Effects of Funneliformis mosseae and Potassium Silicate on Morphological and Biochemical Traits of Onion Cultivated under Water Stress

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Abstract: Water stress negatively impacts the physiology of plants, affecting their growth and development. It is considered among the most important environmental factors responsible for reduced crop production. In this regard, biofertilizers may be considered significant for their repara- 
tive properties to increase stress tolerance in crop plants. We studied the effects of water stress on the morphological and biochemical characteristics of onion plants with AMF (Funneliformis mosseae) and potassium silicate application. The water stress significantly affected all the studied traits, each with minimum recorded levels. Plants that received combined treatments of AMF and potassium silicate showed maximum percent increments in all the studied characteristics, e.g., plant height (156.7%), weight of bulb (416.8%), antioxidant activity (224.0%), membrane stability index (74.5%), relative water content (87.3%), and total soluble solids (63.71%). Therefore, the study demonstrated that all the investigated variables were affected negatively by water stress. However, bio-fortification of onion plants with silicates and AMF inoculation may be considered useful for functional food production, with numerous health promoting properties.

Keywords: onion; Funneliformis; potassium silicate; water stress

1. Introduction

Onion (Allium cepa L.) is a member of the Liliaceae family of plants, which includes species native to Europe, Asia, North America, and Africa [1]. The onion is a major crop grown in Egypt and around the globe. Onion is a shallow-rooted crop that requires frequent irrigation to maximize yield [2]. Numerous biotic and abiotic stresses impair plant development and production, with water shortage being one of the most significant abiotic stressors affecting crop growth and output. Additionally, water stress impairs plant development by interfering with a variety of physiological and biochemical activities, including photosynthesis, respiration, translocation, ion absorption, carbohydrates, nutrition metabolism, and growth stimulants [3].

Microbial strains enhance nutrient uptake, soil fertility, and crop yields via a variety of mechanisms, including nitrogen fixation, potassium and phosphorus solubilization, phytohormone excretion, the production of substances that suppress phytopathogens, re- sistance to abiotic and biotic stresses, and the detoxification of belowground pollutants [4].

Beneficial rhizospheric microorganisms, such as arbuscular mycorrhizal fungi (AMF), enhance agroecosystems by increasing crop nutrient uptake and resistance to abiotic and biotic stressors [5]. Co-inoculation with AMF benefits the plant by establishing a
bipartite symbiosis in which AMF absorbs nutrients, mostly phosphates, and then utilizes them to create energy for biological activity [6]. The plant gives AMF photosynthetic carbohydrates in exchange. The association of AMF with plants’ rhizosphere region provides various growth-related benefits, including enhanced nutrition, improved stress resistance (both biotic and abiotic), and modulated soil structure [7]. Onion inoculation with AMF may increase production under water stress since AMF promotes appropriate hydration throughout the plant, as seen by the plant’s high water content. AMF colonization improves root hydraulic conductivity and root development in onions, resulting in a larger surface area for nutrient and water absorption [8]. Additionally, AMF enhances resistance to water stress by boosting the absorption of critical plant nutrients such as N and P, which encourages the host plant’s development and increases tolerance to water stress [9].

On the other hand, potassium silicate is a remarkably soluble source of potassium and silicon [10]. Silicon is a non-essential nutrient for plants. However, it may aid in their disease resistance [11]. Plants need silica in order to resist biotic and abiotic stress. It has enormous potential as a growth and development medium for plants. Apart from its role as a fertilizer (potassium silicate contains 27% silicon oxide), silicon assists in growth, photosynthesis, transpiration and evaporation efficiency, leaf strength and chlorophyll concentration per leaf area, and product quality [12].

Silicon may help plants to withstand the adverse effects of metal elevation while simultaneously enhancing their water consumption efficiency and photosynthetic rate [13]. Further, silicon has been discovered to have a suppressive impact on some fungal infections and has been utilized as a chemical control alternative [14]. Additionally, silicon has the ability to boost the resistance of plants to environmental stress and agricultural productivity [15]. However, not much research has been conducted to evaluate the combined effects of AMF and silicon on the physiological and biochemical characteristics of onion plant. Therefore, in this study, we have tried to evaluate the consequences of AMF (Funneliformis mosseae) and potassium silicate application on various growth- and yield-related parameters of onion plants to explore their potential use as biofertilizers.

