Pol. J. Environ. Stud. Vol. XX, No. X (XXXX), 1-9
DOI: 10.15244/pjoes/192973 ONLINE PUBLICATION DATE:

Original Research

Interactive Effect of Zinc and Phosphorus Application on Growth and Yield of Bt. Cotton

Muhammad Usman[1*], Hafiz Mohkum Hammad[1,2], Muhammad Sohail Shahzad[3], Allah Ditta Abid[3], Adeel Anwar[4], Musarrat Shaheen[5], Saeed Ahmad[1], Muhammad Nadeem Shah[6***], Muhammad Bilawal Junaid[7], Imran Haider[8] Muhammad Akhtar[9], Munirah Abdullah Al-Dosary[10]**

[1]Department of Agronomy, Muhammad Nawaz Shareef University of Agriculture, Multan, Pakistan
[2] Department of Agricultural and Biological Engineering, University of Florida 32611, USA
[3]Department of Plant Protection, Ministry of National Food Security and Research, Pakistan
[4]Department of Agronomy PMAS-Arid Agriculture University Rawalpindi, Pakistan
[5]Cotton Research Institute (CRI), Khanpur, Rahimyar Khan, Punjab, Pakistan
[6] Department of Agriculture, Government College University, Lahore, Pakistan
[7]Department of Plant Production College of Food and Agriculture, King Saud University, P.O. Box 2455, Riyadh 11451, Saudi Arabia
[8]National Research Center of Intercropping, The Islamia University of Bahawalpur Punjab Pakistan (63100)
[9]Institute of Crop Sciences, Chinese Academy of Agricultural Sciences/Key Laboratory of Crop Physiology and Ecology, Ministry of Agriculture and Rural Affairs of China, Beijing 100081, China
[10]Department of Botany and Microbiology, College of Science, King Saud University, P.O. Box 2455, Riyadh 11451, Saudi Arabia

Received: 24 January 2024
Accepted: 4 September 2024

Abstract

Cotton is the main cash and fiber crop worldwide, including Pakistan. Sustainable cotton production is threatened by excessive and injudicious use of inorganic fertilizers, especially phosphorus (P) and zinc (Zn). Due to their antagonistic interaction, P and Zn levels must be optimized. This study examined P-Zn interactions in the cotton crop under arid circumstances. A split-plot design was used to provide five doses of P (P_1=0, P_2=30, P_3=60, P_4=90, and P_5=120 kg ha^{-1}) and three doses of Zn (Zn_1=6, Zn_2=12, and Zn_3=18 kg ha^{-1}). Cotton crop data included soil P and Zn availability, plant growth, morphology, and yield. This demonstrated that increasing Zn and P dosages steadily boosted the growth, physiology, and yield traits of the cotton crop. Compared to other combinations, 12 kg Zn ha^{-1} and 90 kg P ha^{-1} improved the studied growth, physiological, and yield parameters of the cotton crop. This combination had the maximum chlorophyll contents (62.2 SPAD value), net leaf photosynthetic rate (13.6 μmol CO_2

*e-mail: musmankhan2755@gmail.com
**e-mail: hafiz.mohkum@mnsuam.edu.pk
***e-mail: nadeemshah@gcu.edu.pk
Tel.: +92-305-688-5211

m^{-2} s^{-1}), stomatal conductance (0.47 mmol m^{-2} s^{-1}), sub-sub conductance (292.3 µmol H_2O m^{-2} s^{-1}), leaf transpiration rate (9.6 mmol m^{-2} s^{-1}), and water usage efficiency (2.42 kg ha^{-1} mm^{-1}). Similarly, the highest plant height, peak leaf area index, sympodial branches, total bolls, and mean boll weight were obtained with the application of 12 kg Zn ha^{-1} and 90 kg P ha^{-1}. The maximum soil available P (16.0±0.240 mg kg^{-1}) and Zn (9.00±0.335 mg kg^{-1}) was recorded in the P_4Zn_2 treatment. Thus, the present study found that increasing Zn and P dosages increased cotton crop growth, morphology, physiology, yield traits, and availability of P and Zn in the soil. The growth, morphological, physiological, and yield parameters of the cotton crop and soil available P and Zn were recorded the highest with 12 kg Zn ha^{-1} and 90 kg P ha^{-1}. Therefore, the highest seed cotton yield (1.278 ton ha^{-1}) and biological yield (10.492 ton ha^{-1}) were with the application of 12 kg Zn ha^{-1} and 90 kg P ha^{-1}. The findings of this research work suggest that the combined application of 12 kg Zn ha^{-1} and 90 kg P ha^{-1} is the best fertilizer management approach to increase cotton seed yield under the conditions of an arid climate.

Keywords: sustainable cotton production, antagonistic interaction, zinc, phosphorus

Introduction

Cotton is the backbone of Pakistan's economy, contributing a 0.8% share of GDP. However, a severe decline in its yield has been observed in the last decade, mainly due to biotic and abiotic factors. Some of these factors include improper sowing time, low nitrogen use efficiency, drought and heat stress, insect pests, and diseases [1-5]. Imbalanced fertilization is one of the major constraints to cotton production in an arid climate [6, 7].

Phosphorus (P) is an essential plant nutrient that must be present in all plant cells in optimum concentration because it helps them carry out their functions properly. It is involved in the storage and transfer of energy, photosynthesis, respiration, cell division, and expansion in plants [8]. Many plants contain P at a concentration of 0.2% of their total dry weight [9]. However, the deficiency of P leads to decreased shoot dry weight, root dry weight, and whole plant weight and an increased root-to-shoot ratio in cotton crops [10]. Previous studies have reported that optimum P availability increases chlorophyll a, b, and carotenoids and total soluble protein contents and reduces the level of malondialdehyde in plants [11]. Moreover, P use efficiency is low due to the application of lower doses than the optimum doses of P by poor and marginal farmers. This situation could become worse, which might be correlated with increased prices of P fertilizer due to the limited available resources of P worldwide [12]. In addition, soils with higher concentrations of calcium (Ca), aluminum (Al), and iron (Fe) reduce the availability of P because it forms strong bonds with Ca, Al, and Fe and thereby becomes unavailable [13]. The deficiency or lower supply leads to a minimum photosynthetic rate and metabolism that ultimately decreases the seed cotton yield of the cotton crop [12, 14].

