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Mitigation of Osmotic Stress in Cotton for the Improvement in Growth and Yield through Inoculation of Rhizobacteria and Phosphate Solubilizing Bacteria Coated Diammonium Phosphate

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Abstract: Cotton (*Gossypium hirsutum* L.) is one of the major fiber crops. Its production is under threat due to scarcity of water resources under a changing climatic scenario. Limited water availability also decreases the uptake of phosphorus, and less uptake of phosphorus can deteriorate the quality attributes of cotton fiber. There is a need to introduce bio-organic amendments which can mitigate osmotic stress on a sustainable basis. Inoculation of rhizobacteria can play an imperative role in this regard. Rhizobacteria can not only improve the growth of roots but also enhance the availability of immobile phosphorus in soil. That is why the current experiment was conducted to explore and compare the efficacy of sole application of diammonium phosphate (DAP) over plant growth-promoting rhizobacteria (PGPR) and phosphorus solubilizing bacteria (PSB) coated DAP on growth and quality attributes of cotton under artificially induced osmotic stress at flowering stage. The impact of phosphorus levels was found to be significant on the plant height, leaf area, average boll weight, stomatal conductance, net photosynthetic rate, and seed cotton yield, while the irrigation effect was significant on all the parameters. The PGPR coated phosphorus performed better as compared to other treatments under normal irrigation and osmotic stress. Results showed that PGPR coated phosphorus increased by 29.47%, 21.01%, 41.11%, 32.73%, 15.63% and 22.89% plant height, average boll weight, stomatal conductance, net photosynthetic rate, fiber length, and seed cotton yield respectively. In conclusion, PGPR coated DAP can be helpful to get higher cotton productivity as compared to control and sole application of DAP under normal irrigation and osmotic stress.

Keywords: cotton; inorganic fertilizers; PGPR; PSB; osmotic stress

1. Introduction

Pakistan is the world's fifth largest producer of cotton after China, India, United States, Brazil and Pakistan second largest exporter and seventh largest producer of cloth in the world. The cotton production during 2018–2019 was 9.86 million bales from a cultivated area of 2.37 million ha. [1]. Cotton has 0.8% share in GDP and 4.5% contribution to agriculture. Cotton supports many industries such as terrycloth, used for making highly absorbent bath towels and robes, and denim, used for making blue jeans, chambray, and popularly used in making blue work shirts [2]. However, management of abiotic stresses is a major concern under a changing climatic situation [3–8].

The cotton production requires a sufficient amount of water during its vegetative and reproductive cycle. Water deficiency during cotton production affects leaf enlargement which causes reduction of energy. The cotton plant growth under water stress reduces stomatal conductance, leaf temperature, carbon dioxide assimilation rate, and chlorophyll contents [9]. Low soil moisture reduces root growth of the cotton. The flowering stage is affected more by water stress, which ultimately reduces boll formation and cotton yield [10]. In addition, water deficit conditions can create a negative response, disrupting hormonal stability in squares and bolls, which leads to fruit shedding [11]. Thus, water stress could be a major abiotic factor that could adversely affect plant growth, yield and fiber quality [12].

Water stress is an important factor which reduces the uptake of nutrients to the plants [13–16]. Moreover, limited water conditions suppress the availability of water in cotton. The availability of essential nutrients, especially phosphorus, under water deficit conditions could increase stomatal conductance, water-use efficiency, and net photosynthesis as well as increase cellular membrane stability, and osmotic adjustment [6,13,17–19]. Using phosphorus fertilizer decreases the soil phosphorus deficiency, increases the stress-tolerant ability of plants and results in improvement of physiological, morphological, and biochemical processes that lead to better cotton productivity [20–22].

The availability of phosphorus can be increased by coating it with phosphorus-solubilizing bacteria (PSB) and plant growth-promoting bacteria (PGPR) [22–26]. These micro-organisms may also release soluble inorganic phosphates into the soil by decomposing organic compounds rich in phosphate [27]. Phosphate-solubilizing microbes dissolve the soil's phosphorous content by forming organic acids and reduce the pH of the rhizosphere [28]. Phosphorus-solubilizing bacteria can also produce hormones such as auxins, gibberellins, and cytokinins. Phosphorus-solubilizing bacteria inoculation and plant growth-promoting rhizobacteria help to reduce 50% of P fertilizer application without significant crop yield declines [29].

The PGPR is a group of bacteria that can be present in the rhizosphere [30]. Plant growth-promoting rhizobacteria clearly affect seed germination and growth of seedlings and thus increase crop yields through phytohormone development, nutrient mobilization, and suppression of plant pathogens [31]. PGPR inoculation with phosphorus induces structural modification, and biochemical and physiological improvements in plant cell walls attributable to salicylic acid, lipopolysaccharides and siderophores synthesis [32]. A number of studies proved that use of arbuscular mycorrhizal fungi (AMF) proved helpful to increase plants' tolerance of drought stress due to extraradical hyphal growth, osmotic adjustment, production of antioxidant enzymes, glomalin-bounded soil structural improvement, and water transport by hyphae [33–35].