2. Material and Methods

2.1. Plant Material and Experimental Design

The experiment was conducted in 2019–20 and 2020–21. In both years, seeds were sown in nursery beds in November in the portrays, and later, healthy seedlings were transplanted into the pots during the month of December. The polyhouse was located in Ranchi, Jharkhand, India (24°22′18″ N, 86°19′27″ E) and the experiment was carried out using a randomized complete block design (RCBD) with three replications of each treatment comprising 15 plants. Seeds of onion cultivar Pusa Red were grown in portraits following seed treatment with fungicide Thiram. Later, six-week-old seedlings were transplanted in the polyhouse and maintained at a temperature of 60 to 70°F and humidity of 55–65%. Seedlings were transplanted in plastic pots filled with sieved and autoclaved soil media. The package and practices followed for the onion cultivation are defined in detail elsewhere [16].

According to an analysis conducted using an auto discrete analyzer, model SmartChem® 200 (KPM Analytics, Frepillon, France), the composition of the soil was 70 percent sand, 24 percent silt, 5 percent clay, 0.04 percent nitrogen, 0.02 percent available phosphorus, 0.05 percent organic carbon, and a pH of 7.2.

2.2. Funneliformis Mosseae and Potassium Silicate Treatment

In a polyhouse, Funneliformis mosseae was maintained on Zea mays plants using the method described by Owusu-Bennoah and Mosse [17]. For this investigation, infected root pieces and rhizospheric soil that contained 20 spores/g of soil were used. In treatments with Funneliformis mosseae, a 10 g inoculum of mycorrhizal fungus was supplied 2 cm below the soil’s surface, whereas potassium silicate solution (K₂SiO₃) with a purity of 99%
and net weight 1.331 gm at 20 °C (Lobo Chemie Pvt. LTD. India) was applied as the dipp- ing treatment of onion transplants before planting at concentrations of 0.4%, and also as a soil drenching treatment at 30 days after planting.

Regular water supply was maintained until 45 days after transplanting (DAT). Water stress was created by providing water for up to 45–50% field capacity. The water supply was stopped for 35 days during bulb development (45–80 DAT), and all treatments were supplied with this constant water stress. Treatments used in the present study were as follows: T1: plants under water stress with conventional package and practices [16]; T2: plants supplied with Funneliformis mosseae (Fm) under water stress in addition to conventional package and practices; T3: plants supplied with potassium silicate (Ps) under water stress in addition to conventional package and practices; T4: plants provided with a combination of Funneliformis mosseae + Potassium silicate (Fm + Ps) under water stress in addition to conventional package and practices.

2.3. Estimation of Morphological Traits and Mineral Content

Morphological traits, including plant height, number of leaves per plant, and leaf area, were measured at 75 DAT. The plant height (cm) of the plant was determined by measuring from the base of the plant to the tip of the longest leaf, whereas the total number of leaves on each plant was determined by counting. Using a LICOR 3100 leaf area meter, the leaf area was estimated. At harvesting time, the yield was determined for all of the plants in each replication. The bulb weight (g) was determined as the average weight of 5 bulbs in each replication, whereas, for estimating the equatorial and polar diameter (mm), the 5 bulbs of each replication were cut open longitudinally and horizontally, respectively.

According to the procedures described by Cottenie et al. [18], total nitrogen, phosphorus, potassium, and sulfur levels in the bulb were analyzed [19].

2.4. Estimation of Biochemical Traits

After harvesting, the sampled bulbs were cleaned, removing the broken outer shells and cutting them with a plastic knife to form thin slices. An aliquot of fresh slices was dried at 70 °C to a constant weight and used for biochemical composition analysis. The reducing and non-reducing sugars, phenolics, and amino acids were determined following AOAC’s method [20]. The reducing sugars were measured using dinitro salicylic acid (DNS) and total sugars using anthrone. Total amino acids were estimated with the ninhydrin method [21]. This was followed by reading the absorbance at 570 nm using a UV–Vis Spectrophotometer (Specord-205 Analytik Jena AG, Jena, Germany). Phenolics concentration was determined with extracts in 70% ethanolic solution using the Folin–Ciocalteu colorimetric method [22], whereas the antioxidant activity of onion bulbs was assessed using the redox titration method. For this, titration of aqueous/ethanolic plant extracts was carried out with 0.01 N KMnO₄ solution and the values were expressed in mg GAE g⁻¹ dw [23].