Zinc (Zn) is an essential plant micronutrient required for cell division and expansion and helps to complete the life cycle in plants [15]. It is involved in a wide variety of metabolic processes, such as the activation of enzymes, metabolism of proteins, photosynthetic carbon, and the metabolism of indole acetic acid [16, 17].

Limited knowledge is available on the interactions between P and Zn in plants. Thus, it demands additional research, particularly in plants having high requirements of P and Zn. Cotton is one of the crops in which plants have high requirements for both P and Zn. It has been reported that when there is a balanced supply of P and Zn, the maximum biomass can be achieved, whereas an unequal supply of these nutrients results in a Zn shortage and P or Zn toxicity [18, 19]. Many studies have reported antagonistic interactions between P and Zn due to excess or low doses that lower physiological and biochemical processes [20, 21, 22]. Imbalanced P and Zn fertilization could decrease the P and Zn use efficiencies in the cotton crop [19]. Thus, the application of P and Zn in balanced quantity can increase the P and Zn use efficiency in cotton production.

This comprehensive information on the interactions between P and Zn in plants is essential for commercially valuable plants having high requirements of P and Zn. However, no extensive research work has been executed to explore the interactive effect of P and Zn fertilization on their soil availability and also uptake by the roots and physiology, growth, and yield components of the cotton crop. For this purpose, we hypothesize that the interactive effect between Zn and P may help to assess the optimum doses of P and Zn for achieving a higher yield of the cotton crop.

Materials and Methods

Experimental Site and Climate

The experiment was conducted at the selected Agronomic Research Area, MNS University of Agriculture, Multan, Pakistan (30˚14''N, 71˚43''E) during the summer season, on May 15, 2022. The climate of the experimental site was arid, being characterized as a hot and moderately humid summer (May-June) and a warm and humid rainy season (July-September).

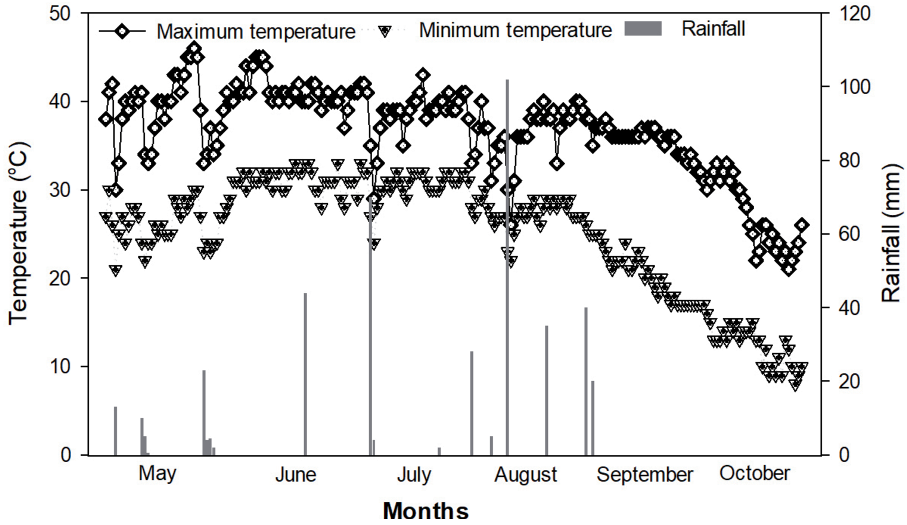

Fig. 1. Weather data during the study period collected from automatic weather station of MNS-University of Agriculture, Multan, Pakistan.

Weather data during the study period was collected from the automatic weather station of MNS-University of Agriculture, Multan, Pakistan (Fig. 1).

Experimental Design and Treatments

A split-plot design was used to conduct the proposed research trial. There were three replications, the size of the plots was adjusted to 5× 3 m, and all the blocks were equal in size. Different doses of Zn and P were applied to different experimental units to study the interactive effect of Zn and P application in cotton production. The experimental treatments were comprised of five doses of P (P_1=0, P_2=30, P_3=60, P_4=90, and P_5=120 kg ha^{-1}) and three doses of Zn (Zn_1=6, Zn_2=12, and Zn_3=18 kg ha^{-1}). The 90 kg ha^{-1} was designed as the recommended dose of P for cotton crops. Different Zn and P doses were kept in main plots and subplots, respectively.

Soil Analysis

According to the experimental plan, soil samples from each plot after sowing and at cotton harvest were collected with the help of a soil auger. These samples were collected from different soil depths (0-15, 15-30, and 30-45 cm), and one composite soil sample having soil of three depths for each treatment was made. Upper soil layers are the source of the majority of nutrients; therefore, these three soil depths (0-15, 15-30, and 30-45 cm) were considered during the study. The sampling was performed following the methodology of Mason [23]. After analysis, soil samples were ground and sieved (2 mm mesh) to remove the dirt and other remnants of plants. Soil available P was estimated using the sodium bicarbonate method [24]. An atomic absorption spectrometer (Varian, Spectra A 220) was used to determine the Zn concentration in the soil samples. This system contains a multi-element hollow cathode lamp for Zn and is operated at 213.7 nm wavelength [25].