Whitaker et al. [36] also found that water supply during the flowering and boll formation process increases the levels of boll initiation, photosynthetic rate, stomatal conductance, and chlorophyll contents. Gerik et al. [37] reported that water-deficit conditions result in a reduction of plant height, leaf area index, stomatal conductance, number of bolls per plant^{-1}, boll weight, and quality parameters due to reduced expansion of cells and leaves, and reduced stem elongation in the plant. Tank and Saraf [38] found that phosphorus-solubilizing bacteria (PSB) promote the efficiency of hormones, i.e., auxins, gibberellins, and cytokinins, which improve the crop growth and yield parameters in cotton. Phosphorus-solubilizing bacteria (PSB) coated DAP at the flowering stage could mitigate the negative impact of water shortage by enhancing the growth, quality, and yield parameters of cotton [27]. Zahid et al. [39] found an increase in the total number of bolls per plant, index of the leaf area, net photosynthetic rate, and seed cotton yield with the use of PGPR coated phosphorus. Similar results were found by Majeed et al. [40], who reported increased in growth and yields of cotton with PGPR coated phosphorus. The main hypothesis of this study was that use of inoculation of bacteria could be helpful in the mitigation of drought. The main objective of this study was to compare the effect of PGPR and PSB coated DAP with uncoated DAP and untreated DAP plots.

2. Materials and Methods

2.1. Experiment Site and Soil Characteristics

A field experiment was conducted on the research area of MNS-University of Agriculture, Multan (32.14° N, 73.65° E) during kharif season 2019. The climate of the experimental site was arid (Figure 1). The texture of soil was loam with EC*e* (2.58 dS·m^{-1}), pH*s* (8.60), organic matter (0.91%), available phosphorus (8.77 mg·kg^{-1}), and exchangeable potassium (250 mg·kg^{-1}).

2.2. Treatments

The coated material was in powder form while DAP fertilizers were in granular form. The 60 g PSB and PGPR, and DAP fertilizer 5 kg, were put in a mechanical mixer and shaken for 30 min for complete coating of PSB (*Bacillus* sp.; batch # PSB190201; date of manufacturing 02/2019; manufacture Koppert Biological System) and PGPR (*Rhizobium* sp.; batch # PGPR190201; date of manufacturing 02/2019; manufacture Koppert Biological System) on the fertilizer surface. The irrigation levels (normal and skip) were applied in the main plot while DAP treatments (0, 85 kg·DAP·ha^{-1}, PSB coated 85 kg·DAP·ha^{-1}, and PGPR coated 85 kg·DAP·ha^{-1} were applied in subplots. In normal irrigation plots, twelve irrigations were applied while in skip irrigation plots 9 irrigations were applied. The phosphorus coated with PSB and PGPR was applied through a hand drill at flowering stage.

