation for the x-axis, however the horizontal error bars represent standard deviation for the y-axis.

Table 3. Interactive effect of Zn and P application on quality traits onion bulb skin colour and foliage colour of the onion.

Treatment	Onion bulb skin colour			Red	Onion foliage colour	
	Brown	Light brown	Dark brown		Bullish green	Light green
Zn_1P_1	+					+
Zn_1P_2	+					+
Zn_1P_3		+				+
Zn_1P_4				+	+	
Zn_1P_5				+	+	
Zn_2P_1	+	+				+
Zn_2P_2			+		+	
Zn_2P_3				+	+	
Zn_2P_4				+	+	
Zn_2P_5				+	+	
Zn_3P_1			+			+
Zn_3P_2				+	+	
Zn_3P_3				+	+	
Zn_3P_4				+	+	
Zn_3P_5				+	+	

The presence of a plus sign indicates dominant quality trait, whereas a blank value signifies subpar quality traits. Zn=Zinc; P=Phosphorus; Zn_1=5, Zn_2=10 and Zn_3=15 kg ha^{-1}, P_1=75, P_2=100, P_3=125, P_4=150, and P_5=175 kg ha^{-1}

Table 4. Interactive effect of Zn and P application on Zn and P concentration in leaves and bulb of the onion.

Treatment	Zinc concentration (mg kg^{-1})		Phosphorus concentration (mg kg^{-1})	
	Leaves	Bulbs	Leaves	Bulbs
Zn_1P_1	0.13 ± 0.01	0.13 ± 0.01	1.02 ± 0.13	1.23 ± 0.07
Zn_1P_2	0.17 ± 0.02	0.17 ± 0.02	1.32 ± 0.18	1.57 ± 0.10
Zn_1P_3	0.22 ± 0.01	0.21 ± 0.03	1.47 ± 0.10	1.70 ± 0.08
Zn_1P_4	0.25 ± 0.03	0.27 ± 0.02	1.57 ± 0.14	1.72 ± 0.18
Zn_1P_5	0.27 ± 0.03	0.29 ± 0.02	1.50 ± 0.02	1.88 ± 0.10
Zn_2P_1	0.16 ± 0.03	0.18 ± 0.01	1.27 ± 0.10	1.58 ± 0.12
Zn_2P_2	0.23 ± 0.01	0.25 ± 0.02	1.47 ± 0.10	1.82 ± 0.15
Zn_2P_3	0.27 ± 0.03	0.29 ± 0.02	1.62 ± 0.18	1.82 ± 0.19
Zn_2P_4	0.31 ± 0.03	0.33 ± 0.01	2.06 ± 0.15	2.34 ± 0.13
Zn_2P_5	0.26 ± 0.03	0.26 ± 0.01	1.75 ± 0.12	2.11 ± 0.10
Zn_3P_1	0.16 ± 0.03	0.17 ± 0.01	1.17 ± 0.10	1.46 ± 0.08
Zn_3P_2	0.18 ± 0.03	0.20 ± 0.01	1.34 ± 0.13	1.59 ± 0.10
Zn_3P_3	0.25 ± 0.02	0.26 ± 0.02	1.43 ± 0.09	1.83 ± 0.13
Zn_3P_4	0.28 ± 0.03	0.29 ± 0.02	1.76 ± 0.10	2.02 ± 0.11
Zn_3P_5	0.26 ± 0.02	0.26 ± 0.02	1.61 ± 0.10	1.93 ± 0.08
Mean	0.23	0.24	1.49	1.77
Significance level	$p<0.001$	$p<0.000$	$p<0.015$	$p<0.024$
LSD ($p\leq0.05$)	0.03	0.04	0.49	0.46
CV	11.4	6.21	8.14	6.12

Values are given as means ±standard error of the means (n=3). Means within columns sharing different letters vary significantly at $p\leq0.05$; LSD = Least significance difference, CV = Coefficient of variance; Zn=Zinc; P=Phosphorus; Zn_1=5, Zn_2=10, and Zn_3=15 kg ha^{-1}, P_1=75, P_2=100, P_3=125, P_4=150, and P_5=175 kg ha^{-1}

