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The Use of Soil Conditioners to Ensure a Sustainable Wheat Yield under Water Deficit Conditions by Enhancing the Physiological and Antioxidant Potentials

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Abstract: Traditional mulch material (farmyard manure) has long been used in agriculture. However, recent developments have also introduced the scientific community and farmers to advanced chemicals such as potassium polyacrylamide (KPAM), which has revolutionised the concept of the soil water-holding capacity to many compared with other materials being used. To compare the effect of different organic and inorganic soil amendment materials under water stress conditions, a two-year (2018 and 2019) field study was conducted. The main plots consisted of irrigation treatments, i.e., I_0 (control irrigation), I_1 (drought-induced by skipping irrigation at the 4th leaf stage), and I_2 (drought-induced by skipping irrigation at the anthesis stage). The subplots included a control treatment and soil amended with different conditioners such as potassium polyacrylamide (KPAM, 30 kg/ha), farmyard manure (FYM, 4 tons/ha), and biochar (10 tons/ha); these were mixed thoroughly with the soil before sowing. The results showed a significant reduction in the water relation parameters (water potential up to 35.77% and relative water content up to 21%), gas exchange parameters (net CO_2 assimilation rate up to 28.85%, stomatal conductance up to 43.18%, and transpiration rate up to 49.07%), and yield attributes (biological yield up to 8.45% and grain yield up to 32.22%) under drought stress conditions. In addition, water stress also induced an increase in the synthesis of osmoprotectants (proline up to 77.74%, total soluble sugars up to 27.43%, and total free amino acids up to 11.73%). Among all the soil conditioners used, KPAM significantly reduced the negative effects of drought stress on the wheat plants. Thus, it could be concluded that the use of soil conditioners is a promising method for dealing with the negative consequences of drought stress for achieving sustainable crop yields.

Keywords: wheat; drought stress; KPAM; farmyard manure; biochar; water relations; yield; arid climate

1. Introduction

Drought stress is one of the most devastating yield-limiting factors in field crops, particularly for cereals such as wheat, rice, and maize. Wheat (*Tritium aestivum* L.) is the most widely grown cereal in the world after maize; however, its sustainable production and yield under water deficit conditions is a major concern for growers [1]. Cereals and cereal derivatives are staple foods in most human diets, supplying a significant amount of dietary calories and nutrients in both developed and developing countries [2]. Drought stress is reported to negatively affect global wheat production and results in economic losses every year. Low water availability during critical stages of wheat growth has a direct impact on the performance of the crop as it reduces the biomass accumulation and chlorophyll synthesis [3]. Water deficiency during the grain filling stage results in lower grain numbers and an inconsistent grain size that ultimately decreases the grain yield [4]. Drought-induced alterations in the plant–water relations reduce carbon dioxide assimilation and increase oxidative stress at the cellular level [5,6]. Such alterations also inhibit enzymatic and hormonal activities, leading to a reduced wheat growth and yield under water-stressed conditions [5,6]. In addition, water stress also impairs a variety of plant functions including water use efficiency, osmotic adjustment, ionic balance, membrane purity and elasticity, and protein biosynthesis [7]. Consequently, different physiological and biochemical processes such as transpiration, photosynthesis, stomatal conductance, translocation, and source-sink relations are affected, consequently reducing the grain yield [8].

In recent years, numerous approaches have been proposed to alleviate the damaging effects of drought on wheat crops. Superabsorbent polymers (SAPs) are a type of polymer with a larger cross-linkage and molecular weight and are made from acrylate or acrylic acid and acrylamide. Oil-based polymers made of acrylamide have toxic effects whereas other polymers have minimal or no toxic effects [9]. SAPs and their derivatives such as potassium polyacrylamide are known to absorb a large amount of water with absorption capacities ranging from hundreds to thousands of times their weight [10]. The current inconsistency in rainfall and a rising trend in temperatures in low annual precipitation areas demands efficient water management and conservation through supplementing the soil with a variety of materials such as plant waste, zeolite, and synthetic superabsorbent polymers [11]. It is well-reported that SAPs can store water as well as provide nutrients to plants [12]. Polymers are also important for enhancing the physical properties of soil, acting as buffers against temporary water deficiencies and reducing agricultural production costs [10]. Riad et al. [13] presented that the use of biochar (1% w/w) or/and SAPs (0.7% w/w) in green peas significantly improved the leaf chlorophyll, nitrogen, phosphorus, potassium contents, and the leaf relative water content. In another study, Islam et al. [14] concluded that, under drought conditions, soil amended with 30 kg/ha of SAP significantly increased the plant height, biomass accumulation, and grain production by improving the leaf relative water content, total sugars, proteins, and starch percentage in the grains. Similarly, the use of superabsorbent polymers in combination with a biofertilizer significantly improved the wheat seed germination, plant height, and soil fertility [15].

Biochar, similar to SAPs, has the potential to be used in the amelioration of stress-induced consequences in plants. Biochar is not a new material. Soils all around the world have charcoal from grassland and forest fires. Biochar is produced by heating organic matter in the confined supply or absence of oxygen [16]. The value of biochar is growing due to its use as a soil conditioner for a reduction in nutrient loss, limiting the metal availability and phytotoxicity [17]. The application of biochar has recently received significant attention due to its ability to optimise the physiochemical properties of the soil, soil fertility, soil pH, and microbial activities as well as its cation exchange capacity and water use efficiency along with its ability to act as an organic and inorganic pollutant control and a fertilizer [18–20]. Biochar is also a valuable product for improving soil qualities such as nutrient availability and uptake, soil porosity, and bulk density as well as the soil water-holding and retention capacity [21]. Biochar amendments to the soil, in comparison with other amendment materials, has the benefit of having a wide surface area and pore spaces, allowing the biochar to absorb and retain water and nutrients whilst also providing an environment for the growth of helpful microbes [22]. In this context, Nawaz et al. [23] revealed that biochar makes a crucial contribution to wheat productivity under limited water conditions. It helps in the alleviation of the damaging effects of drought by activating the antioxidant defence system and preserving soil moisture. Under drought stress, biochar reduces the irrigation frequency and improves the gaseous exchange behaviour. Farmyard manure (FYM) is an excellent organic fertilizer, widely used for conserving soil fertility in alternative agricultural systems. Organic manures are utilised in farming systems as potential sources of plant growth and development as they create suitable environments for the physical, chemical, and biological characteristics of the soil [24]. FYM stimulates and provides an ideal environment for crop growth by providing essential plant nutrients along with micronutrients, thereby improving the structure, physiochemical, and biological attributes of the soil [25].

Potassium, polyacrylamide, and biochar are considered to be new types of soil conditioners used in agriculture [13]. Studies related to the positive effects of soil amendments on crop yields are well-reported; however, most of the experiments were performed under controlled greenhouse conditions with little knowledge about the response of wheat to soil amendments with such materials under field conditions [14,26]. Therefore, the general objective of the present study was to investigate the effect of a soil amendment material in field-grown wheat under water deficit conditions. The specific objectives of the study were to understand how these soil amendment materials improve the soil water status and to determine how these materials can regulate the physiological and biochemical processes to alleviate the damaging effects of water stress on wheat.

2. Materials and Methods

2.1. Experimental Site and Layout

The study involved field experiments conducted over two years at the field research area of the Department of Agronomy, Faculty of Agriculture and Environment, The Islamia University of Bahawalpur, Pakistan (29.37° N, 71.77° E; altitude 112 m above sea level). The experiments were laid out in a randomised complete block design (RCBD) with four replications under a split-plot arrangement. The seed bed was prepared with the help of a tractor-mounted cultivator followed by planking. The NPK was applied at the ratio of 120:100:60 kg/ha. At the time of sowing, all of the recommended phosphorus (DAP) and potash (SOP) doses were applied whereas nitrogen (urea) was applied in two split doses. KPAM, biochar, and FYM were added to the soil at the rate of 30 kg/ha, 4 tons/ha, and 10 tons/ha, respectively. KPAM, FYM, and biochar were incorporated into the soil with the help of a cultivator before sowing. A single high yielding variety, Johar-2016, from the Regional Agriculture Research Institute (RARI), Bahawalpur, was used for sowing purposes at a rate of 125 kg/ha. For all of the treatments, all other agronomic practices were followed as recommended. The wheat seeds were sown in rows with a manual drill by maintaining a 12 cm row-to-row distance. The net plot dimension was 2 m × 6 m. The stress was induced by skipping irrigation at the 4th leaf (I_1) and anthesis (I_2) stages; there were also control plots (I_0) with no amendments and water stress. The soil was analysed at the soil and water testing laboratory of RARI Bahawalpur and was found to be sandy loam with a pH of 8.2, organic matter of 0.61%, saturation percentage of 36%; the available P was 6.58 mg/kg and the extractable K was 145.36 mg/kg. The wheat crop was sown on 15 November each year (2018–2019) and the mature crop was harvested in the last week of April each year. The metrological data of both years of the crop growth seasons were collected from the Cholistan Institute of Desert Studies (CIDS), IUB (Figures 1 and 2).