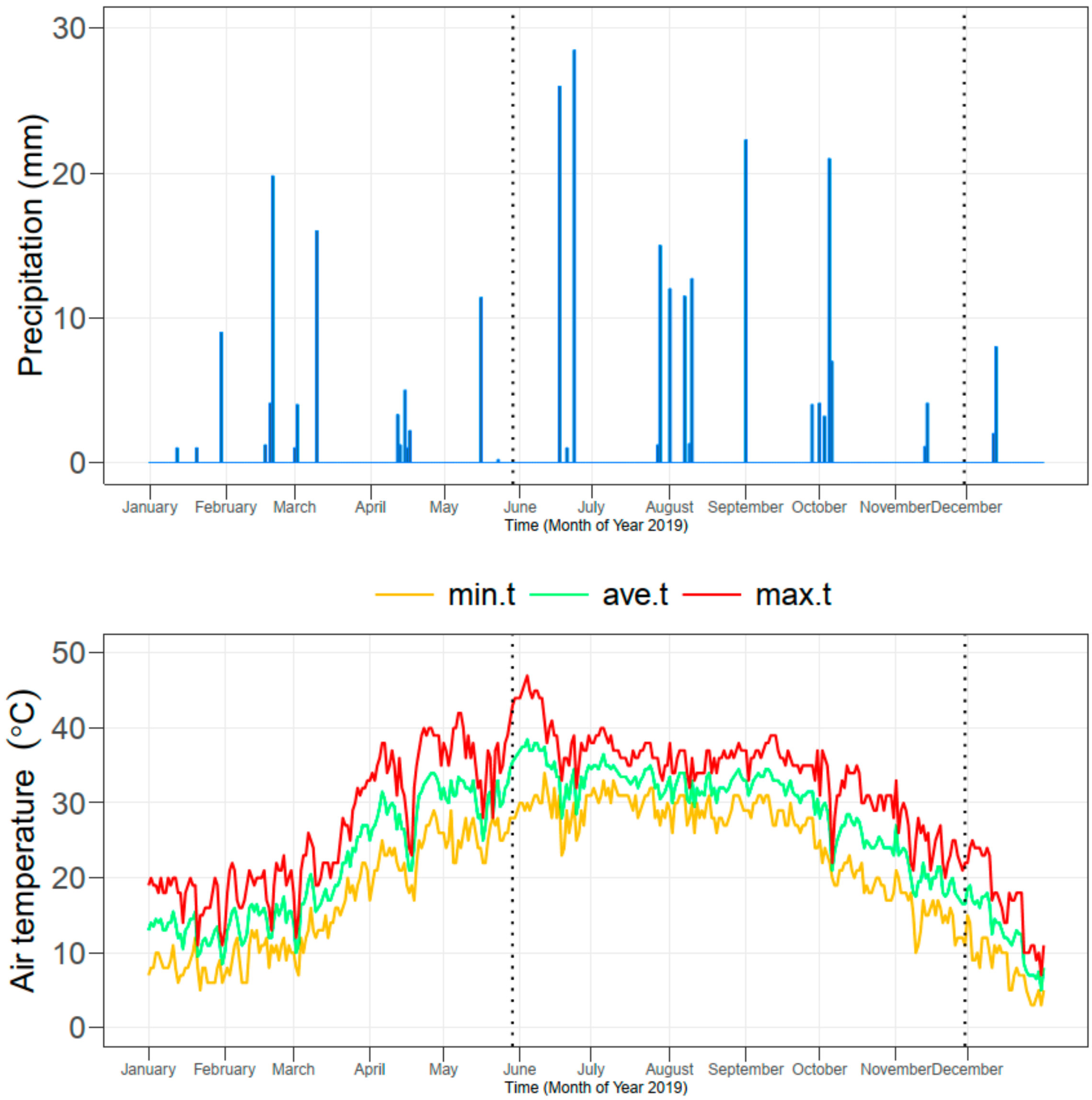

Figure 1. The daily minimum, maximum, and average temperature and rainfall in Multan, Pakistan during the year 2019. The dotted lines show the duration of the cotton crop.

2.3. Field Preparation

Seedbeds were prepared 3–4 times by deep ploughing with tractor-mounted cultivator followed by planking. The beds were prepared with a bed shaper. The treatments were applied according to split-plot RCBD design. The irrigation was in main plots and DAP treatment in subplots. Cotton was sown on the bed by dipper method using seed @ 20 kg·ha^{-1}. Plant-to-plant and row-to-row spacing of 22.5 and 75 cm was maintained, respectively.

2.4. Fertilizer Application

The recommended dose for cotton NK fertilizers (150 and 50 kg ha^{-1}) was applied. All K was applied at sowing while N was applied in two splits, one at squaring and second on boll formation stage and phosphorus coated with PSB and PGPR was applied at flowering stages. The fertilizer sources used were urea (46% N), diammonium phosphate (18% N: 46% P_2O_5), and SOP (50% K_2O).

2.5. Pest Management

The pesticides acetamaprid (617 mL·ha^{-1}), imidacloprid (593 mL·ha^{-1}, and emamectin benzoate (494 mL·ha^{-1}) were used to control whitefly, jassid, thrips, and bollworm. Weed control was done by using labor and application of weedicide (Dualgold). Cotton picking was done when more than 90% of bolls were matured. Harvesting was done on 24 November 2019.

2.6. Harvesting and Data Collection

Plant height was taken with scale at maturity. At the time of picking, number of sympodial branches per plant^{-1}, number of monopodial branches per plant^{-1}, number of nodes per plant^{-1} and number of bolls per plant^{-1} of five plants were selected randomly from every plot. The seed cotton yield ha^{-1} was measured by using the seed cotton obtained from net plot area. Seed cotton yield of each plot was converted into kg ha^{-1}. Photosynthetic rate, stomatal conductance, and transpiration rate from each of the five randomly selected plants were measured by using portable infrared gas analyzer (IRGA) (CID Bio-Science, Inc, Camas, WA, USA, photosynthetic system CI-340). Leaf area index was calculated by using the following equation from Watson [41].

$$\mathrm{LAI} = \frac{\text{Leaf area per plant }(\mathrm{cm}^2)}{\text{Land area per plant }(\mathrm{cm}^2)} \tag{1}$$

2.7. Chlorophyll Contents and Total Dry Matter

Chlorophyll contents were measured with the help of SPAD-502. The whole plant was weighed via electric balance to measure TDM. Fiber length is the size of fiber in millimeters (mm).

2.8. Crop Growth Rate

Crop growth rate (CGR) was computed at each sample date. Final calculations were made by using the below equation and represented as g m^{-2} day^{-1}.

$$\mathrm{CGR} = \frac{W_2 - W_1}{t_2 - t_1} \tag{2}$$

2.9. Statistical Analyses

The collected data of growth, yield, and fiber quality attributes of the cotton crop were analyzed by using a linear model in R software version 4.0.0 [42] and Origin 2020b. The effect of treatments on all measured parameters was tested within normal and skip irrigation separately. The means of the treatments were separated by least-square means and the adjusted Tukey multiple comparison test at $p < 0.05$. The least-square means and the adjusted multiple comparison procedure was adopted by using "emmeans" package in R software [43].

3. Results

3.1. Plant Height, Sympodial Branches Plant^{-1}, and Nodes Plant^{-1}

Overall, normal irrigation showed higher response on plant height as compared to skip irrigation. All treatment of DAP application showed higher response as compared to control in both normal and skip irrigation. The response of PGPR was higher as compared to PSB coated DAP, DAP, and control (no DAP). In normal irrigation, PGPR coated DAP showed 30.87%, 19.59%, and 9.20% higher plant height as compared to control, DAP, and PSB coated DAP, respectively, while in skip irrigation, PGPR coated DAP increased plant height 39.06%, 25.26%, and 12.26% as compared to control, uncoated DAP, and PSB coated phosphorus, respectively (Table 1).

Table 1. Impact of phosphorus coated diammonium phosphate (DAP) on plant height, sympodial branches, and number of nodes per plant of cotton under normal and skip irrigation. The values are the mean of three replications. Within irrigation levels, the values with the same letter (s) are statistically non-significant at $p < 0.05$.