Total sugars were analogically determined after acidic hydrolysis of water extracts with 20% hydrochloric acid. Fructose was used as an external standard. Total soluble solids (TSS) were determined using a hand refractometer (RA-130-KEM, Kyoto Electronics Manufacturing Co., Ltd., Kyoto, Japan) by pouring two or three drops of clear onion juice obtained by filtering the crushed onion extracts and expressed in °Brix. Based on the method developed by Barrs and Weatherley [24], relative water content was measured using a fully developed fourth leaf. For membrane stability index estimation, leaves were collected, chopped into small 2 cm discs, and then cleaned with distilled water to remove debris from the leaf surface. MSI was determined by placing 100 mg of leaf disc in two test tubes containing 10 mL of double-distilled water, as defined in detail by Sairam et al. [25].
2.5. Statistical Analysis

Statistical analysis was performed using Statgraphics Centurion XVIII software (version 18, StatPoint Technologies, Warrenton, VA, USA). Significant differences between means of the treatment groups were subsequently calculated and statistically scrutinized with the help of the Newman–Keuls multiple-range test.

3. Results

The morphological traits, mineral content, and biochemical characteristics of onion under water stress and after inoculation with *F. mosseae* and potassium silicate were investigated separately as well as in combination and are presented in Table 1 and Table 2, respectively.

3.1. Effect on Morphological Traits and Mineral Content

As indicated in Table 1, more than a two-fold increment was observed in plant height, which recorded values of 65.25, 67.19, and 70.48 cm, respectively, after T2, T3, and T4 (Table 1). Further, the number of leaves also increased significantly under the influence of *F. mosseae* and potassium silicate, and the maximum increase was observed with T4 (14.69), followed by T3 (13.69) and T2 (13.17) (Table 1). For polar diameter also, the values were considerably higher than T1, at 41.86, 43.29, and 45.00 mm, respectively, with T2, T3, and T4 (Table 1). Moreover, T4 gave remarkable results for equatorial diameter as well, with the corresponding value of 56.3 mm; however, T2 and T3 were also efficient, with values of 52.09 and 54.42 mm, respectively (Table 1). Further, the weight of the bulb, which was reduced to 14.12 g after T1, increased dramatically to 62.41, 68.99, and 72.98 g, respectively, after T2, T3, and T4 (Table 1).

Likewise, the unexpectedly higher augmentation observed in the total yield of onion from 3.78 t/ha at T1 to 34.96, 38.79, and 43.13 t/ha, respectively, at T2, T3, and T4 again proved the efficiency of *F. mosseae* and potassium silicate in giving the desired results (Table 1). As with all other morphological characteristics, the leaf area was increased to its maximum value of 44.55 cm² when treated with T4. At the same time, T2 and T3 were also significant, with respective values of 24.57 and 36.75 cm² (Table 1). Similarly, there was a drastic increase in the mineral composition of onion as compared to T1 when treated with the AMF and potassium silicate. The N content increased to 1.97, 2.49, and 2.97%; P content increased to 0.12, 0.17, and 0.26%; K content increased to 1.50, 1.67, and 1.87%; and S content increased to 0.56, 0.65, and 0.77%, respectively, after treatment with T2, T3, and T4 (Table 1).

Table 1. Effects of *Funneliformis mosseae* and potassium silicate on morphological traits and mineral content of onion under water stress.