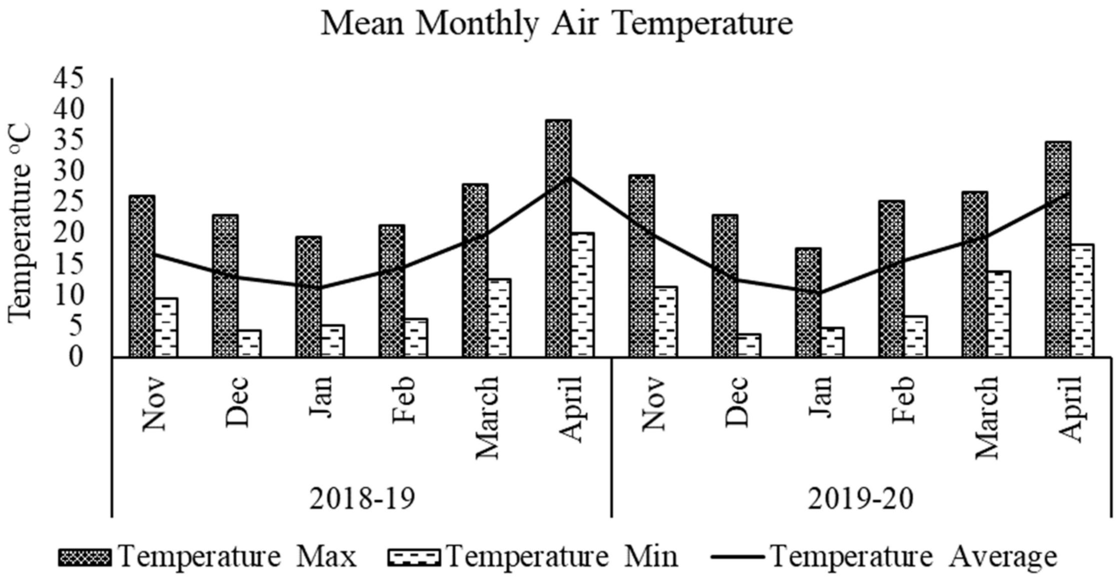

Figure 1. Monthly maximum, minimum, and average temperatures during crop growing seasons (2018–2019 and 2019–2020).

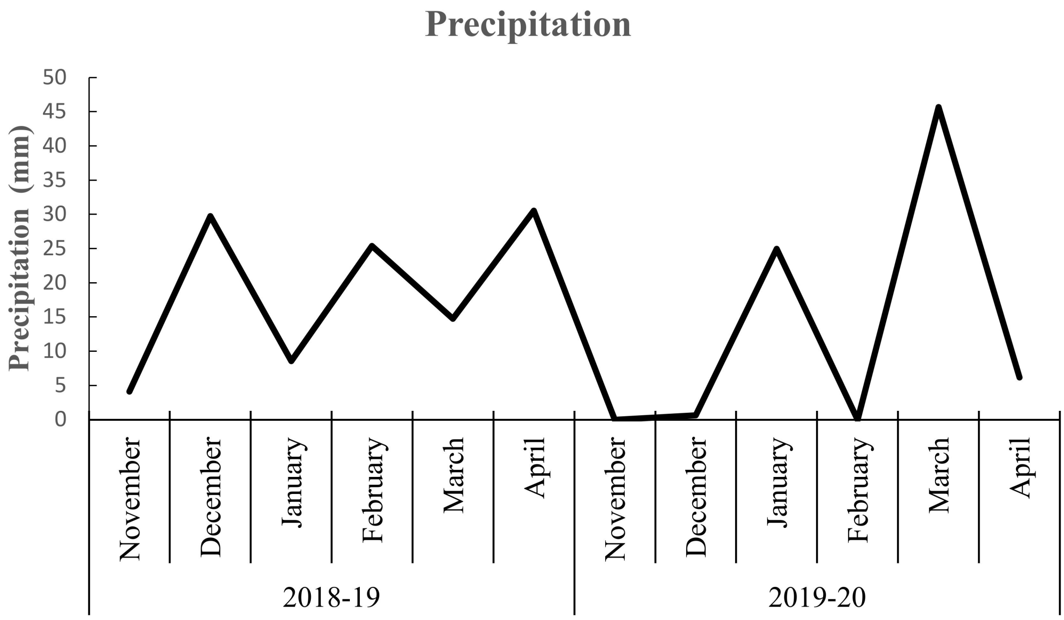

Figure 2. Monthly precipitation during crop growing seasons (2018–2019 and 2019–2020).

2.2. *Estimation of Plant Water Content*

The leaf water potential was estimated using the young fully stretched third leaf from the top of each treatment plot by using a Scholander-type pressure chamber apparatus. The readings were taken from 7:00 a.m. to 10:00 a.m.

The fresh weight (FW) was calculated by removing three fully grown top leaves from each treatment plot and weighing them with an electric balance. These leaves were steeped in distilled water for 24 h and cleaned with tissue paper to remove any excess water. These leaves were then weighed to determine the turgid weight (TG), dried in an oven at 65 °C for 72 h, and then weighed again to determine the dry weight (DW). The formula of Karrou [27] given below was used to calculate the relative water content for each treatment.

$$RWC = (FW - DW)/(TW - DW) \times 100 \quad (1)$$

where FW = fresh weight, DW = dry weight, and TW = turgid weight.

2.3. Gas Exchange Attributes

The gas exchange attributes such as the net CO_2 assimilation rate (A), stomatal conductance (gs), and transpiration rate (E) were measured using an open system LCA-4 ADC portable infrared gas analyser. The readings were taken between 8:30 a.m. and 10:30 a.m. on clear days with the following adjustments. The air molar flow per unit of leaf area was set to 400 $mmol/m^2 s^{-1}$, the atmospheric pressure was 99.9 kPa, the vapour pressure of the water into the chamber ranged from 6.0 to 8.9 mbar, the PAR (photosynthetically active radiation) at the leaf surface was set to 1500 mol $m^{-2} s^{-1}$, the leaf temperature was set to an ambient temperature (i.e., around 27 °C), and the ambient CO_2 concentration was 352 mol^{-1}.

2.4. Determination of Osmoprotectants

To determine the total soluble proteins (TSP), the procedure reported by Lowry et al. [28] was used. A phosphate buffer, three copper reagents, a folin phenol reagent, and a fresh plant leaf extract were used in this procedure. In a test tube, 1 mL of the phosphate buffer solution, 1 mL of the plant leaf extract (chopped, ground, and centrifuged to form the extract), and a copper reagent were added, thoroughly mixed, and allowed to stand for 10 min. Following this, 0.5 mL of the folin phenol reagent was added and incubated for 30 min at room temperature. A spectrophotometer at a 620 nm wavelength was used to assess the total soluble proteins of the supernatant.