Phosphorus Application	Plant Height (cm)		Sympodial Branches Plant^{-1}		Number of Nodes Plant^{-1}	
	Normal Irrigation	Skip Irrigation	Normal Irrigation	Skip Irrigation	Normal Irrigation	Skip Irrigation
Control (No DAP)	87.97 ± 1.68 a	61.43 ± 2.47 a	22 ± 1.00 a	18.00 ± 1.00 a	30.00 ± 1.00 a	19.67 ± 0.58 a
DAP	96.27 ± 0.50 b	68.20 ± 2.04 b	26 ± 1.00 b	21.33 ± 0.58 b	31.33 ± 0.58 b	21.00 ± 0.01 b
PGPR Coated DAP	115.13 ± 4.75 d	85.43 ± 1.52 d	31 ± 1.73 d	27.00 ± 1.00 d	34.00 ± 1.00 d	23.33 ± 0.58 c
PSB Coated DAP	105.43 ± 2.47 c	76.10 ± 2.14 c	28.67 ± 1.53 c	24.33 ± 0.58 c	32.33 ± 0.58 c	22.00 ± 0.01 b

The same results were found on sympodial branches. In normal irrigation, PGPR coated DAP showed 40.72%, 19.15%, and 8.47% higher sympodial branches per plant^{-1} as compared to no DAP, DAP, and PSB coated DAP, respectively, while in skip irrigation, PGPR coated DAP increased sympodial branches per plant^{-1} 50.01%, 26.58%, and 10.97% as compared to control, DAP, and PSB coated phosphorus, respectively (Table 1).

In normal irrigation, PGPR coated DAP showed 13.33%, 8.52%, and 5.16% higher number of nodes per plant^{-1} as compared to control, DAP, and PSB coated DAP, respectively, while in skip irrigation, PGPR coated DAP increased number of nodes per plant^{-1} 18.60%, 11.09%, and 6.04% as related to control, DAP, and PSB coated phosphorus, respectively (Table 1).

3.2. Bolls Plant^{-1}, Boll Weight, and Seed Cotton Yield

The normal irrigation showed higher number of bolls per plant^{-1}, boll weight, and seed cotton yield over skip irrigation in all DAP treatments. The PGPR DAP coated application effect was more as compared to PSB coated DAP in both normal and skip irrigation regimes. In normal irrigation, PGPR coated DAP showed 51.57%, 36.21%, and 18.98% more total bolls per plant^{-1} as compared to control, DAP, and PSB coated DAP, respectively, while in skip irrigation, PGPR coated DAP increased the number of bolls plant^{-1} 79.43%, 56.38%, and 27.06% as related to control, DAP, and PSB coated DAP, respectively (Table 2).

Table 2. Impact of phosphorus coated diammonium phosphate (DAP) on number of bolls per plant, boll weight, and seed cotton yield of cotton under normal and skip irrigation.

Phosphorus Application	No. of Bolls Plant^{-1}		Boll Weight (g)		Seed Cotton Yield (kg ha^{-1})	
	Normal Irrigation	Skip Irrigation	Normal Irrigation	Skip Irrigation	Normal Irrigation	Skip Irrigation
Control (No DAP)	20.67 ± 1.53 a	11.33 ± 0.58 a	2.36 ± 0.16 a	2.03 ± 0.06 a	2153 ± 47.29 a	1555.67 ± 46.2 a
DAP	23.00 ± 1.00 b	13.00 ± 1.00 a	2.53 ± 0.13 b	2.15 ± 0.04 b	2346 ± 33.56 b	1691.33 ± 45.39 b
PGPR Coated DAP	31.33 ± 1.15 d	20.33 ± 1.15 c	2.80 ± 0.06 c	2.28 ± 0.06 c	2694 ± 49.49 d	1950.67 ± 49.66 d
PSB Coated DAP	26.33 ± 0.58 c	16.00 ± 1.00 b	2.66 ± 0.11 bc	2.20 ± 0.03 b	2511 ± 41.49 c	1849.33 ± 52.2 c

The values are the mean of three replications. Within irrigation levels, the values with same letter (s) are statistically non-significant at $p < 0.05$.

In normal irrigation, PGPR coated DAP showed 18.64%, 10.67%, and 5.26% higher boll weight as compared to control, DAP, and PSB coated DAP respectively, while in skip irrigation, PGPR coated DAP increased boll weight 12.31%, 6.04%, and 3.63% as related to control, DAP, and PSB coated phosphorus, respectively (Table 2).

In normal irrigation, PGPR coated DAP showed 25.12%, 14.88%, and 7.27% higher cotton yield as related to control, DAP, and PSB coated DAP, respectively, while in skip irrigation, PGPR coated DAP increased seed cotton yield 25.39%, 15.33%, and 5.47% as related to control, DAP, and PSB coated phosphorus respectively (Table 2).

3.3. Photosynthetic Rate, Stomatal Conductance, and Transpiration Rate

The normal irrigation showed higher photosynthetic rate, stomatal conductance, and transpiration rate over skip irrigation in all DAP treatments. The PGPR DAP coated application effect was more as compared to PSB coated DAP in both normal and skip irrigation regimes. In normal irrigation, PGPR coated DAP showed 28.05%, 17.45%, and 6.90% higher photosynthetic rate as compared to control, DAP, and PSB coated phosphorus respectively, while in skip irrigation, PGPR coated DAP increased photosynthetic rate 24.29%, 14.52%, and 9.26% as related to control, DAP, and PSB coated phosphorus, respectively (Figure 2).