| Traits               | Years | C (T1)            | Fm (T2)          | Ps (T3)          | Fm + Ps (T4)     |
|----------------------|-------|-------------------|------------------|------------------|-----------------|
| Plant height (cm)    | 2019  | 22.50 ± 2.21 c    | 64.97 ± 2.74 b   | 66.87 ± 1.52 b   | 69.6 ± 1.63 a,b |
|                      | 2020  | 32.42 ± 2.06 a    | 65.54 ± 2.72 d   | 67.52 ± 2.04 d   | 71.37 ± 2.53 b  |
|                      | Overall | 27.46 ± 1.20 a   | 65.25 ± 1.73 a   | 67.19 ± 2.06 d   | 70.48 ± 1.08 b  |
| Number of leaves     | 2019  | 4.45 ± 0.08 c     | 13.06 ± 1.02 b   | 13.50 ± 1.03 b   | 14.24 ± 1.01 a  |
|                      | 2020  | 6.13 ± 0.06 a     | 13.29 ± 1.09 a   | 13.88 ± 1.06 c   | 15.14 ± 1.04 b  |
|                      | Overall | 5.29 ± 0.54 c    | 13.17 ± 1.65 a   | 13.69 ± 1.04 a   | 14.69 ± 1.90 b  |
| Polar diameter (mm)  | 2019  | 23.17 ± 1.54 b    | 41.55 ± 1.37 a   | 43.01 ± 1.53 a   | 44.40 ± 1.83 a  |
|                      | 2020  | 30.94 ± 2.06 a    | 42.18 ± 1.75 a   | 43.58 ± 2.65 a   | 45.61 ± 2.20 a  |
|                      | Overall | 27.05 ± 1.87 c   | 41.86 ± 1.32 a   | 43.29 ± 1.89 b   | 45.00 ± 1.67 d  |
| Equatorial diameter (mm) | 2019 | 20.27 ± 1.43 c    | 51.97 ± 1.54 b   | 54.19 ± 1.34 b   | 55.38 ± 1.75 a  |
|                      | 2020  | 25.1 ± 0.93 a     | 52.21 ± 1.20 a   | 54.66 ± 1.34 c   | 57.23 ± 1.07 b  |
|                      | Overall | 22.68 ± 1.09 c   | 52.09 ± 1.03 a   | 54.42 ± 1.05 a   | 56.3 ± 1.20 b   |
| Weight of bulb (g)   | 2019  | 10.37 ± 1.06 d    | 61.63 ± 1.20 c   | 68.52 ± 1.87 b   | 71.53 ± 1.25 a  |
Yield (t/ha) & 2020 & 17.88 ± 1.07 & 63.20 ± 1.62 & 69.46 ± 1.28 & 74.44 ± 1.23 & 2019 & 2.00 ± 0.54 & 34.35 ± 1.20 & 38.2 ± 1.40 & 41.24 ± 1.90 & 2020 & 5.57 ± 0.65 & 35.58 ± 1.34 & 39.39 ± 1.84 & 45.03 ± 1.76 & Overall & 3.78 ± 0.06 & 34.96 ± 1.21 & 38.79 ± 1.87 & 43.13 ± 1.34 & Leaf area (cm²) & 2019 & 17.8 ± 1.34 & 18.32 ± 1.21 & 34.62 ± 1.21 & 43.36 ± 1.20 & 2020 & 19.91 ± 1.21 & 30.82 ± 1.03 & 38.89 ± 1.21 & 45.74 ± 1.23 & Overall & 18.85 ± 1.93 & 24.57 ± 1.05 & 36.75 ± 1.08 & 44.55 ± 1.09 & N (%) & 2019 & 0.18 ± 0.03 & 1.95 ± 0.23 & 2.46 ± 0.56 & 2.6 ± 0.65 & 2020 & 0.66 ± 0.03 & 1.99 ± 1.23 & 2.53 ± 1.34 & 3.35 ± 0.21 & Overall & 0.42 ± 0.35 & 1.97 ± 0.56 & 2.49 ± 0.32 & 2.97 ± 0.64 & P (%) & 2019 & 0.07 ± 0.01 & 0.12 ± 0.05 & 0.16 ± 0.02 & 0.22 ± 0.06 & 2020 & 0.10 ± 0.06 & 0.13 ± 0.02 & 0.19 ± 0.06 & 0.30 ± 0.04 & Overall & 0.08 ± 0.02 & 0.12 ± 0.01 & 0.17 ± 0.05 & 0.26 ± 0.03 & K (%) & 2019 & 0.24 ± 0.12 & 1.48 ± 0.63 & 1.61 ± 0.45 & 1.80 ± 0.67 & 2020 & 0.37 ± 0.14 & 1.53 ± 0.13 & 1.74 ± 0.63 & 1.95 ± 0.43 & Overall & 0.30 ± 0.05 & 1.50 ± 0.54 & 1.67 ± 0.14 & 1.87 ± 0.43 & S (%) & 2019 & 0.13 ± 0.06 & 0.54 ± 0.06 & 0.65 ± 0.06 & 0.74 ± 0.15 & 2020 & 0.21 ± 0.14 & 0.58 ± 0.07 & 0.66 ± 0.21 & 0.81 ± 0.08 & Overall & 0.17 ± 0.06 & 0.56 ± 0.04 & 0.65 ± 0.21 & 0.77 ± 0.13 &