Cultivation of Cotton

The soil was plowed twice, followed by land leveling. The bed planter was used to make beds of 75 cm spacing, and seed beds were irrigated. After irrigation, the seeds were planted manually by maintaining a 30 cm plant-to-plant distance. The recommended dose of K (60 kg ha^{-1}) and planned doses of P and Zn, half of the recommended dose of N (80 kg ha^{-1} of a total of 160 kg ha^{-1}) were applied at sowing time, while the remaining dose of N (80 kg ha^{-1}) was applied in two equal splits (each of 40 kg ha^{-1}). Fertilizer sources of N, P, K, and Zn used in this study were urea, di-ammonium phosphate, murat of potash, and zinc sulfate, respectively. Irrigations were given according to the crop requirement and prevailing environmental conditions. All the intercultural operations except those under study were kept uniform during the whole growing season.

Observations and Measurements

Data on growth, phenology, physiology, morphology, and yield traits of cotton crops was recorded using standard scientific protocols and procedures. The number of days from the date of sowing to square initiation, flower initiation, boll initiation, and boll opening was recorded during the study. Physiological traits (i.e., net leaf photosynthesis rate, stomatal conductance, sub-stomatal conductance, net leaf transpiration rate, and water use efficiency) were recorded using the CIRAS-Portable Photosynthesis System. These physiological traits were recorded from 10:30 am to 3:00 pm. The plant height of randomly tagged five plants in each experimental unit from plant base to tip of the plant's main stem was recorded using measuring tape, and

Table 1. Different properties of soil assessed before cotton sowing.

Soil depth	Electricatl conductivity (dS m^{-1})	Soil pH	Organic matter (%)	Available Phosphorus (ppm)	Available Potassium (ppm)	Saturation (%)	Soil Texture
0-15	1.84	8.0	0.57	13.9	173	36	Loam
15-30	1.93	8.1	0.57	13.9	173	36	Loam
30-45	1.91	8.3	0.57	13.9	173	36	Loam

the average plant height was calculated. The peak of the leaf area index was calculated at the full canopy development stage using the method of [26]. The number of monopodial, sympodial, and total bolls of the tagged five plants was counted, and their average was calculated. The boll weight of randomly selected five bolls from each experimental unit was determined, and the average boll weight was recorded. At maturity, the plants were harvested from a meter-square area and separated into leaves, stems, and reproductive parts. Then, these samples were oven-dried at 65°C-70°C until the constant dry weight of the samples was recorded and converted into total dry matter in tons ha^{-1}. The seed cotton of each experimental unit was picked, and then it was converted into seed cotton yield in tons ha^{-1}.

Statistical Analysis

The recorded data was subjected to the analysis of variance (ANOVA) technique to analyze the interactive effect of different P and Zn doses on the studied traits of cotton crops [27]. Furthermore, the treatment means were compared with the help of the mean separation test, Tukey's Honestly Significant Difference (HSD), at $p \leq 0.05$.

Results and Discussion

Effect of Zinc and Phosphorus on Physiological Traits of Cotton

The leaf photosynthetic rate, water use efficiency, chlorophyll content, stomatal and sub-stomatal

Table 2. Effect of zinc and phosphorus on physiological traits of cotton crop.

Treatment	Leaf photosynthetic rate (μmol CO_2 m^{-2} s^{-1})	Water use efficiency (kg ha^{-1} mm^{-1})	Chlorophyll content (SPAD value)	Stomatal conductance (mmol H_2O m^{-2} s^{-1})	Sub-stomatal conductance (μmol H_2O m^{-2} s^{-1})	Leaf transpiration rate (mmol H_2O m^{-2} s^{-1})
P_1Zn_1	8.97±0.20 e	4.73±0.13e	42.7±0.17g	0.33±0.01c	221±2.75h	6.69±0.01e
P_1Zn_2	9.21±0.04 de	4.71±0.17e	43.0±0.37g	0.33±0.01c	227±2.49gh	6.69±0.04e
P_1Zn_3	9.57±0.05 c-e	5.07±0.07de	45.3±0.32f	0.34±0.01c	232±2.30fg	7.09±0.04de
P_2Zn_1	9.40±0.11 c-e	5.05±0.10de	45.0±0.07f	0.35±0.01c	231±1.68fg	6.99±0.08de
P_2Zn_2	9.80±0.16 cd	5.24±0.06de	46.3±0.16f	0.33±0.01c	237±2.23f	7.22±0.04de
P_2Zn_3	9.53±0.04 c-e	5.08±0.04de	45.3±0.86f	0.343±0.01c	229±1.68f-h	6.99±0.08de
P_3Zn_1	9.69±0.06 c-e	5.15±0.07de	45.0±0.48f	0.34±0.01c	234±1.30fg	7.17±0.02de
P_3Zn_2	10.1±0.20 c	5.47±0.11cd	48.7±0.26e	0.33±0.01c	251±1.65e	7.64±0.04cd
P_3Zn_3	9.67±0.03 c-e	5.10±0.04de	45.0±0.42f	0.32±0.00c	232±1.41fg	7.06±0.04de
P_4Zn_1	11.6±0.11 b	6.23±0.06b	54.3±0.50bc	0.40±0.01b	275±3.28bc	8.52±0.09b
P_4Zn_2	13.6±0.24 a	7.06±0.12a	62.0±0.43a	0.45±0.00a	317±2.96a	9.57±0.11a
P_4Zn_3	11.4±0.47 b	6.03±0.07bc	53.0±0.46c	0.39±0.01b	267±3.54cd	8.23±0.12bc
P_5Zn_1	9.77±0.34 cd	5.26±0.38de	53.0±0.45c	0.34±0.01c	274±4.28c	7.29±0.51de
P_5Zn_2	9.81±0.19 cd	5.50±0.34cd	55.3±0.97b	0.340±0.01c	283±5.85b	7.59±0.42cd
P_5Zn_3	9.810±0.10 cd	4.78±0.40e	51.0±0.43d	0.343±0.01c	261±0.01d	6.56±0.53e