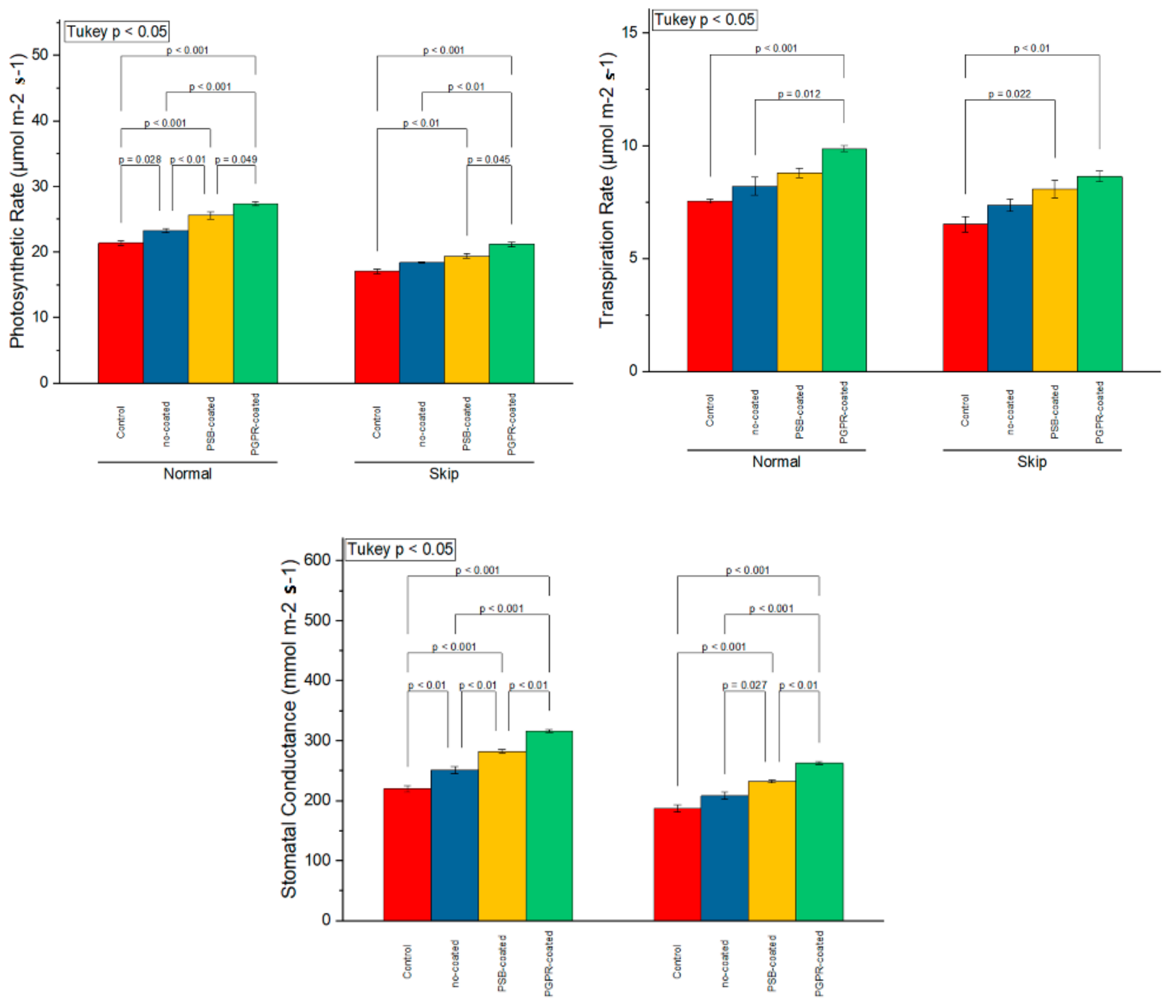

Figure 2. Impact of phosphorus coated diammonium phosphate (DAP) on photosynthetic rate, stomatal conductance, and transpiration rate of cotton under normal and skip irrigation. The values are the mean of three replications. Bars having no *p*-values are statistically non-significant at $\alpha < 0.05$.

In normal irrigation, PGPR coated DAP showed 43.66%, 25.94%, and 12.02% higher stomatal conductance as compared to control, DAP, and PSB coated DAP respectively, while in skip irrigation, PGPR coated DAP increased stomatal conductance 40.37%, 26.26%, and 13.21% as compared to control, DAP, and PSB coated DAP, respectively (Figure 2).

In normal irrigation, PGPR coated DAP showed 30.99%, 20.31%, and 12.38% higher transpiration rate as compared to control, DAP and PSB coated phosphorus respectively, while in skip irrigation, PGPR coated DAP increased transpiration rate 32.46%, 17.20%, and 7.05% as related to control, DAP and PSB coated phosphorus, respectively (Figure 2).