Discussion

The growth traits are key indicators for determining the yield and quality of any crop. Numerous prior studies have highlighted a strong correlation between growth traits and both yield and quality across various field crops (Ul-Allah *et al.,* 2017; Manaf *et al.,* 2019; Ahmad *et al.,* 2021). Notably, the growth traits of onion crops exhibit significant variations due to the fertilization of Zn (Almendros *et al.,* 2015) and P (Tekeste *et al.,* 2018), resulting in enhanced onion yield and quality (Bhat *et al.,* 2018; Qazi *et al.,* 2020). Onion yield, a key source of economic return, is largely determined by a balanced proportion of zinc and phosphorus fertilizers.

Zinc plays a crucial role in the synthesis of the vital plant growth hormone indole acetic acid (Grant *et al.,* 1993; Rai *et al.,* 2021). Consequently, the optimal application rate of Zn enhances the growth traits of onions, as observed in the current study. Therefore, the onion crop exhibited superior growth traits (such as leaf length, plant height, and leaf density) with the combined application of 10 kg ha^{-1} Zn and 150 kg ha^{-1} P compared to other treatment combinations. Our research findings further support those of Almendros *et al*., (2015), who demonstrated that onion fertilization with an optimal Zn rate improves growth traits compared to lower rates and control treatments. Similarly, a previous study reported higher leaf length of onions with the application of higher Zn rates compared to control and lower Zn rates (Ballabh & Rana, 2012) which are consistent with our findings.

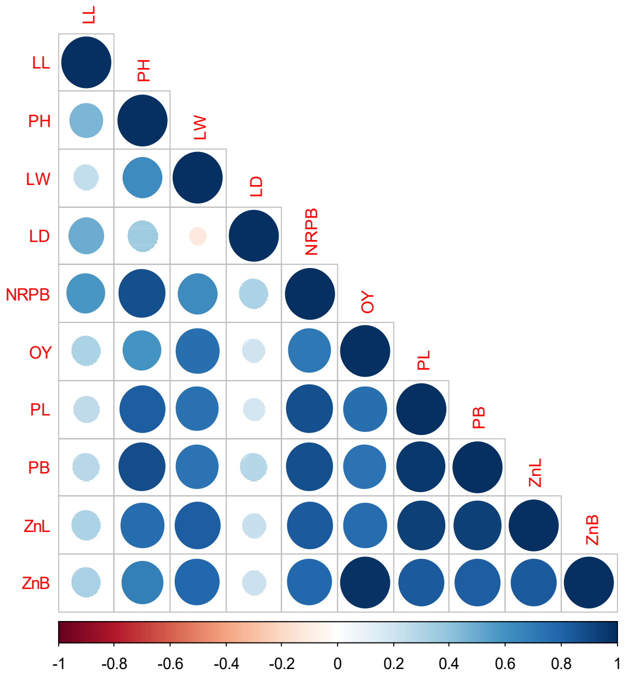

Fig. 4. Correlation map shows interactive effect of Zn and P application on growth, yield, and quality traits of onion; Leaf length (LL), Plant height (PH), Leaf width (DW), Leaf density (LD), Number of rings per bulb (NRPB), Onion yield (OY), P concentration in leaves (PL), P concentration in bulb (PB), Zn concentration in leaves (ZnL), and Zn concentration in bulb (ZnB). The blue shade showed a positive correlation and the pink shade showed a negative correlation. The size of the circle showed how the traits are associated with each other.