* Means with the same letter are not significantly different at p < 0.05 based on the Student–Newman–Keuls test.

3.2. Effect on Biochemical Traits

For biochemical characteristics also, the values presented in Table 2 demonstrate that the *F. mosseae* and potassium silicate combination was the most efficient treatment in augmenting the traits considered for this study. For instance, the maximum increase in total sugar content was observed with T4, which was up to 21.46% fresh weight, followed by T3 (13.8) and T2 (10.00) (Table 2). The amount of reducing sugars, which was reduced to 6.66 under T1, was increased to 7.6, 8.89, and 9.68% fresh weight, respectively, after T2, T3, and T4, almost three to four times higher than T1 (Table 2). Similarly, the increase in the amount of non-reducing sugars was commendably higher than that observed in T1. The values increased to 2.25, 4.75, and 12.63% fresh weight, respectively, when treated with T2, T3, and T4, from 0.57 in T1 (Table 2). Further, total amino acids were recorded at 1.39, 2.52, and 2.79 mg g⁻¹ of fresh weight, respectively, when applied with T2, T3, and T4 (Table 2). The concentration of phenolics increased by almost triple the amount when treated with *F. mosseae* and potassium silicate compared to that observed under water stress. This is indicated by the values recorded in Table 2, i.e., 4.36, 6.32, 8.74, and 13.53 mg g⁻¹ of dry weight, respectively, with treatments T1, T2, T3, and T4.

Furthermore, the enhanced antioxidant activity could also show the effects of the given fertilizers on the onion plant. Its antioxidant activity, approximately 0.83 μg g⁻¹ dry weight under T1, increased to 1.54, 2.24, and 2.69 μg g⁻¹ dry weight, respectively, after T2, T3, and T4 (Table 2). Similarly, the combination of *F. mosseae* and potassium silicate significantly affected the membrane stability index. The maximum values were obtained with T4 (73.7), followed by T3 (69.52), T2 (63.76), and T1 (42.23) (Table 2). Furthermore, the relative water content of the plant, as indicated by the study, was raised from 37.34% with T1 to 69.94% with T4. However, T2 and T3 were also significant, with respective values of 54.51 and 59.92% (Table 2). Finally, the total soluble solids increased to 9.37, 11.07, and 12.95 °Brix, respectively, after T2, T3, and T4 (Table 2).
Table 2. Effects of Funneliformis mosseae and potassium silicate application on biochemical traits of onion under water stress.