The procedure developed by Hamilton [29] was used to estimate the total free amino acids (TFA). Fresh plant leaves (0.5 g) were chopped and extracted with a phosphate buffer solution of 0.2 M (pH 7.0). In each test tube, 1 mL of the extract was then added followed by a 10% pyridine and 2% ninhydrin solution. The ninhydrin solution was made by mixing 2 g ninhydrin with 100 mL distilled water. In a boiling water bath, the test tube containing the sample mixture was heated for 30 min. To bring the volume of each test tube up to 50 mL, distilled water was added. The optical density of the coloured solution was measured using a spectrophotometer at 570 nm. A standard curve was created with the help of leucine; the free amino acids were calculated using the formula below:

$$\text{TFA (mg g}^{-1}\text{ fresh wt.)} = \text{Graph reading of sample} \times \text{volume of sample} \times \text{dilution factor/ weight of fresh tissue} \times 1000. \quad (2)$$

The leaf total soluble sugars (TSS) were determined by the procedure defined by Yemm and Willis [30]. Briefly, the plant material was dried, ground thoroughly in a micromill, then sieved using the 1 mm sieve of the micromill. In an ethanol (80%) solution, 0.1 g of the plant material was extracted. The extract was then incubated at 60 °C for 6 h. The plant extract was added to a 25 mL test tube along with 6 mL of an anthrone reagent prepared by dissolving 150 mg of anthrone in a solution of 72% H_2SO_4. The test tubes were heated in a boiling water bath for 10 min. The test tubes were ice-cold for 10 min before being incubated at 25 °C for 20 min. A spectrophotometer (Hitachi, 220, Tokyo, Japan) was used to measure the absorbance at 625 nm. The concentration of TSS was calculated using the standard curve made by the above procedure. The leaf proline content was determined using the method of Bates et al. [31]. The proline concentration was calculated using the following formula based on the fresh weight and estimated using a standard curve:

$$\mu\text{moles proline g}^{-1}\text{ fresh weight} = (\mu\text{g proline mL}^{-1} \times \text{mL of toluene}/115.5\mu\text{g }\mu\text{mole}^{-1})/(\text{wt. of sample}/5). \quad (3)$$

2.5. Grain and Biological Yield

The wheat from each plot was cut from the quadrate of a meter square, separately threshed to obtain the grains, and weighed with an electric balance calibrated in kilograms then converted into tons per hectare. The biological yield included all the plant biomass and the harvested crop in the square meter quadrates from each treatment, and was weighed using an electric balance.

2.6. Statistical Analysis

The data were statistically analysed using the factorial design of the analysis of variance (ANOVA). MSTAT-C (Michigan State University, USA) version 2.10 was used to compare the means of the treatments. The least significant difference test (LSD) was used to determine the mean differences of the treatments at a 5% probability level [32]. Microsoft Office Excel 2016 was used for the graphical representation of the metrological data and all attributes.

3. Results

3.1. Water Relation and Gas Exchange Parameters

Water scarcity had a considerable impact on the wheat water status and gas exchange characteristics. In both years of the trial, drought stress significantly ($p < 0.01$) reduced the leaf water potential (Figure 3) and relative water content (Figure 4). The drought induced by skipping irrigation, particularly at the anthesis stage, had more detrimental effects in terms of the water potential (−1.41 and −1.46 MPa, respectively) and relative water content (58.44% and 56%, respectively). Moreover, it also reduced the net CO_2 assimilation rate (Figure 5), stomatal conductance (Figure 6), and transpiration rate (Figure 7) at the 4th leaf and anthesis stages. There was a decrease in the net CO_2 assimilation rate (6.35 and 6.23 µmol CO_2 m^{-2} s^{-1}, respectively), stomatal conductance (2.54 and 2.49 mmol H_2O m^{-2} s^{-1}, respectively), and transpiration rate (2.16 and 2.05 mmol H_2O m^{-2} s^{-1}, respectively) compared with the control irrigation treatment in years 1 and 2, respectively. For the soil amendment treatments, KPAM had the highest values of water potential, relative water content, net CO_2 assimilation rate, stomatal conductance, and transpiration rate compared with the control, FYM, and biochar. Furthermore, except for the transpiration rate, the relationship between the soil amendment and irrigation treatment was shown to be significantly different for all of the above-mentioned parameters. The year was also observed to be significant in all the parameters (Table 1).

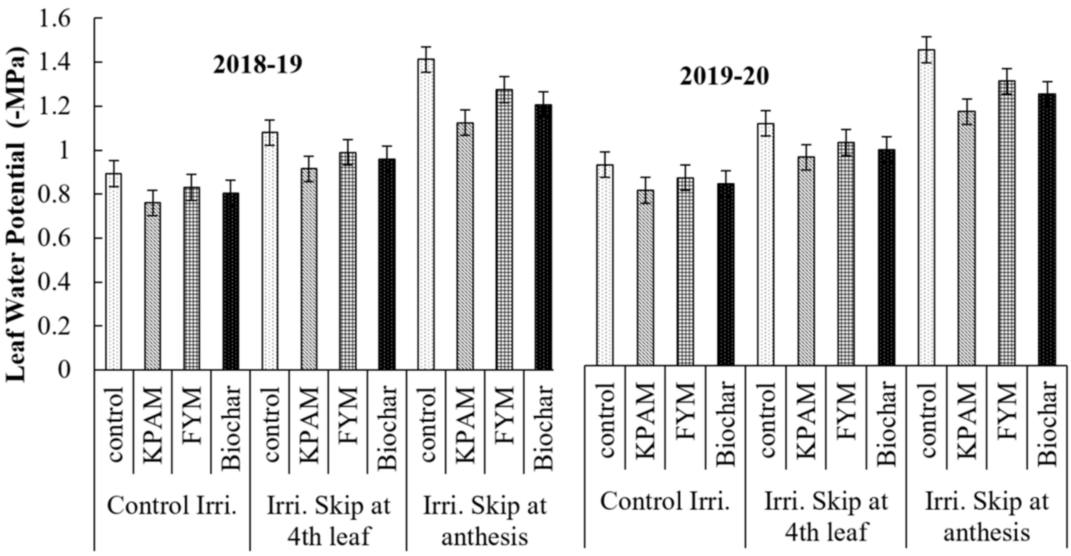

Figure 3. Effect of soil amendment materials on water potential in the wheat crops grown under normal and water stress imposed by skipping irrigation at 4th leaf and anthesis stage of growth (mean values ± S.E).

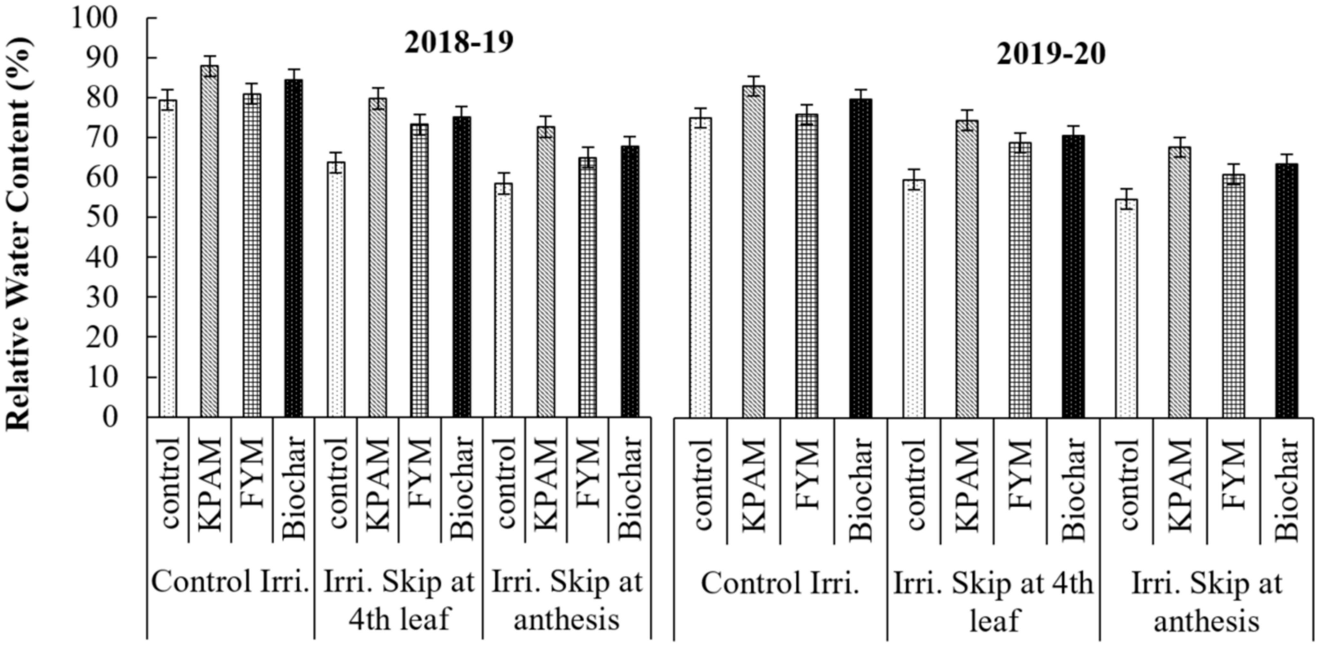

Figure 4. Effect of soil amendment materials on relative water content in the wheat crops grown under normal and water stress imposed by skipping irrigation at 4th leaf and anthesis stage of growth (mean values ± S.E).