Phosphorus fertilization also plays a role in energy transfer during photosynthesis and respiration (Khan *et al.,* 2014), thereby maximizing assimilated production and leading to improved growth traits in onions, as observed in our study. Our research findings are consistent with those of Qazi *et al*., (2020), who observed that higher rates of P fertilization increased growth traits, especially leaf length and plant height, in onions. Zn fertilization is also involved in the formation of chlorophyll content (Rai *et al.,* 2021) which leads to more assimilate production and ultimately greater plant height and leaf length in onions with the Zn fertilization at 10 kg ha^{-1}. Our results also strengthened the previous (Manna *et al.,* 2016; Bhat *et al.,* 2018) where higher growth traits were observed with a higher rate of Zn fertilization. Furthermore, higher leaf width and leaf density of onions recorded due to the interactive effect of 10 kg ha^{-1} Zn and 150 kg ha^{-1} P confirm Zn ability in the promotion of cell division and cell elongation of plants under optimum P availability. Similar results have also been reported by Begum *et al*., (2015) where a higher rate of Zn showed greater leaf width over control. Moreover, the higher leaf density of onions might be closely associated with a higher number of leaves per plant at Zn 10 kg ha^{-1} and P 150 kg ha^{-1}. Thus, our research findings suggest that 10 kg ha^{-1} Zn and P 150 kg ha^{-1} are the optimum treatments of Zn and P, respectively, for improving onion growth traits. On the other hand, the linear decrease in the studied onion growth traits may be correlated with the negative interaction (antagonistic effect) among Zn and P which is supported by our hypothesis and also previous research findings.

Zn fertilization also improves physiological and biochemical processes in the plants (Wasaya *et al.,* 2017; Zafar *et al.,* 2018) which leads to improved efficiency of plants to use all available resources and ultimately higher yield traits of onion. Thus, onion showed maximum studied yield traits with the application of Zn 10 kg ha^{-1} and P 150 kg ha^{-1}. This supported previous studies that reported the maximum onion yield with Zn fertilization at a higher rate as compared to the lower rate and control treatment (Kumar *et al.,* 2021; Miah *et al.,* 2020). On the other hand, P fertilization showed the greater onion yield where higher rate of P was applied as compared to lower rates (Júnior *et al.,* 2016). Moreover, higher onion yield was correlated with the higher recorded growth traits in the present study (Fig. 2a and b). This study also rejects the findings of Boyhan *et al*., (2007) that reported no significant differences in onion yield with P application up to 160 kg ha^{-1}. In this context, our findings suggest Zn 10 kg ha^{-1} and P 150 kg ha^{-1} are the optimum rates of Zn and P, respectively for improving yield traits of onion. Similar to growth traits of onion, the decrease in studied yield traits of onion due to linear increase in Zn and may be correlated with the negative interaction among Zn and P which supported also our hypothesis.

The quality traits of onions are commonly associated with genetics (Lee *et al.,* 2015a, 2020). However, significant differences in foliage and onion bulb skin color were observed with the application of Zn and P in the present study. Yellow and red color onions are considered best colors of onion bulb due to greater pungency, antioxidant activities, anthocyanins, flavonoids, and quercetin levels (Lee *et al.,* 2015b; Zhang *et al.,* 2016). In the present study, onion bulbs showed variety of colors i.e. brown, dark brown, light brown and red. The dominant color of onion was red, which might be due to imperative role of P in the synthesis of anthocyanins that produces red color (Zheng *et al.,* 2020; Li *et al.,* 2023). These results indicate that P can be used to improve the skin color of onion bulbs. Further, P availability can be enhanced with application of Zn as observed in the current study. There was also an increasing trend in Zn and P concentration in leaves and bulb of onion with the increasing Zn and P rates, which was highest at 150 kg ha^{-1} P and 10 kg ha^{-1} Zn and then started to decrease, which might be due to an antagonistic effect of Zn with P. There is an antagonistic effect between Zn and P fertilization as reported by previous studies (Vafaei & Sarraf, 2014; Prasad *et al.,* 2016; Thangasamy, 2016), hence it may be a possible reason behind the reduced Zn and P concentration in onion leaves and bulbs as observed in the current study.

Conclusion

The study summarized that the initial increase in Zn and P application linearly enhanced onion growth and yield. The results revealed that among all treatment combinations, the combined application of 10 kg Zn ha^{-1} with 150 kg P ha^{-1} produced the maximum onion yield (26.5 ton ha^{-1}), which was attributed to superior growth and quality attributes of onion in this treatment. Further increase in Zn and P application showed an antagonistic effect and could not enhance onion yield and growth. Therefore, it is recommended that application of 10 kg Zn ha^{-1} and P 150 kg ha^{-1} is the best fertilizer management practice for onion crop production under semiarid region.

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Data Availability: All data generated or analyzed during this study will be made available upon reasonable request to the corresponding author.

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