| Traits                                | Years | C (T1)       | Fm (T2)       | Ps (T3)       | Fm+Ps (T4)     |
|---------------------------------------|-------|--------------|--------------|--------------|---------------|
| Total sugars (% fresh weight)         | 2019  | 6.13 ± 0.92  | 9.47 ± 1.21  | 12.43 ± 1.76  | 18.12 ± 1.54  |
|                                       | 2020  | 6.17 ± 0.12  | 10.53 ± 0.92 | 15.17 ± 1.21  | 24.81 ± 1.42  |
|                                       | Overall | 6.15 ± 0.21  | 10.00 ± 0.23  | 13.8 ± 0.21  | 21.46 ± 1.24  |
| Reducing sugars (% fresh weight)      | 2019  | 2.04 ± 0.03  | 7.43 ± 0.21  | 8.81 ± 0.34  | 9.33 ± 0.24  |
|                                       | 2020  | 3.28 ± 0.43  | 7.78 ± 0.05  | 8.97 ± 0.04  | 10.03 ± 0.54  |
|                                       | Overall | 2.66 ± 0.06  | 7.6 ± 0.05  | 8.89 ± 0.12  | 9.68 ± 0.54  |
| Non-reducing sugars (% fresh weight)  | 2019  | 0.43 ± 0.06  | 2.03 ± 0.21  | 3.52 ± 0.65  | 9.22 ± 0.43  |
|                                       | 2020  | 0.71 ± 0.04  | 2.48 ± 0.47  | 5.99 ± 0.06  | 16.05 ± 0.87  |
|                                       | Overall | 0.57 ± 0.01  | 2.25 ± 0.07  | 4.75 ± 0.04  | 12.63 ± 0.14  |
| Total amino acids (mg g⁻¹ of fresh weight) | 2019  | 0.28 ± 0.01  | 1.38 ± 0.08  | 2.49 ± 0.05  | 2.62 ± 0.05  |
|                                       | 2020  | 0.82 ± 0.08  | 1.4 ± 0.06  | 2.55 ± 0.09  | 2.97 ± 0.06  |
|                                       | Overall | 0.55 ± 0.95  | 1.39 ± 0.03  | 2.52 ± 0.08  | 2.79 ± 0.8  |
| Phenolics (mg g⁻¹ of dry weight)      | 2019  | 3.77 ± 0.84  | 6.07 ± 1.23  | 7.98 ± 1.43  | 11.63 ± 1.43  |
|                                       | 2020  | 4.96 ± 1.32  | 6.57 ± 1.43  | 9.51 ± 1.65  | 15.43 ± 1.54  |
|                                       | Overall | 4.36 ± 1.73  | 6.32 ± 1.54  | 8.74 ± 2.54  | 13.53 ± 2.54  |
| Antioxidant activity (µg g⁻¹ dry weight) | 2019  | 0.76 ± 0.06  | 1.4 ± 0.06  | 2.08 ± 0.06  | 2.48 ± 0.56  |
|                                       | 2020  | 0.91 ± 0.45  | 1.68 ± 0.03  | 2.4 ± 0.34  | 2.91 ± 0.65  |
|                                       | Overall | 0.83 ± 0.08  | 1.54 ± 0.04  | 2.24 ± 0.04  | 2.69 ± 0.34  |
| Membrane stability index              | 2019  | 41.26 ± 1.30  | 63.15 ± 1.23  | 69.15 ± 1.04  | 72.48 ± 1.04  |
|                                       | 2020  | 43.2 ± 1.21  | 64.37 ± 1.34  | 69.9 ± 2.03  | 74.92 ± 2.12  |
|                                       | Overall | 42.23 ± 1.04  | 63.76 ± 2.43  | 69.52 ± 1.24  | 73.7 ± 1.21  |
| Relative water content (%)            | 2019  | 33.26 ± 1.32  | 54.08 ± 1.02  | 59.25 ± 1.04  | 69.22 ± 1.9  |
|                                       | 2020  | 41.42 ± 1.28  | 54.95 ± 2.05  | 60.59 ± 1.23  | 70.66 ± 1.21  |
|                                       | Overall | 37.34 ± 2.02  | 54.51 ± 1.23  | 59.92 ± 2.20  | 69.94 ± 2.53  |
| Total soluble solids (°Brix)          | 2019  | 7.00 ± 0.45  | 8.21 ± 0.68  | 10.37 ± 1.34  | 12.47 ± 1.24  |
|                                       | 2020  | 8.83 ± 0.92  | 10.53 ± 0.05  | 11.78 ± 1.65  | 13.44 ± 1.26  |
|                                       | Overall | 7.91 ± 0.04  | 9.37 ± 1.06  | 11.07 ± 0.03  | 12.95 ± 1.03  |

* Means with the same letter are not significantly different at p < 0.05 based on the Student–Newman–Keuls test.

4. Discussion

It is evident from the present study that both AMF and potassium silicate are beneficial for improved morphological and biochemical characteristics in onion; however, their combined application was the most prominent. The application of F. mosseae and potassium silicate, both separately and in combination, significantly increased the bulb weight. The findings are comparable to those described in previous publications regarding the increase in onion and garlic bulb yield due to AMF inoculation, ranging from 1.45 to 1.50 times, indicating that AMF plays a significant role in bulb weight formation [23]. Mycorrhiza could enhance all parameters because it improves the absorption of water and mineral nutrients [26]. This can be seen by the increased content of N, P, K, and S in the present study after AMF inoculation. Biomass accumulation and plant development are assumed to be temperature-dependent and the plant’s response to water stress generally considers the durations of peak temperature. Zafar et al. suggested that higher temperatures than optimally required impacted the physiology, morphology, and yield of cotton plants negatively [27].