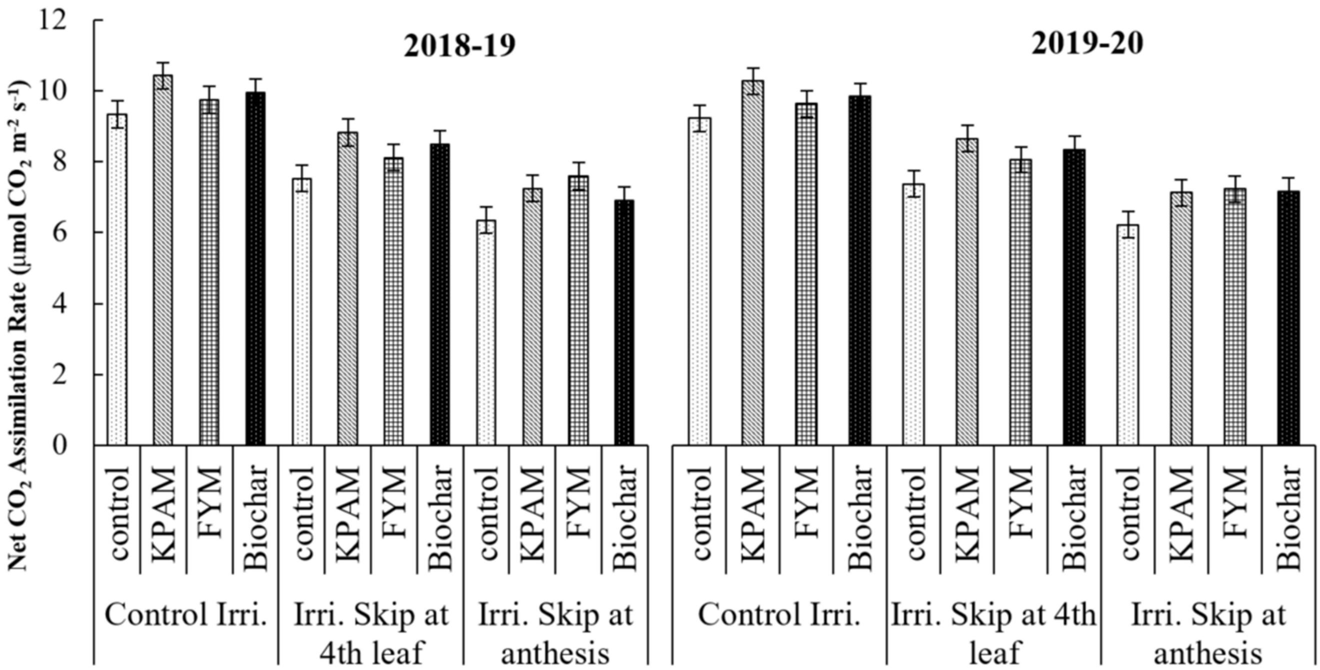

Figure 5. Effect of soil amendment materials on net CO_2 assimilation rate in the wheat crops grown under normal and water stress imposed by skipping irrigation at 4th leaf and anthesis stage of growth (mean values ± S.E).

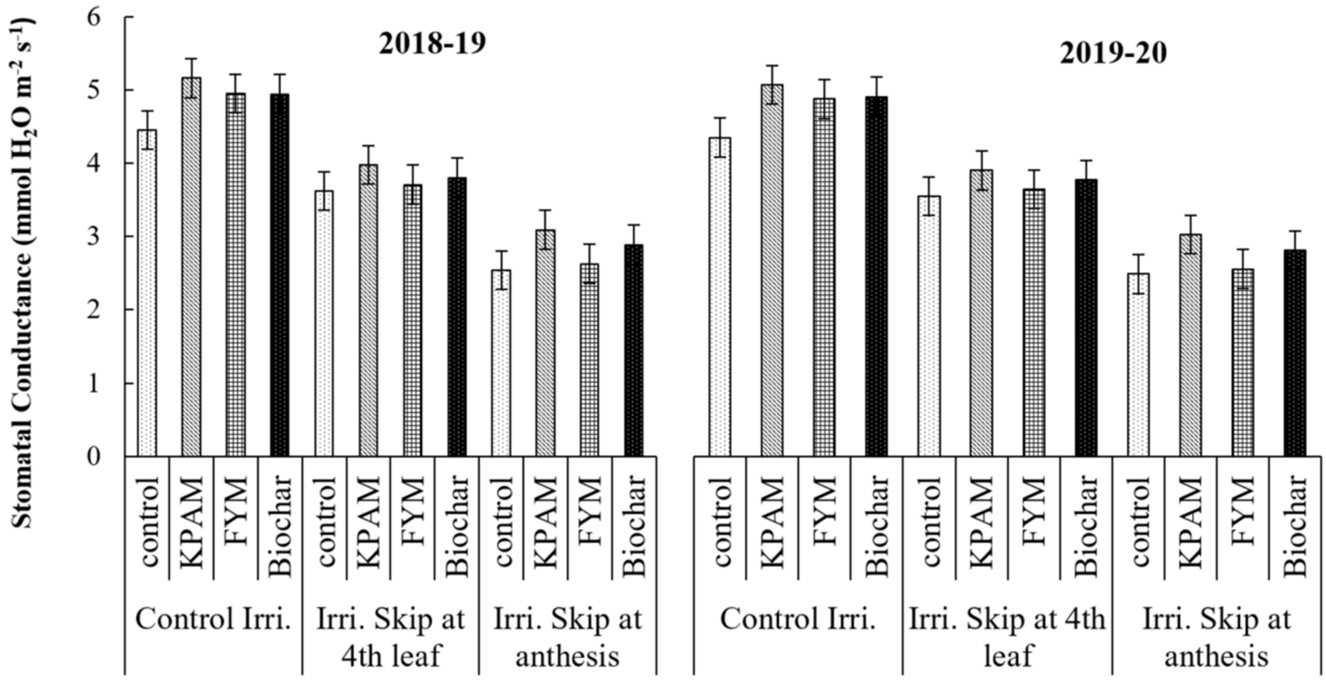

Figure 6. Effect of soil amendment materials on stomatal conductance in the wheat crops grown under normal and water stress imposed by skipping irrigation at 4th leaf and anthesis stage of growth (mean values ± S.E).