3.4. Leaf Area Index, Chlorophyll Contents, and Total Dry Matter

The normal irrigation showed higher leaf area index, chlorophyll contents, and total dry matter over skip irrigation in all DAP treatments. The PGPR DAP coated application effect was more as compared to PSB coated DAP in both normal and skip irrigation regimes. In normal irrigation, PGPR coated DAP showed 30.01%, 15.55%, and 6.77% higher leaf area index as compared to control, DAP and PSB coated phosphorus respectively, while in skip irrigation, PGPR coated DAP increased leaf area index 32.35%, 20.64%, and 32.50% as related to control, DAP, and PSB coated phosphorus, respectively (Table 3).

Table 3. Impact of phosphorus coated diammonium phosphate (DAP) on leaf area index, chlorophyll contents, and total dry matter of cotton under normal and skip irrigation.

Phosphorus Application	Leaf Area Index		Chlorophyll Contents (SPAD Value)		Total Dry Matter (g Plant^{-1})	
	Normal Irrigation	Skip Irrigation	Normal Irrigation	Skip Irrigation	Normal Irrigation	Skip Irrigation
Control (No DAP)	4.00 ± 0.10 a	3.40 ± 0.10 a	49.70 ± 0.8 a	45.91 ± 1.56 a	320.5 ± 10.27 a	255.8 ± 13.22 a
DAP	4.50 ± 0.10 b	3.73 ± 0.06 b	53.47 ± 2.78 ab	54.04 ± 4.91 a	371.26 ± 10.25 b	281.48 ± 10.99 a
PGPR Coated DAP	5.20 ± 0.10 d	4.50 ± 0.10 d	53.57 ± 3.18 ab	57.64 ± 11.34 a	442.31 ± 20.08 d	358.32 ± 8.43 c
PSB Coated DAP	4.87 ± 0.06 c	3.40 ± 0.10 a	55.34 ± 2.12 b	57.67 ± 4.31 a	406.42 ± 14.2 c	326.6 ± 14.39 b

The values are the mean of three replications. Within irrigation levels, the values with the same letter (s) are statistically non-significant at $p < 0.05$.

In normal irrigation, PGPR coated DAP showed 11.34%, 3.49%, and 3.30% higher chlorophyll content as compared to control, DAP and PGPR coated DAP, respectively, while in skip irrigation, PGPR coated DAP increased chlorophyll content 25.48%, 6.71%, and 0.05% as compared to control, DAP and PGPR coated DAP, respectively (Table 3).

In normal irrigation, PGPR coated DAP showed 38.01%, 19.13%, and 8.83% higher total dry matter as compared to control, DAP, and PSB coated DAP, respectively while in skip irrigation, PGPR coated DAP increased total dry matter 40.07%, 27.29%, and 9.71% as compared to control, DAP and PSB coated DAP respectively (Table 3).

3.5. Fiber Length, Fiber Strength, and Fiber Fineness

The normal irrigation showed higher fiber length, fiber strength, and fiber fineness over skip irrigation in all DAP treatments. The PGPR DAP coated application effect was more as compared to PSB coated DAP in both normal and skip irrigation regimes. In normal irrigation, PGPR coated DAP showed 15.63%, 8.21%, and 4.52% higher fiber length as compared to control, DAP, and PSB coated phosphorus, respectively, while in skip irrigation, PGPR coated DAP increased fiber length 17.30%, 12.83%, and 3.12% as related to control, DAP, and PSB coated phosphorus, respectively (Figure 3).

In normal irrigation, PGPR coated DAP showed 18.32%, 12.72%, and 8.30% higher fiber strength as compared to control, DAP, and PSB coated phosphorus, respectively while in skip irrigation, PGPR coated DAP increased fiber strength 20.14%, 13.24%, and 5.55% as related to control, DAP and PSB coated phosphorus, respectively (Figure 3).

In normal irrigation, PGPR coated DAP showed 19.35%, 9.81%, and 3.21% higher fiber fineness as compared to control, DAP, and PSB coated phosphorus, respectively, while in skip irrigation, PGPR coated DAP increased fiber fineness 23.80%, 15.72%, and 5.97% as compared to control, DAP and PSB coated phosphorus, respectively (Figure 3).