Onion roots are fibrous and devoid of root hairs. Such plants are frequently obligate mycorrhizal crops that cannot complete their life cycle without AMF due to insufficient phosphorus uptake [28]. Mycorrhiza helps plants with shallow, sparse roots to absorb...
phosphorus. AMF can increase phosphorus availability to varying degrees by acidifying the soil, thereby promoting the growth and development of host plants [29]. It is also critical for leaf stability and the capacity to expose more leaves to light, which improves the photosynthetic efficiency of the plant [30]. This might be the reason for the increased leaf area as well as number of leaves. Our findings are further supported by those of Haddad et al., who discovered that silicon promotes leaf growth and photosynthesis [31]. On the other hand, a deficiency of silicon may decrease the quantity of chlorophyll in plant leaves.

AMF induces adaptations in plants, significantly affecting the formation of photosynthetic pigments, carbohydrates, and sugars, thereby enhancing the enzymatic activity and subsequently the development of the plant [32]. This might be the reason for the increased concentrations of total sugars and reducing and non-reducing sugars indicated in our study. Further, it was observed that compared to the water stress, AMF and potassium silicate inoculation of onion led to an increase in bulb phenolics and amino acids under all treatments. However, the combined application of AMF and potassium silicate had the largest positive effect on phenolics and amino acid concentrations. According to Cordeiro et al., regarding the concentration of phenolics in strawberries, a higher amount of phenolics was observed in plants inoculated with AMF [33]. Moreover, the increase in the relative water content in onion plants after AMF and potassium silicate application conforms with the findings of Moradtalab et al. [34], which demonstrated that both AMF and silicon treatments eased the adverse effects of drought and increased the water content of leaves, resulting in a more significant production of biomass [34].

The higher ability for water uptake, which prevented stomatal closure and allowed higher photosynthetic activity, was apparently responsible for the rise in leaf relative water content. Plants inoculated with AMF and potassium silicate are reported to display increased antioxidant enzyme activity. Numerous studies have shown a relationship between silicon availability and increased antioxidant metabolism in plants [35]. Further, the combination of potassium silicate with AMF is also reported to increase antioxidant activity [36]. Moreover, the antioxidant ability shown by the plants treated with Fm+Ps in our study might be related to a mechanism for enhancing tolerance against heat stress [37], considering that plants under this treatment (Fm+Ps) showed an increased % of relative water content in leaves. In addition, our study also indicated a significant increase in the concentration of total soluble solids after the application of AMF and potassium silicate. This was also observed in the study conducted by Ordookhani and Zare [38], which showed an improved concentration of total soluble solids in tomato fruit after AMF inoculation. Therefore, the inoculation of onion plants with AMF and silicates is verified to give beneficial results for the evaluated characteristics, thereby proving their potential to be used as biofertilizers.

5. Conclusions

The AMF improved the overall quality of onion through various morphological and biochemical characteristics compared to the untreated control. Although all the treatments were efficient in enhancing the investigated traits, T4 showed the best results. Our data confirmed the hypothesis that the dual inoculation of AMF and potassium silicate has a synergistic effect on all the growth parameters considered for this study. Moreover, this environmentally friendly method of farming has the ability to boost the characteristics and nutritional value, as well as the yield, of onion plants over the long term. These results indicate that AMF will be an important component in sustainable agriculture in the near future, as an alternative green strategy to reduce synthetic fertilizer use.

Author Contributions: Conceptualization, A.K.D.; methodology, P.K. and A.K.D.; software analysis, P.K. and M.S.; data curation, M.S.; writing, P.K. and M.S.; review and editing, P.K.; supervision, A.K.D. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.
**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Data are available on request.

**Acknowledgments:** The authors wish to thank the anonymous reviewers for their careful reading and corrections.

**Conflicts of Interest:** The authors declare no conflict of interest.

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