Note: Means sharing the same case did not differ significantly at $p \leq 0.05$

conductance, and leaf transpiration rate varied significantly among all the treatments (Table 2). The significantly highest leaf photosynthetic rate was found in the P_4Zn_2, where the value of the leaf photosynthetic rate was 13.6 ±0.24 µmol CO_2 m^{-2} s^{-1}. However, the lowest value was observed in P_1Zn_1, i.e., 8.97±0.20 µmol CO_2 m^{-2} s^{-1}. The highest value of chlorophyll content (62.0±0.43 SPAD value) was recorded in P_4Zn_2, while the lowest (42.7±0.17 SPAD value) was in the P_1Zn_1 treatment. Similarly, the maximum sub-stomatal conductance (317±2.96 µmol H_2O m^{-2} s^{-1}) in P_4Zn_2 treatment was reduced to 221±2.75 µmol H_2O m^{-2} s^{-1} in P_1Zn_1 treatment. Furthermore, the highest stomatal conductance (0.45±0.00 mmol H_2O m^{-2} s^{-1}) was recorded in the P_4Zn_2 treatment, while the lowest value of stomatal conductance (0.33±0.01 mmol H_2O m^{-2} s^{-1}) was observed in the P_1Zn_1. The leaf transpiration rate was recorded as the highest in P_4Zn_2 treatment with a value of 9.57±0.11 mmol H_2O m^{-2} s^{-1}, while the lowest value was in P5Zn3, i.e., 6.56±0.53 mmol H_2O m^{-2} s^{-1} (Table 2).

Effect of Zinc and Phosphorus on Vegetative Growth of Cotton Plants

The main growth and morphological features of cotton, such as leaf area index, monopodial branches, plant height, and sympodial branches, varied significantly among all the treatments (Table 3). The highest value of leaf area index, i.e., 3.15±0.02, was observed in the P_4Zn_2 treatment, and the lowest value of 2.17±0.02 was observed in the P_1Zn_1 treatment. The maximum monopodial branches (2.00±0.00 branches $plant^{-1}$) were observed in P_4Zn_2, and the minimum value (1.00±0.00 branches $plant^{-1}$) was recorded in P_1Zn_2 treatment. The highest value of plant height (95.0±0.68 cm) was observed in the P_4Zn_2 treatment, while the lowest (64.3±0.55 cm) was in the P_1Zn_1 treatment. The sympodial branches (22.7±0.96 branches $plant^{-1}$) were also recorded as the highest in P_4Zn_2, while the lowest value (13.7±0.39 branches $plant^{-1}$) in P_1Zn_1 treatment (Table 3).

Effect of Zinc and Phosphorus on Phenology and Reproductive Growth of Cotton

The number of days to flower and boll formation and boll opening, total bolls per plant, and boll weight varied significantly among all the studied treatments (Table 4). The cotton crop took significantly the highest days to flower formation (57.67±0.72) in the P_4Zn_2 treatment, while it took the lowest (49.0±0.47) in the P_1Zn_3 treatment. Similarly, the maximum days to boll formation (48.0±0.47) were observed in the P_4Zn_3 treatment and the minimum value (43.7±0.54) in the P_5Zn_3 treatment. On the other hand, the highest days to boll opening (78.7±0.98) were recorded in the P_4Zn_2 treatment and the lowest value (66.3 ±3.03) in the P_3Zn_3 treatment. The total boll per plant was observed to be substantially the highest (34.0±0.12) in P_4Zn_2, and the lowest value (23.7±0.05) was recorded in P_1Zn_2 treatment. The highest value of boll weight (9.59 ±0.15)

Table 3. Effect of zinc and phosphorus on vegetative growth parameters of cotton.

Treatment	Leaf area index	Monopodial branches $plant^{-1}$	Plant height (cm)	Sympodial branches $plant^{-1}$
P_1Zn_1	2.17±0.02i	1.33±0.27ab	64.3±0.55g	13.7±0.39g
P_1Zn_2	2.20±0.01i	1.00±0.00b	64.6±0.60fg	14.3±0.15fg
P_1Zn_3	2.32±0.02gh	1.33±0.27ab	68.2±0.62e	15.3±0.22d-f
P_2Zn_1	2.29±0.01gh	1.33±0.27ab	67.5±0.47ef	14.7±0.35e-g
P_2Zn_2	2.35±0.01g	1.33±0.27ab	68.9±0.78e	16.0±0.10de
P_2Zn_3	2.27±0.02h	1.33±0.27ab	66.5±0.73e-f	14.3±0.52fg
P_3Zn_1	2.32±0.02gh	1.33±0.27ab	68.3±0.60e	15.0±0.40d-g
P_3Zn_2	2.48±0.01f	1.33±0.27ab	72.6±1.03d	16.3±0.42cd
P_3Zn_3	2.28±0.01gh	1.33±0.27ab	67.7±0.39e	15.3±0.24d-f
P_4Zn_1	2.74±0.03bc	1.67±0.27ab	82.2±0.92b	18.3±0.25b
P_4Zn_2	3.15±0.02a	2.00±0.00a	95.0±0.68a	22.7±0.96a
P_4Zn_3	2.59±0.03e	1.67±0.27ab	81.4±1.07b	17.7±0.23bc
P_5Zn_1	2.71±0.03cd	1.33±0.27ab	79.2±1.35bc	18.0±0.07b
P_5Zn_2	2.80±0.05b	1.33±0.0ab	79.7±2.09b	18.3±0.34b
P_5Zn_3	2.59±0.02e	1.33±0.0ab	76.4±0.44c	17.7±0.50bc

Note: Means sharing the same case did not differ significantly at $p \leq 0.05$

Table 4. Effect of zinc and phosphorus on phenology and reproductive growth parameters of cotton crop.