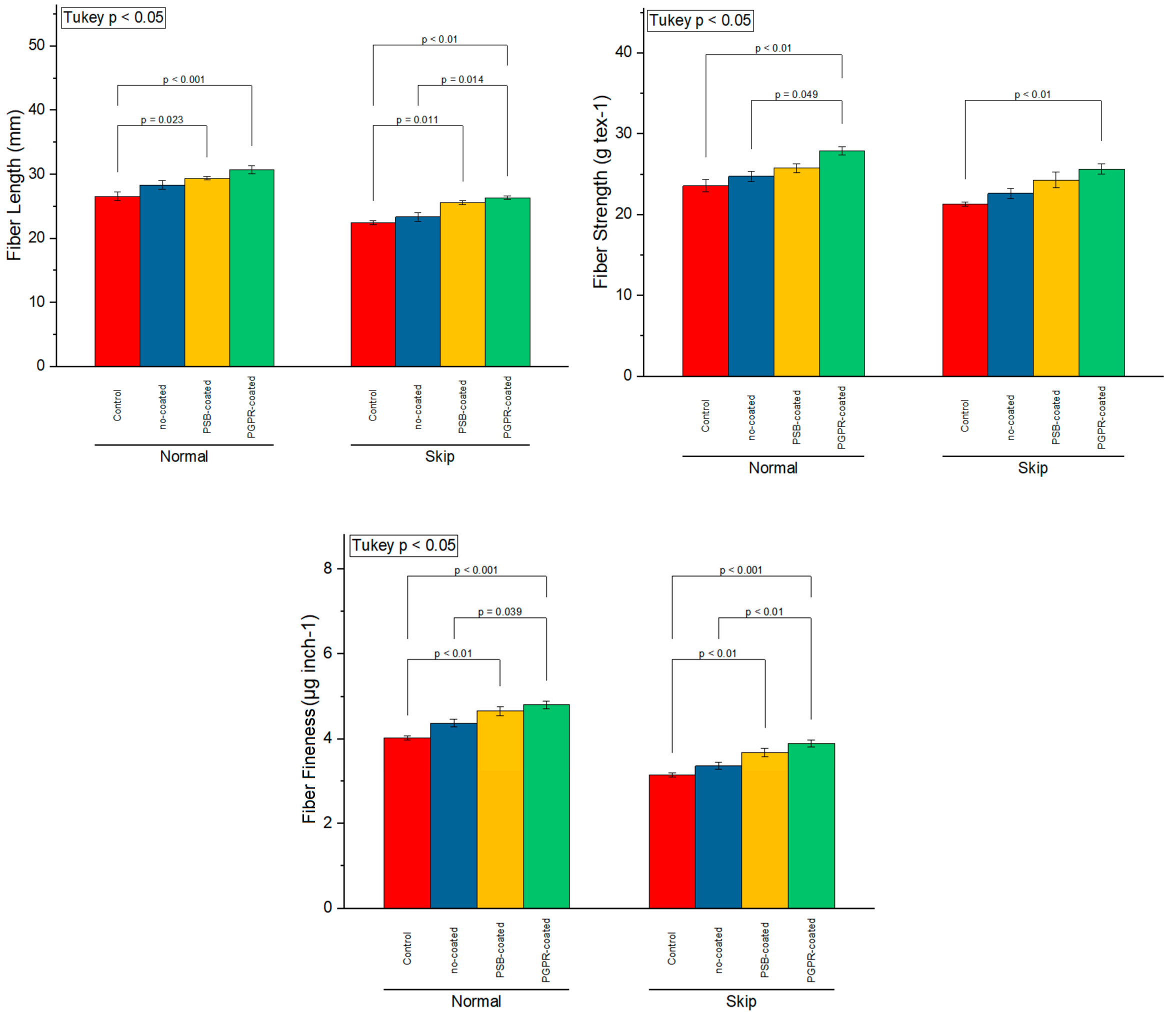

Figure 3. Impact of phosphorus coated diammonium phosphate (DAP) on fiber length, fiber strength, and fiber fineness of cotton under normal and skip irrigation. The values are the mean of three replications. Bars having no *p*-values are statistically non-significant at $p < 0.05$.

3.6. Uniformity Index and Crop Growth Rate

The normal irrigation showed higher uniformity index, number of microbes, and crop growth matter over skip irrigation in all DAP treatments. The PGPR DAP coated application effect was more as compared to PSB coated DAP in both normal and skip irrigation regimes. In normal irrigation, PGPR coated DAP showed 6.57%, 3.80%, and 1.55% higher uniformity index as compared to control, DAP and PSB coated phosphorus, respectively, while in skip irrigation, PGPR coated DAP increased uniformity index 8.51%, 6.05%, and 3.21% as related to control, DAP and PSB coated phosphorus, respectively (Figure 4).

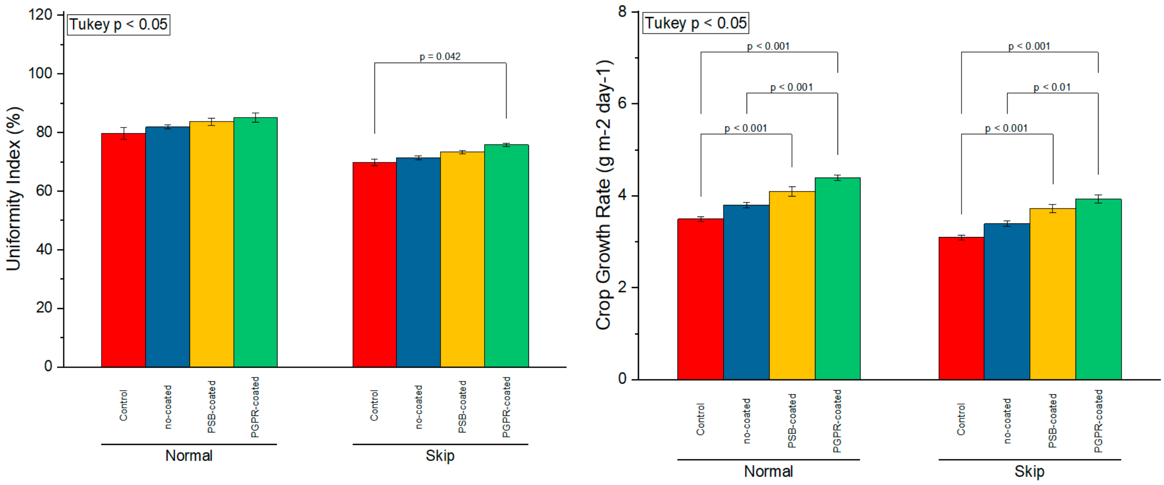

Figure 4. Impact of phosphorus coated diammonium phosphate (DAP) on uniformity index and crop growth rate of cotton under normal and skip irrigation. The values are the mean of three replications. Bars having no *p*-values are statistically non-significant at $p < 0.05$.