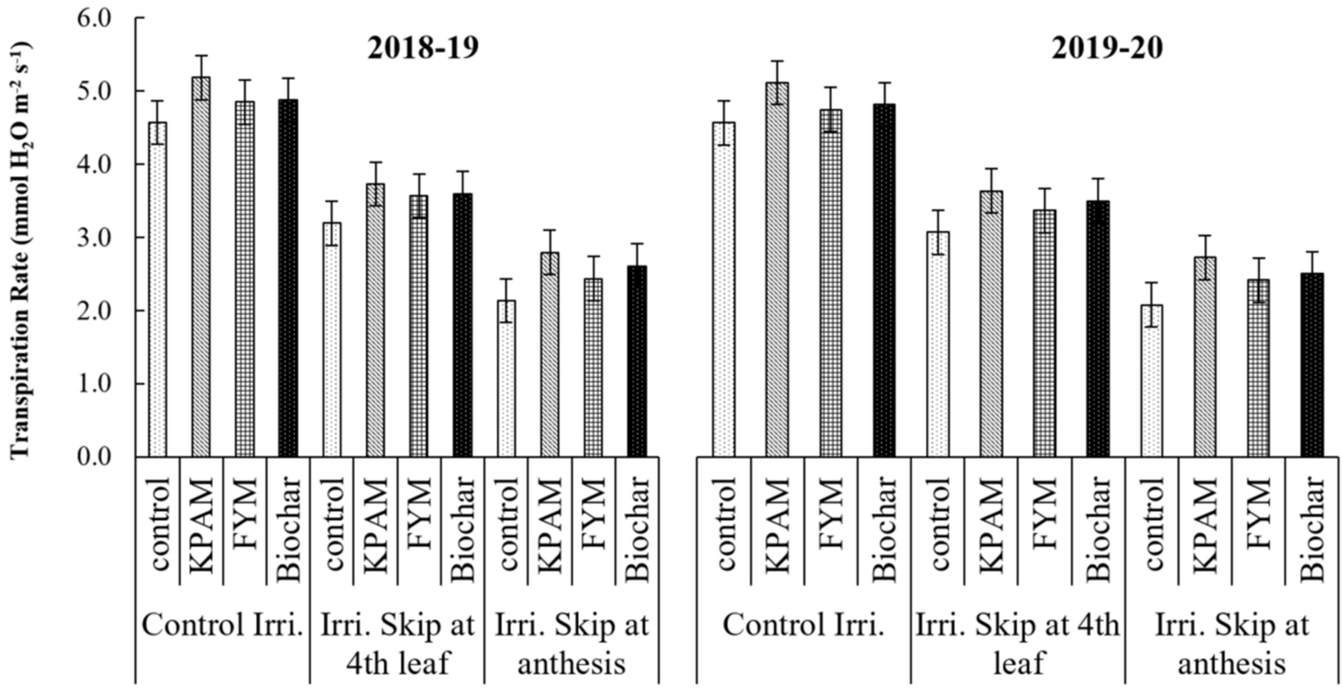

Figure 7. Effect of soil amendment materials on transpiration rate in the wheat crops grown under normal and water stress imposed by skipping irrigation at 4th leaf and anthesis stage of growth (mean values ± S.E).

Table 1. Analysis of variance table for water relation and gas exchange parameters of wheat crops.

Source of Variation (SOV)	Water Potential	Relative Water Content	Net CO_2 Assimilation Rate	Stomatal Conductance	Transpiration Rate
Year	0.04 **	210.92 **	0.31 *	0.11 **	0.55 *
Replication (Year)	0.001 NS	23.51 **	0.24 **	0.02 **	0.16 NS
Irrigation	1.55 **	2383.19 **	64.30 **	34.77 **	47.25 **
Year × Irrigation	0.0001	0.10	0.005	0.001	0.10
Treatments	0.16 **	661.52 **	5.06 **	1.23 **	1.60 **
Year × Treatments	0.0001	0.64	0.04	0.001	0.09
Irrigation × Treatment	0.01 **	29.17 **	0.43 **	0.10 **	0.07 NS
Year × Irrigation × Treatment	0.0001	0.11	0.05	0.001	0.10

* and ** = significant at 0.05 and 0.01 levels, respectively; NS = non-significant.

3.2. Osmoprotectants

Drought stress had a significant impact on the synthesis of TSP, TSS, TFA, and proline at the 4th leaf and anthesis stages of growth when compared with the control ($p < 0.01$). The effect was more pronounced in the wheat crop at anthesis with significantly lower total soluble proteins (7.38 and 7.21 mg g^{-1} FW, respectively) (Figure 8) and higher total soluble sugars (4.52 and 4.56 mg g^{-1} FW, respectively) (Figure 9), total free amino acids (24.77 and 24.97 mg g^{-1} FW, respectively) (Figure 10), and proline contents (3.33 and 3.39 μmol proline g^{-1} FW, respectively) (Figure 11) in years 1 and 2, respectively, compared with the control treatment. In the induced drought, the KPAM performed better than the other soil amendment materials in terms of the drought resistance, producing more TSP with less TSS, TFA, and proline. The relationship between the soil amendment and irrigation treatment was also found to be significantly different in the cases of TSP, TFA, and proline but not in the case of TSS. The year appeared to be non-significant in the cases of TSS and TFA but significant in the cases of TSP and proline (Table 2).

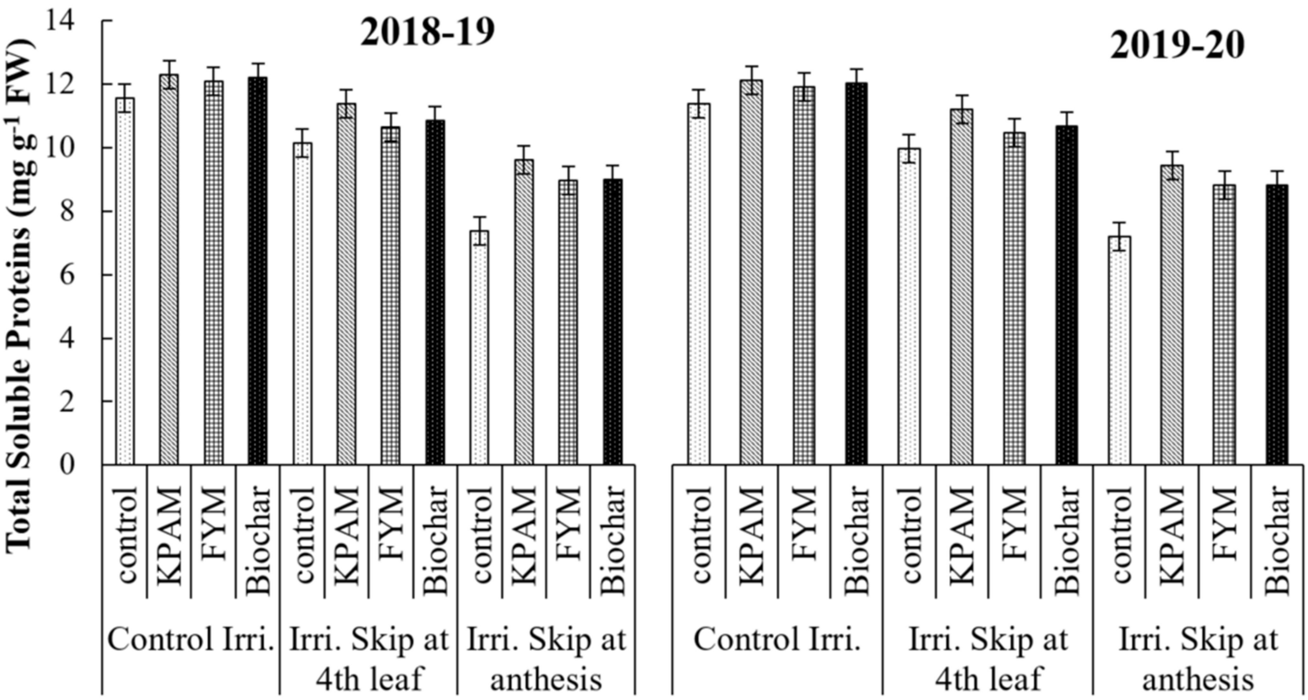

Figure 8. Effect of soil amendment materials on total soluble proteins in the wheat crops grown under normal and water stress imposed by skipping irrigation at 4th leaf and anthesis stage of growth (mean values ± S.E).