Treatment	Days to flower formation	Days to boll formation	Days to boll opening	Total bolls per plant	Boll weight (g)
P_1Zn_1	50.0±1.25b	44.3±0.98c	70.0±1.70 de	24.0±0.17f	5.92±0.31c
P_1Zn_2	50.0±0.47b	44.3±1.09c	70.3±0.72 de	23.7±0.05f	6.66±0.44c
P_1Zn_3	49.7±0.72b	45.7±0.98ab	72.3±1.44b-d	25.3±0.22ef	6.87±0.33c
P_2Zn_1	49.0±0.47b	45.3±0.98ab	71.0±1.41c-e	24.7±0.21ef	6.46±0.25c
P_2Zn_2	49.0±1.25b	45.0±1.25bc	68.3±1.96 de	26.0±0.20e	6.68±0.60c
P_2Zn_3	51.0±1.41b	44.7±1.44bc	70.3±0.72 de	25.0±0.19ef	6.29±0.29c
P_3Zn_1	49.7±0.27b	43.7±1.09c	71.3±1.19c-e	26.0±0.17e	6.84±0.26 c
P_3Zn_2	50.0±1.25b	44.3±1.52c	71.0±1.25c-e	26.3±0.15de	6.93±0.32 c
P_3Zn_3	50.3±0.54b	43.0±1.41c	66.3±3.03 e	25.3±0.08ef	6.45±0.28 c
P_4Zn_1	55.3±0.72a	48.0±0.47a	76.0±2.49a-c	30.7±0.30b	8.70±0.03ab
P_4Zn_2	57.6±0.72a	47.3±0.72ab	78.7±0.98 a	34.0±0.12a	9.59±0.15a
P_4Zn_3	55.0±0.47a	48.0±0.47a	77.3±1.52 ab	29.7±0.38bc	8.25±0.26b
P_5Zn_1	50.7±1.36b	44.0±1.70c	69.3±2.60 de	28.7±0.27c	6.88±0.21 c
P_5Zn_2	49.7±0.72b	43.3±1.09c	70.7±1.19 de	29.3±0.61bc	6.92±0.31 c
P_5Zn_3	50.7±0.72b	43.7±0.54c	70.0±2.05de	28.0±0.23ed	6.62±0.31c

Note: Means sharing the same case did not differ significantly at $p \leq 0.05$

was observed in P_4Zn_1 and the lowest value of boll weight (5.92±0.30) in the P_1Zn_1 treatment (Table 4).

Effect of Zinc and Phosphorous on Seed Cotton Yield, Total Dry Matter, and Phosphorus and Zinc Availability in the Soil

Seed cotton yield and total dry matter also varied significantly among all the studied treatments (Fig. 2). The highest seed cotton yield (1.278 ±0.067 ton ha^{-1}) was found in the P_4Zn_2 treatment. However, the lowest value of the seed cotton yield (0.828±0.038 ton ha^{-1}) was observed in the P_1Zn_1 treatment (Fig. 2). Similarly, the highest total dry matter (10.492 ±0.870 ton ha^{-1}) was observed in P_4Zn_2 treatment, while the lowest total dry matter contents (7.271±0.573 ton ha^{-1}) were recorded in P_1Zn_1 treatment (Fig. 2). The maximum availability of the P (16.0±0.240 mg kg^{-1}) was observed in the P_4Zn_2 treatment, and the minimum value of available P (13.4±0.201 mg kg^{-1}) was recorded in the P_5Zn_3 treatment. Similarly, the highest availability of Zn (9.00±0.335 mg kg^{-1}) was recorded in P_4Zn_2 treatment, and the lowest value of Zn (4.49±0.280 mg kg^{-1}) was recorded in P_1Zn_1 treatment (Fig. 2).

Discussion

Growth and morphological traits (plant height, peak of leaf area index, and sympodial branches per plant) were affected significantly due to the application of different rates of Zn and P. The cotton crop produced the highest growth and the values of morphological traits in the object with the combined application of 12 kg Zn ha^{-1} and 90 kg P ha^{-1} in comparison to other treatment combinations. Based on the results, there was a gradual increase in studied growth and morphological traits of cotton crops with the increasing Zn and P doses. In contrast, cotton showed a decreasing trend in values of studied growth and morphological traits at 18 kg Zn ha^{-1} and 120 kg P ha^{-1}. Phosphorus is directly involved in energy transfer in the processes of photosynthesis and respiration and is a structural component of nucleic acids [28] that led to the maximum studied growth and morphological traits of cotton in the current study. Similarly, higher growth and morphological traits of cotton crops were recorded with the application of the optimum dose of Zn with P application [29]. In addition, the highest growth and morphological traits of the cotton crop were recorded due to the imperative role of Zn in the activation of enzymes, metabolism of proteins, photosynthetic carbon, and the metabolism of indole acetic acid [17, 30]. Thus, the application of 12 kg Zn ha^{-1} and 90 kg P ha^{-1} are the optimum doses of Zn and P, respectively, to achieve the maximum growth and morphological traits of the cotton crop.

However, monopodial branches per plant of cotton were not affected due to the application of Zn and P, which might be due to the genetic character of the studied cotton cultivar. The highest physiological traits of the cotton crop were recorded when the cotton crop was fertilized with 12 kg Zn ha^{-1} and 90 kg P ha^{-1}.