In normal irrigation, PGPR coated DAP showed 25.71%, 15.78%, and 7.31% higher crop growth rate as compared to control, DAP, and PSB coated phosphorus, respectively while in skip irrigation, PGPR coated DAP increased crop growth rate 27.77%, 15.58%, and 5.36% as related to control, DAP, and PSB coated phosphorus, respectively (Figure 4).

4. Discussion

The current study was conducted to evaluate the effect of PGPR and PSB coated DAP on cotton growth, yield, and fiber quality attributes under normal and skip irrigation conditions in Multan, Pakistan. The results revealed that all DAP treatments performed better where normal irrigation was applied as compared to skip irrigation. In addition, DAP applied treatments (DAP, PGPR coated, and PSB coated) showed higher response as compared to control (no DAP). Further, PGPR coated DAP treatments' effect on the cotton productivity was higher as compared to PSB coated DAP.

The normal irrigation showed improved plant height, nodes per plant^{-1}, bolls per plant^{-1}, boll weight, seed cotton yield, photosynthetic rate, stomatal conductance, transpiration rate, leaf area index, chlorophyll contents, and total dry matter. Sufficient supply of water may be the reason for increased growth, and physiological, quality, and yield attributes of cotton crop in the current study. The greater availability of water usually increases nutrient availability and uptake, as reported in a number of studies. Gwathmey et al. [44] reported an increase in leaf area index, total dry matter, and seed cotton yield in normal irrigation due to the availability of essential nutrients to the plant. Similar results were reported by Pettigrew and Meredith [45]; that a proper amount of irrigation increased plant height, boll weight, and nodes per plant^{-1}.

In another study, Whitaker et al. [36] found that water supply during flowering and boll formation processes could increase levels of boll initiation, photosynthetic rate, stomatal conductance, and chlorophyll contents. The lower values of growth parameters such as the index of the leaf area, physiological features such as net photosynthetic rate, stomatal conductance, and chlorophyll content and cotton yield parameters in the current study might be due to production of reactive oxygen species within plants which affected the plant cell organelles, accumulation of dry matter, and uptake of water and essential nutrients. These findings are in line with the existing literature. Gerik et al. [37] reported that water-deficit conditions resulted in reduction of plant height, leaf area index, stomatal conductance, bolls per plant^{-1}, boll weight, and fiber quality parameters due to reduced expansion of cells and leaves and reduced stem elongation.

In another study, Jaleel et al. [46] reported that water stress induced a reduction to the whole plant leaf area index by decreasing the leaf number rather than the leaf size. Similar results were reported by Lawlor and Cornic [47]; that water deficit stress in cotton reduced photosynthetic rates and chlorophyll content. Water deficit could affect all growth, physiology, and yield parameters by various mechanisms related to osmotic oxidative damage at the cellular level. The oxidative damage decreases the plant's capacity to divide cells in a water stress environment [48].

The application of PGPR coated DAP showed positive effects on plant height, sympodial branches per plant^{-1}, nodes per plant^{-1}, bolls per plant^{-1}, boll weight, seed cotton yield, photosynthetic rate, stomatal conductance, transpiration rate, leaf area index, chlorophyll contents, and total dry matter as compared to other treatments in both normal and skip irrigation conditions. These findings are in line with the literature. Yasmin et al. [49] reported that PGPR coated phosphorus increased the cotton yield due to a greater number of monopodial branches and crop growth rate. Zahid et al. [39] found increased total cotton bolls per plant^{-1}, leaf area index, net photosynthetic rate, and seed cotton where PGPR coated phosphorus was applied. Shao et al. [50] after 12 weeks of AMF inoculation found 15.12% to 40.23% increase in root mycorrhizal colonization along with an increase in plant height, root and shoot biomass, and leaf area in tea plants.

Similarly, Majeed et al. [40] reported increased growth and yield parameters of cotton with the use of PGPR coated phosphorus. In another study, Gomare et al. [51] reported higher cotton plant height, total dry matter, bolls per plant^{-1}, nodes per plant^{-1}, photosynthetic rate, and seed cotton yield were increased by the application of PSB coated DAP. Phosphorus solubilizing bacteria (PSB) promotes the efficiency of hormones, i.e., auxins, gibberellins, and cytokinins, which could improve the crop growth and yield parameters of cotton [38]. Phosphorus solubilizing bacteria (PSB) coated DAP at the flowering stage could mitigate the negative impact of water shortage by enhancing the growth, quality, and yield parameters of cotton [27].

5. Conclusions

The application of PGPR and PSB coated DAP showed promising results on the growth, yield, and fiber quality attributes of cotton. However, cotton productivity was higher with PGPR and PSB coated diammonium phosphate where normal irrigation was applied as compared to skip irrigation. In addition, PGPR coated results were better as compared to PSB coating of DAP in the current study. Therefore, it is recommended to use PGPR coated DAP with normal irrigation to get higher yields of cotton in Multan, Pakistan. However, longer studies in different locations are suggested to get a sustainable increase in cotton productivity with the recommended treatments.

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