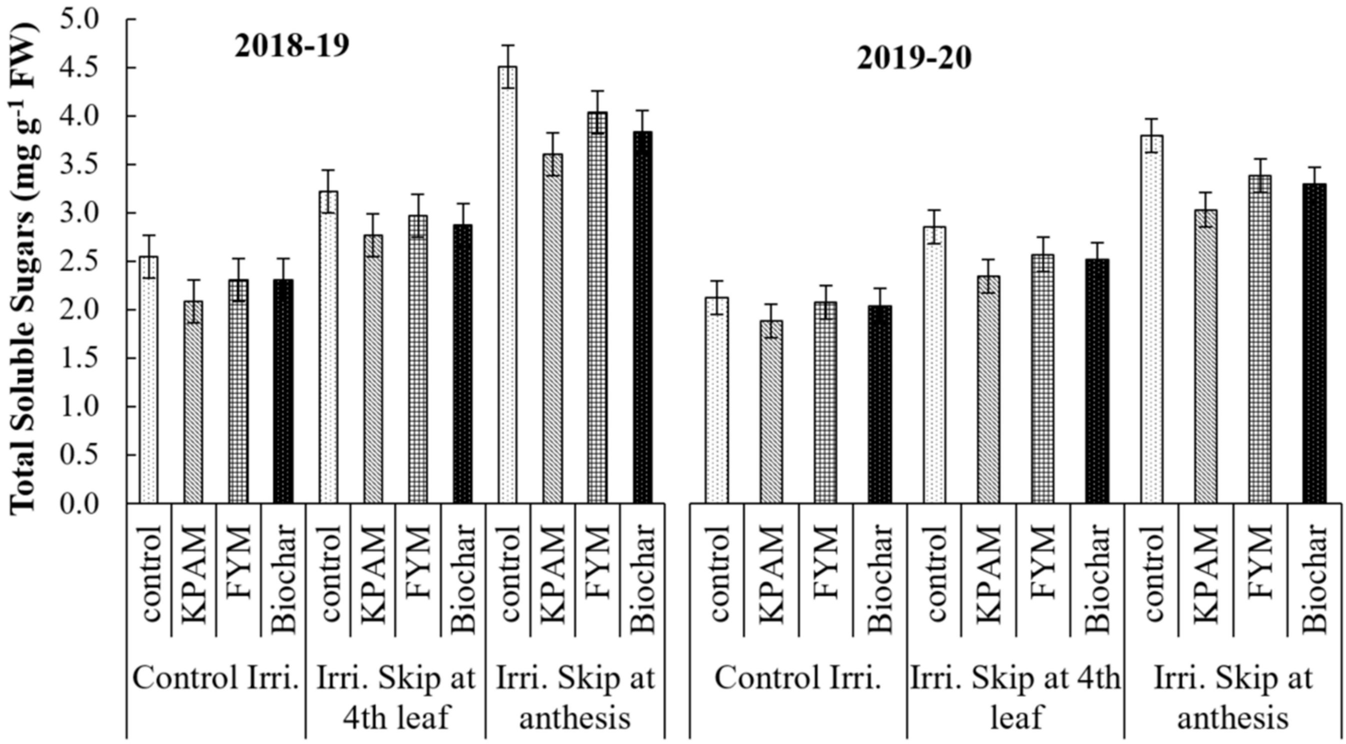

Figure 9. Effect of soil amendment materials on total soluble sugars in the wheat crops grown under normal and water stress imposed by skipping irrigation at 4th leaf and anthesis stage of growth (mean values ± S.E).

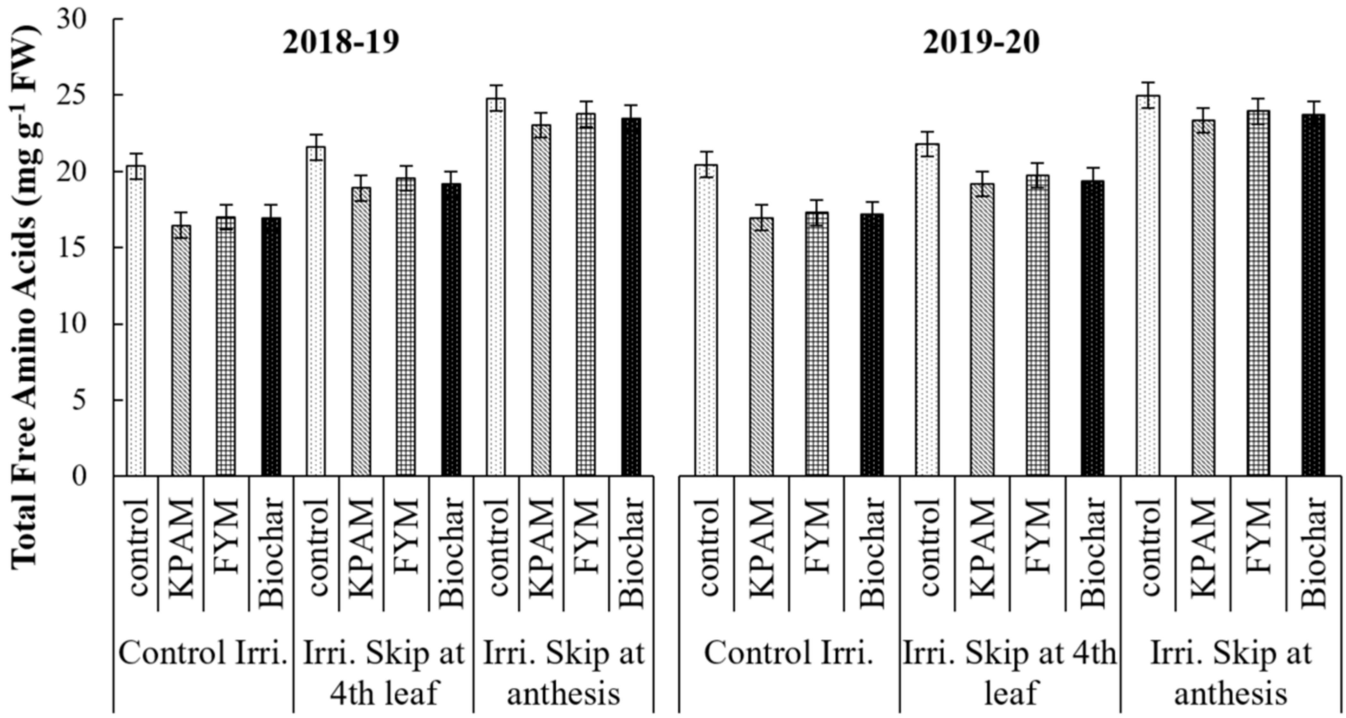

Figure 10. Effect of soil amendment materials on total free amino acids in the wheat crops grown under normal and water stress imposed by skipping irrigation at 4th leaf and anthesis stage of growth (mean values ± S.E).

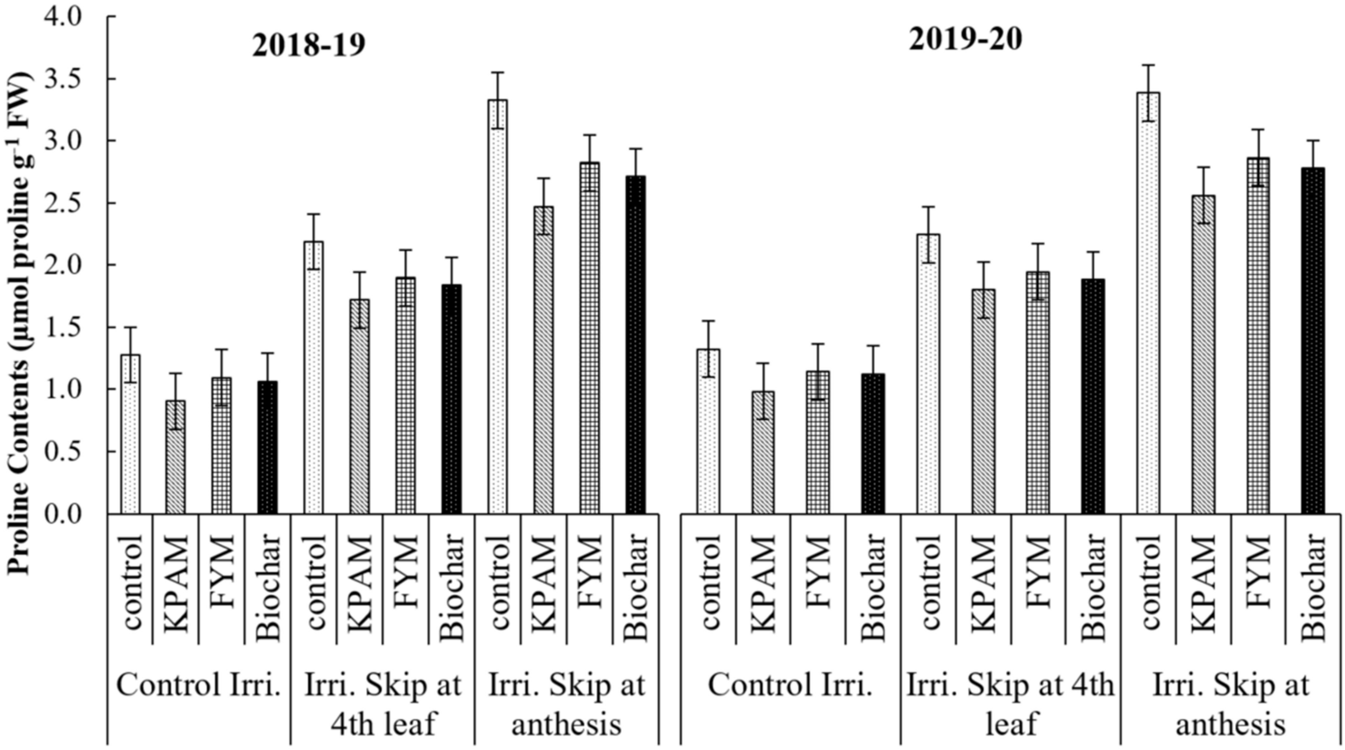

Figure 11. Effect of soil amendment materials on proline contents in the wheat crops grown under normal and water stress imposed by skipping irrigation at 4th leaf and anthesis stage of growth (mean values ± S.E).