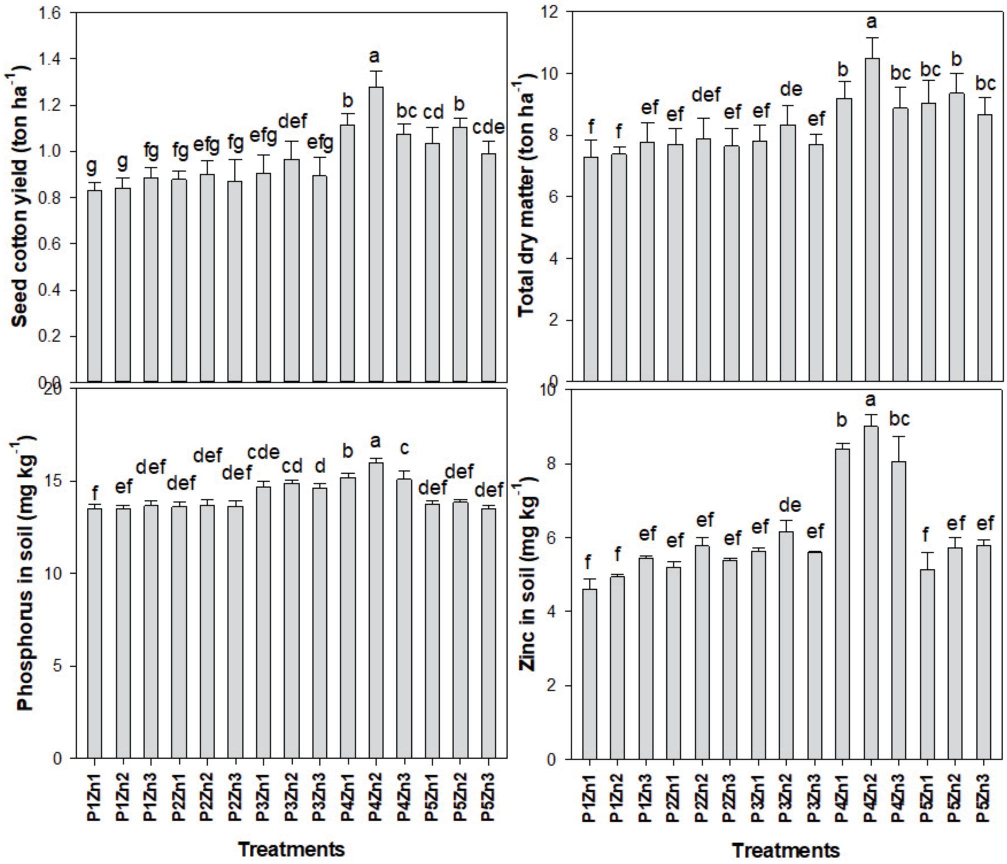

Fig. 2. Phosphorus and zinc available in the soil and seed cotton yield and total dry matter in dependence on particular P-Zn treatments.

Higher physiological traits of cotton crops were closely associated with the important role of P in the synthesis of chlorophyll content [31], which led to increased studied physiological traits. Similar results have been reported in sheep grass [32], wild barley [33], tea [34], and oats [35]. In contrast, one study showed that cotton fertilization with 70 kg P ha^{-1} resulted in higher leaf gas exchange and was regarded as an optimum dose for the cotton crop [36]. It has been reported that high growth and yield components of cotton crops could be achieved with 10-15 kg Zn ha^{-1} and 80-100 kg P ha^{-1} application under conditions of arid climate [37]. In this context, 12 kg Zn ha^{-1} and 90 kg P ha^{-1} are the optimum doses of Zn and P, respectively, to achieve the highest physiological traits of the cotton crop.

All the yield-contributing traits (total bolls per plant, mean boll weight, seed cotton yield, and biological yield) were also affected significantly due to the application of Zn and P. Results showed a linear increase in studied yield traits of the cotton crop with the gradual increase in Zn and P doses, and the maximum yield traits of the cotton crop were recorded at 12 kg Zn ha^{-1} and 90 kg P ha^{-1}. However, our research findings showed that there were no significant differences in yield traits of cotton with P application up to 120 kg P ha^{-1}. The higher studied yield traits of the cotton crop were due to the vital role of Zn in assimilates translocation to plant parts of the cotton crop and P in energy regulation in photosynthesis and respiration [8]. In the present context, our findings suggest 12 kg Zn ha^{-1} and 90 kg P ha^{-1} as the optimum levels of Zn and P for improving yield traits of cotton crops and also support our hypothesis. In contrast, previous studies have shown higher growth and yield components of the cotton crop with P application at a dose of 100 kg ha^{-1} under an arid climate [38-40]. In the present context, the application of 12 kg Zn ha^{-1} and 90 kg P ha^{-1} are the optimum doses of Zn and P, respectively, to achieve the highest yield traits of cotton crops.

Our research findings showed that there was an increasing trend in the availability of P and Zn in the soil, growth, morphological, physiological, and yield traits of the cotton crop with the increasing Zn and P doses up to the maximum at a dose of 12 kg Zn ha^{-1}, and 90 kg P ha^{-1} and then they started to decrease, which might be due to the antagonistic effect of Zn with P. Overall, the performance of the crop was poor due to excessive rainfall during the growing season (Fig. 1), which might cause submerged conditions and ultimately suffocation of the plants. Moreover, there was no significant improvement when the cotton crop was fertilized with 18 kg Zn ha^{-1}, and 120 kg P ha^{-1}. In crux, increasing Zn and P doses significantly increased the studied physiological, growth, and yield traits of the cotton crop and showed the maximum growth, physiological, and yield traits of the cotton crop were recorded with the combined application of 12 kg Zn ha^{-1} and 90 kg P ha^{-1}.

Conclusions

Growth, morphological, physiological, and yield traits of cotton crop and phosphorus and zinc availability in the soil were significantly affected due to the interactive effect of Zn and P. Based on the findings of the present study, increasing Zn and P doses increased the growth, morphological, physiological, and yield traits of the cotton crop. The growth, morphological, physiological, and yield traits of the cotton crop were recorded with the application of 12 kg Zn ha^{-1} and 90 kg P ha^{-1}. Thus, research findings suggest that the combined application of 12 kg Zn ha^{-1} and 90 kg P ha^{-1} should be recommended to the farmers to achieve a higher seed cotton yield of the cotton crop.

Acknowledgments

The authors extend their appreciations to King Saud University, Riyadh, Saudi Arabia for supporting this work through project number (RSP2024R316).

Funding

This research was funded by King Saud University, Riyadh, Saudi Arabia through project number (RSP2024R316).

Conflicts of Interest

The authors declare there are no conflicts of interest.

References

1. ABBAS Q., AHMAD S. Effect of Different Sowing Times and Cultivars on Cotton Fiber Quality under Stable Cotton-Wheat Cropping System in Southern Punjab, Pakistan. Pakistan Journal of Life and Social Sciences, **16** (2), 77, **2018**.
2. MANZOOR S., HABIB-UR-RAHMAN M., HAIDER G., GHAFOOR I., AHMAD S., AFZAL M., NAWAZ F., IQBAL R., YASIN M., DANISH S., GHAFFAR A. Biochar and slow-releasing nitrogen fertilizers improved growth, nitrogen use, yield, and fiber quality of cotton under arid climatic conditions. Environmental Science and Pollution Research, **29** (9), 13742, **2022**.
3. BASHIR M.A., BATOOL M., KHAN H., SHAHID NISAR M., FAROOQ H., HASHEM M., ALAMRI S., EL-ZOHRI M.A., ALAJMI R.A., TAHIR M., JAWAD R. Effect of temperature & humidity on population dynamics of insects' pest complex of cotton crop. PloS One, **17** (5), e0263260, **2022**.
4. HU W., ZHANG J., YAN K., ZHOU Z., ZHAO W., ZHANG X., PU Y., YU R. Beneficial effects of abscisic acid and melatonin in overcoming drought stress in cotton (*Gossypium hirsutum* L.). Physiologia Plantarum, **173** (4), 13550, **2021**.
5. EL SABAGH A., HOSSAIN A., ISLAM M., BARUTCULAR C., RATNASEKERA D., GORMUS O., AMANET K., MUBEEN M., NASIM W., FAHAD S., TARIQ M. Drought and heat stress in cotton (*Gossypium hirsutum* L.): Consequences and their possible mitigation strategies. Agronomic Crops, 613, **2020**.
6. GHAFFAR A., HABIB UR RAHMAN M., ALI H.R., HAIDER G., AHMAD S., FAHAD S., AHMAD S. Modern concepts and techniques for better cotton production. In Cotton production and uses. Springer, Singapore, pp. 589, **2020**.
7. AHMAD S., GHAFFAR A., RAHMAN M.H.U., HUSSAIN I., IQBAL R., HAIDER G., KHAN M.A., IKRAM R.M., HUSSNAIN H., BASHIR M.S. Effect of application of biochar, poultry and farmyard manures in combination with synthetic fertilizers on soil fertility and cotton productivity under arid environment. Communications in Soil Science and Plant Analysis, **52** (17), 2018, **2021**.
8. SHAFI M.I., ADNAN M., FAHAD S., WAHID F., KHAN A., YUE Z., DANISH S., ZAFAR-UL-HYE M., BRTNICKY M., DATTA R. Application of single superphosphate with humic acid improves the growth, yield and phosphorus uptake of wheat (*Triticum aestivum* L.) in Calcareous Soil. Agronomy, **10**, 1224, **2020.**
9. JUN J.J., STEINMETZ N.A., SIEGLE J.H., DENMAN D.J., BAUZA M., BARBARITS B., LEE A.K., ANASTASSIOU C.A., ANDREI A., AYDIN Ç., BARBIC M. Fully integrated silicon probes for high-density recording of neural activity. Nature, **551** (7679), 232, **2017**.
10. CHEN S., YAO H., HAN J., LIU C., SONG J., SHI L., ZHU Y., MA X., GAO T., PANG X., LUO K. Validation of the ITS2 region as a novel DNA barcode for identifying medicinal plant species. PloS One, **5** (1), e8613, **2010**.
11. VENKATACHALAM P., PRIYANKA N., MANIKANDAN K., GANESHBABU I., INDIRAARULSELVI P., GEETHA N., SAHI S.V. Enhanced plant growth promoting role of phycomolecules coated zinc oxide nanoparticles with P supplementation in cotton (*Gossypium hirsutum* L.). Plant Physiology and Biochemistry, **110**, 118, **2017**.
12. JAYAKUMAR M., SURENDRAN U. Intercropping and balanced nutrient management for sustainable cotton production. Journal of Plant Nutrition, **40**, 632, **2017**.
13. RANDRIAMANANTSOA L., MOREL C., RABEHARISOA L. Can the isotopic exchange kinetic method be used in soils with a very low water extractable phosphate content and a high sorbing capacity for phosphate ions? Geoderma, **200**, 120, **2013**.
14. MENG X., CHEN W.W., WANG Y.Y., HUANG Z.R., YE X., CHEN L.S., YANG L.T. Effects of phosphorus deficiency on the absorption of mineral nutrients, photosynthetic system performance and antioxidant metabolism in *Citrus grandis*. PLoS One, **16** (2), e0246944, **2021**.
15. VISHVESHVAR K., KRISHNAN M.A., HARIBABU K., VISHNUPRASAD S. Green synthesis of copper oxide nanoparticles using *ixiro coccinea* plant leaves and its characterization. BioNanoScience, **8**, 554, **2018.**
16. ZHANG W., CHEN X.X., LIU Y.M., LIU D.Y., DU Y.F., CHEN X.P., ZOU C.Q. The role of phosphorus supply in