Table 2. Analysis of variance table for biochemical and yield parameters of wheat crops.

Source of Variation (SOV)	Total Soluble Protein	Total Soluble Sugar	Total Free Amino Acid	Leaf Proline Contents	Biological Yield t/ha	Grain Yield t/ha
Year	1.26 **	0.18 NS	1.44 NS	0.09 *	2.05 **	0.83 **
Replication (Year)	0.87 **	0.13 *	0.94 NS	0.01 NS	7.47 **	19.89 **
Irrigation	88.17 **	21.94 **	302.46 **	24.51 **	0.56 **	0.95 **
Year × Irrigation	0.002	0.002	0.007	0.0001	0.03 NS	0.01 *
Treatments	8.13 **	1.08 **	34.96 **	1.29 **	0.001 NS	0.04 **
Year × Treatments	0.004	0.001	0.03	0.001	0.001	0.001
Irrigation × Treatment	0.97 **	0.08 NS	2.19 **	0.10 **	0.31 **	0.02 **
Year × Irrigation × Treatment	0.003	0.0001	0.01	0.0001	0.001	0.001

* and ** = significant at 0.05 and 0.01 levels, respectively; NS = non-significant.

3.3. Grain and Biological Yield

Drought stress significantly reduced the grain and biological yield of the wheat crop at both the 4th leaf and anthesis stages of growth. The drought had more drastic effects in terms of the biological yield (9.98 and 9.69 t/ha, respectively) at the vegetative (4th leaf) growth stage compared with the control irrigation treatment with a relatively better biological yield (10.51 and 10.22 t/ha, respectively) in years 1 and 2, respectively (Figure 12). The drought stress significantly affected the grain yield and the lowest values (2.98 and 2.87 t/ha, respectively) were observed at the vegetative (4th leaf) growth stage whereas the highest values (4.67 and 4.44 t/ha, respectively) were observed in the well-watered treatments in years 1 and 2, respectively (Figure 13). When compared with the control and other soil amendment materials such as FYM and biochar, the soil treated with KPAM performed better against drought. KPAM withstood drought stress more aggressively followed by biochar, FYM, and the control treatments in that order. For both the biological and grain yield, the relationship between the soil amendment and irrigation treatment and the year was significantly different (Table 2).

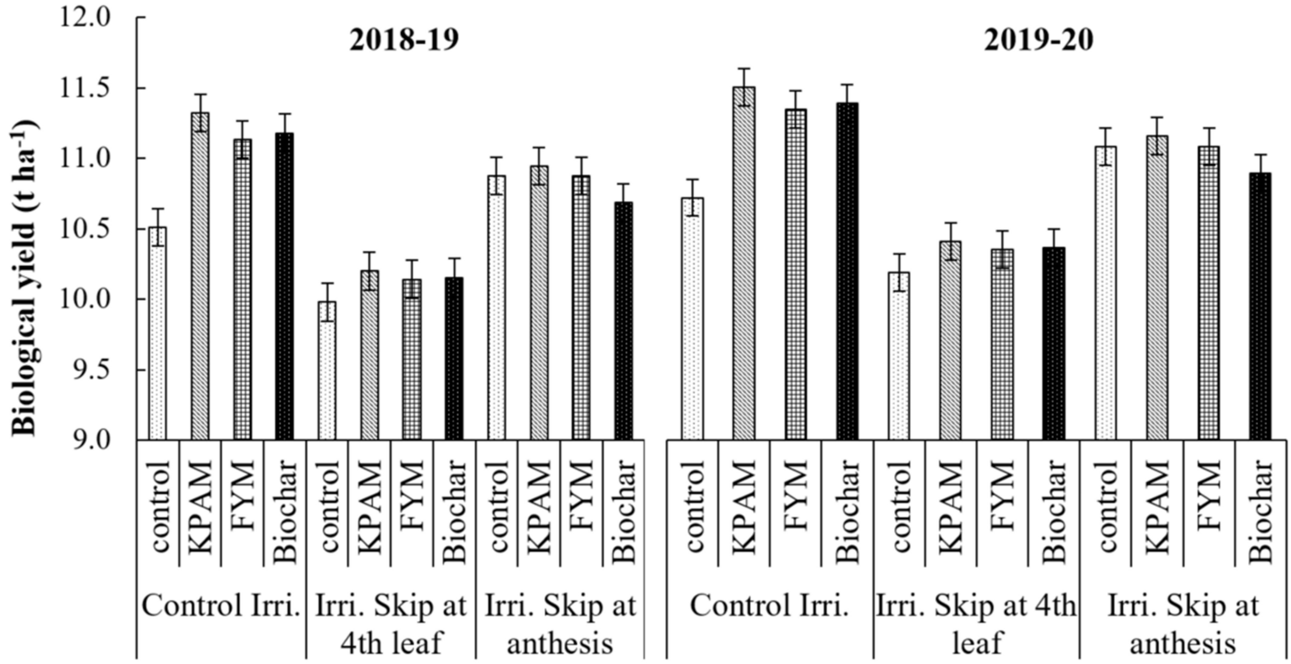

Figure 12. Effect of soil amendment materials on biological yield in the wheat crops grown under normal and water stress imposed by skipping irrigation at 4th leaf and anthesis stage of growth (mean values ± S.E).

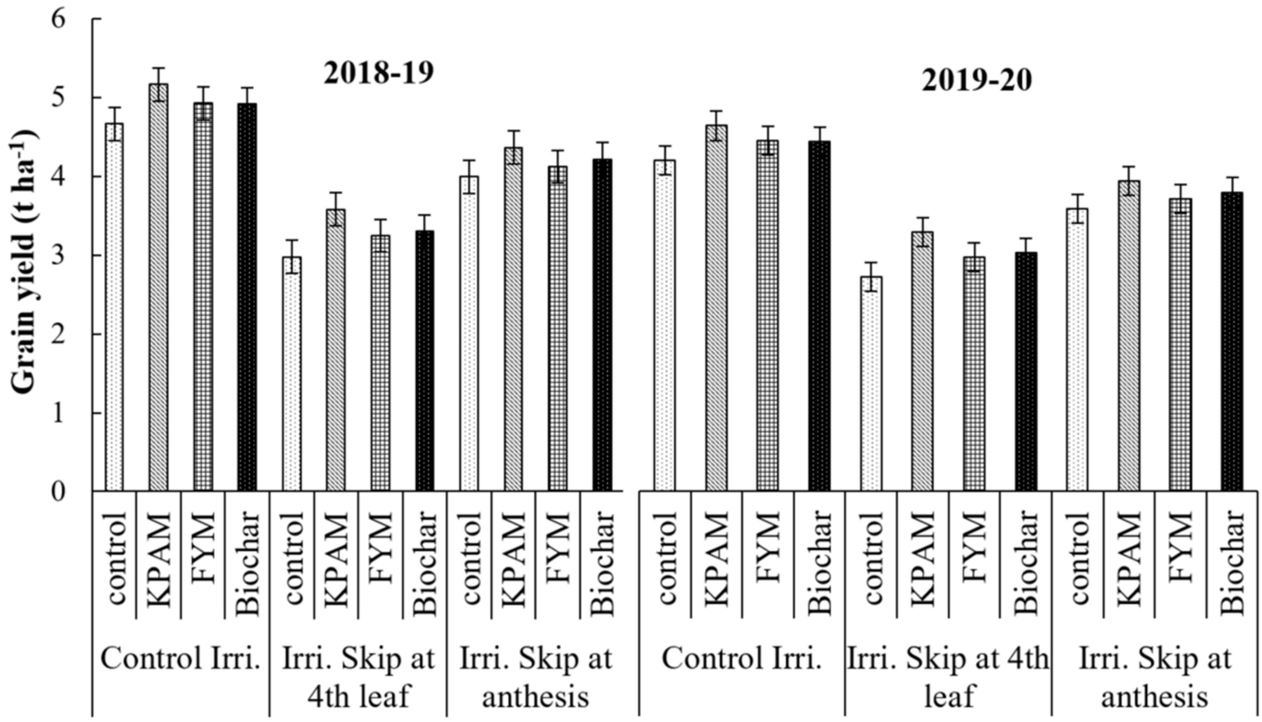

Figure 13. Effect of soil amendment materials on grain yield in the wheat crops grown under normal and water stress imposed by skipping irrigation at 4th leaf and anthesis stage of growth (mean values ± S.E).