maximizing the leaf area, photosynthetic rate, coordinated to grain yield of summer maize. Field Crops Research, **219**, 113, **2018**.
17. ALBERTINI J., ROCHA R.K., BASTOS R.G., CECCATO-ANTONINI S.R., ROSA-MAGRI M.M. Phosphate solubilization and índole acetic acid production by rhizosphere yeast *Torulaspora globosa*: improvement of culture conditions for better performance in vitro. 3 Biotech, **12** (10), 262, **2022**.
18. SANTOS E.F., PONGRAC P., REIS A.R., RABÊLO F.H.S., AZEVEDO R.A., WHITE P.J., LAVRES J. Unravelling homeostasis effects of phosphorus and zinc nutrition by leaf photochemistry and metabolic adjustment in cotton plants. Scientific Reports, **11** (1), 13746, **2021**.
19. SANTOS E.F., PONGRAC P., REIS A.R., WHITE P.J., LAVRES J. Phosphorus–zinc interactions in cotton: consequences for biomass production and nutrient-use efficiency in photosynthesis. Physiologia Plantarum, **166** (4), 996, **2019**.
20. MARTINS L.E.C., MONTEIRO F.A., PEDREIRA B.C. Metabolic change, tillering and root system of *Brachiaria brizantha* in response to phosphorus and zinc nutrition. Journal of Plant Nutrition, **37**, 509, **2014**.
21. BARDEN S.A., HOPKINS B.G., JOLLEY V.D., WEBB B.L., NICHOLS B.A., BUXTON E.A. Zinc, manganese and phosphorus interrelationships and their effects on iron and copper in chelator-buffered solution grown Russet Burbank potato. Journal of Plant Nutrition, **34**, 1144, **2011**.
22. PONGRAC P., MCNICOL J.W., LILLY A., THOMPSON J.A., WRIGHT G., HILLIER S., WHITE P.J. Mineral element composition of red cabbage is affected more by soil type than by phosphorus and zinc amendments. Plant and Soil, **424**, 1, **2018**.
23. MASON B.J. Preparation of Soil Sampling Protocols: Sampling Techniques and Strategies EPA 600/R-92-128.EPA/600/R-92/128, United States Environmental Protection Agency, Washington DC, USA, **1992**.
24. OLSEN A.M. The biology, migration and growth rate of the school shark *Galeorhinus australis* (MacLeay) (Carcharhinidae) in south-eastern Australian waters. Australian Journal of Marine and Freshwater Research, **5** (3), 353, **1954**.
25. DA SILVA MEDEIROS D.C.C., PIECHONTCOSKI F., DA ROCHA WATANABE E.R.L., CHAVES E.S., INGLEZ S.D. Fast and effective simultaneous determination of metals in soil samples by ultrasound-assisted extraction and flame atomic absorption spectrometry: Assessment of trace elements contamination in agricultural and native forest soils from Paraná-Brazil. Environmental Monitoring and Assessment, **192** (2), 111, **2020**.
26. SESTAK Z., CATSKY J., JARVIS P.G. Plant photosynthetic production. Manual of methods. Plant photosynthetic production, Manual of Methods, 818, **1971**.
27. STEEL R.G.D., TORRIE J.H., DEEKEY D.A. Principles and procedures of statistics: A biometrical approach. 3rd ed. McGraw Hill Book, New York, USA, 400, **1997**.
28. KHAN M.S., ZAIDI A., AHMAD E. Mechanism of Phosphate Solubilization and Physiological Functions of Phosphate-Solubilizing Microorganisms. In Phosphate Solubilizing Microorganisms, Springer: Cham, Switzerland, 62, **2014**.
29. KUMAR S., SINGH M.K., KUMAR M., ALAM K. Effect of Micronutrients on Growth of Onion (*Allium cepa* L.). International Journal of Environment and Climate Change, **11** (12), 344, **2021**.
30. MARSCHNER H. Adaptation of plants to adverse chemical soil conditions. In: Mineral Nutrition of Higher Plants 2nd Ed. Academic Press, London. pp. 596, **1997**.
31. VENKATACHALAM P., PRIYANKA N., MANIKANDAN K., GANESHBABU I., INDIRAARULSELVI P., GEETHA N., MURALIKRISHNA K., BHATTACHARYA R.C., TIWARI M., SHARMA N.J.P.P., SAHI S.V. Enhanced plant growth promoting role of phycomolecules coated zinc oxide nanoparticles with P supplementation in cotton (*Gossypium hirsutum* L.). Plant Physiology and Biochemistry, **110**, 118, **2017**.
32. LI L., YANG H., PENG L., REN W., GONG J., LIU P., WU X., HUANG F. Comparative study reveals insights of sheepgrass (*Leymus chinensis*) coping with phosphate-deprived stress condition. Frontiers in Plant Science, **10**, 170, **2019**.
33. LONG L., MA X., YE L., ZENG J., CHEN G., ZHANG G. Root plasticity and Pi recycling within plants contribute to low-P tolerance in Tibetan wild barley. BMC Plant Biology, **19**, 341, **2019**.
34. LIN Z.H., CHEN L.S., CHEN R.B., ZHANG F.Z., JIANG H.X., TANG N. CO2 assimilation, ribulose-1,5-bisphosphate carboxylase/oxygenase, carbohydrates and photosynthetic electron transport probed by the JIP-test, of tea leaves in response to phosphorus supply. BMC Plant Biology, **9**, 43, **2019**.
35. CORDELL D., DRANGERT J.O., WHITE S. The story of phosphorus: global food security and food for thought. Global Environmental Change, **19**, 292, **2009**.
36. WANG J., CHEN Y., WANG P., LI Y.S., WANG G., LIU P., KHAN A. Leaf gas exchange, phosphorus uptake, growth and yield responses of cotton cultivars to different phosphorus rates. Photosynthetica, **56** (4), 1414, **2018.**
37. HALILOĞLU H. The effect of phosphorus and zinc on yield and on some agronomic characteristics of cotton (*Gossypium hirsutum* L.). Applied Ecology and Environmental Research, **17** (2), 2665, **2019**.
38. ALI H., AHMAD A., HUSSAIN S. The effect of exogenous phosphorous application on growth, yield, quality and net returns of upland cotton (*Gossipium hirsutum* L.). Applied Ecology and Environmental Research, **18** (1), 769, **2020**.
39. PONGRAC P., MCNICOL J.W., LILLY A., THOMPSON J.A., WRIGHT G., HILLIER S., WHITE P.J. Mineral element composition of cabbage as affected by soil type and phosphorus and zinc fertilisation. Plant Soil, **434**, 151, **2019**.
40. SANTOS E.F., MACEDO F.G., ZANCHIM B.J., LIMA G.P.P., LAVRES J. Prognosis of physiological disorders in physic nut to N, P, and K deficiency during initial growth. Plant Physiology and Biochemistry, **115**, 249, **2017**.