4. Discussion

An unavailability or a limited supply of irrigational water can pose a serious threat to staple food production by negatively impacting on the growth and yield. The application of soil conditioning materials is one method for increasing the capacity of the soil to retain water and crop performance in water-scarce conditions. The results of this study demonstrated that the use of these soil amendment materials in both normal and stressed conditions enhanced the soil water status and subsequently improved the physiological attributes such as the stomatal conductance, photosynthesis, and yield parameters. It was observed that the KPAM treatment, in comparison with the FYM and biochar treatments, had a considerably more positive impact on the water potential and relative water content of the plant during water stress at the 4th leaf and anthesis stages (Figures 3 and 4). The effect was more pronounced at the anthesis stage. In both normal and drought conditions, soils with soil amendment materials had a higher water potential and relative water content. This could be attributed to a higher amount of water availability for uptake at the root zone as a result of an increased water-holding capacity. In accordance with Islam et al. [14], when superabsorbent polymers were applied to the soil, the RWC increased by 31.80% at the tillering stage, 23.20% at the anthesis stage, and 27% at the grain filling stage compared with the untreated soil. This was primarily related to the ability of KPAM to retain water and raise the water-holding capacity of the soil to provide an optimal supply of water and improve the relative water content. Further, using biochar as a soil conditioner increased the physiological properties of the plant in water-limited situations. These results were consistent with the finding of Keshavarz Afshar et al. [33].

We observed in our study that the use of soil amendment materials improved almost all of the physiological attributes with the KPAM polymer being noticeably more effective than the other materials (Figures 5–7). Suresh [34] also observed that a soil supplemented with superabsorbent polymers had the highest CO_2 assimilation, stomatal conductance, and transpiration rates in all moisture regimes except the control treatment. The increased values for all the gas exchange parameters could be attributed to the superabsorbent polymer supplementing a higher moisture supply. According to another study, superabsorbent polymers outperformed biochar in almost all the physiological attributes. This could be due to the remarkable ability of hydrogel to hold water for a longer period as well as its nutrient retention capability and ability to provide adequate moisture to the plant for a longer period [14]. These results were similar to the findings of our study.

Biochar is the second most efficient soil amendment material after SAPs and is known to improve gas exchange features. In our study, biochar also performed better compared with the FYM and control treatments in all gas exchange parameters due to a better carbon sequestration ratio and its ability to absorb and retain water. These findings were in agreement with the findings of Nawaz et al. [23] who found that, when compared with non-treated soil, the wheat crop with biochar had the highest photosynthetic rate (Pn), stomatal conductance (gs), and transpiration rate (E). This could be attributed to an increase in the water-holding capacity and nutrient supply of the soil as well as a synergistic interaction between the soil water regime and the wheat crop plant. Batool et al. [26] also concluded that biochar played an important role as a soil amendment material and enhanced the photosynthetic rate, transpiration rate, and stomatal conductance due to an improved soil moisture retention capability and porosity of the modified soil. The improvement in the gas exchange parameters in crops could be due to the increased soil nutrients and water status with the biochar addition even under moisture stress conditions [35].

In our experiments, drought stress at the critical growth stages caused a reduction in the synthesis of protein (Figure 8). Water stress caused a reduction in the total soluble protein in plants, which was associated with a decrease in the protein production and a higher protein degradation. Sallam et al. [36] also discovered a declining trend in the total soluble proteins in a wheat crop under water-limited conditions whereas Bukhari et al. [37] reported the restoration of soil moisture and the production of soluble proteins with the use of appropriate chemicals. The use of soil conditioners helped to withstand the water deficit condition; KPAM had the higher TSP values compared with the other amendments (Figure 8). According to Lou et al. [38] the treatment of maize straw with biochar stimulated soluble protein production in plants. In our experiments, soil amendments using KPAM, biochar, and FYM helped in the mitigation of drought effects and lowered the generation of TSS and TFA; this was particularly noticeable with KPAM in the wheat crop (Figures 9 and 10). According to Hammad and Ali [39], moisture stress stimulated the generation of total soluble sugars and total free amino acids in wheat. Similarly, Aranjuelo et at. [40] concluded that plants grown under water-stressed conditions produced more soluble sugars and amino acids than non-stressed plants. The plants increased their production of TSS and TFA despite a decrease in the osmotic potential. All of the above findings were consistent with our study in that a higher production of TSS and TFA in wheat crops occurred in response to water stress. In the current study, a proline accumulation was observed in response to drought stress (Figure 11). The increase in the proline content was attributed to a decrease in the protein biosynthesis and water diffusion into cells for a greater turgor potential. The findings of Bukhari et al. [37] support our findings in that drought stress caused an increase in the proline content in wheat crops when compared with normal irrigation. Soil conditioners significantly reduce the production of proline, which is attributed to a better supply of moisture in water stress. Similarly, Tomášková et al. [35] found that amending the soil with superabsorbent polymers helped to reduce the proline concentration, which rose as a consequence of water stress. The use of biochar also aided in the decrease of drought stress and the formation of proline, which was elevated due to the limited water supply. The decreasing trend of the proline content with biochar could be deemed to be acceptable as biochar enhanced the other growth factors of the plant [41].

Drought stress significantly reduced the biological and grain yields, especially at the critical growth stages (Figures 12 and 13).

The results revealed by Li et al. [41] also followed our study in that, under drought circumstances, the yield drop was most noticeable at the vegetative stage than the reproductive stage. Drought stress significantly reduced the final yield of a barley crop up to 42% compared with the normal moisture regime [4]. Song et al. [42] also found that drought stress at different critical growth stages caused severe losses to the plant growth and yield and its severity depended on the stage of growth at which it occurred. There are other previous studies on wheat crops related to soil, which showed a positive impact under drought and other climatic conditions [43–47]. There are numerous other studies under the same climatic conditions showing the confirmation that soil conditioning materials including biochar and soil conditioner improve the soil properties and are helpful for nitrogen uptake and water-related soil properties in different crops [48–52]. In our study, KPAM produced a significantly higher biological and grain yield compared with other materials (Figures 10 and 11). In a field study, Grabiński and Wyzińka [53] concluded that the addition of superabsorbent polymers at the rate of 30 kg/h in winter wheat elevated all the growth and yield parameters in water stress conditions, which strongly endorsed our experimental treatment of the KPAM polymer and the results. Similarly, Moosavi et al. [54] showed that the cultivation of cowpea with biochar enhanced the seed number per plant due to the relief of water-deficient stress and a higher phosphate and potassium content. Other studies also endorsed that biochar and nitrogen fertilizer improved the yield-related characteristics in arid climates [55,56]. On the basis of the findings from this study, it is recommended that the use of such soil conditioning materials is helpful for the sustainable production of crops in areas of limited water availability and could also be helpful for the community of the farmers for sustainable production under arid climatic conditions.

5. Conclusions

This two-year field study aimed to obtain a sustainable wheat yield under water deficit conditions by using new approaches of soil amendment. Our study concluded that water deficit conditions had a significant influence on the physiological, biochemical, and water relations of wheat. However, soil amendments with different materials such as biochar, FYM, and KPAM could significantly enhance the physiological, biochemical, and water relation attributes of wheat under water-limiting conditions. These materials can ensure moisture is available to the plant when most needed and help the plant withstand drought stress, particularly at critical growth stages, which can improve the crop yield. A positive correlation existed between the soil conditioners and water-holding ability in the soil of these materials. The results of these findings could be useful in the development of existing and new techniques as well as approaches for soil and crop management under water deficit conditions. However, future studies should also test the long-term effect of using inorganic chemicals such as KPAM in the field under contrasting environments to know its fate. Further, precision tools such as modelling approaches may also be applied to these products to observe their adoptability for sustainable crop production in future climate change scenarios.

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