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The Influence of Arbuscular Mycorrhizal Fungus *Rhizophagus irregularis* on the Growth and Quality of Processing Tomato (*Lycopersicon esculentum* Mill.) Seedlings

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Abstract: Tomato (*Lycopersicon esculentum* Mill.) is one of the most valuable horticultural crops, not only for its economic importance but also for its high nutritional value and sensory qualities. The arbuscular mycorrhiza (AM) fungus *Rhizophagus irregularis* can improve plant nutrient uptake and decrease seedling transplanting shock. Although *R. irregularis* is one of the most extensively studied AMF species, there is a paucity of data on the effects of this species on processing tomato seedlings produced in an aerated hydroponic float system. A greenhouse experiment with four treatments and three replications was established in a completely randomized design. The treatments contained the addition of 0, 40, 80, and 120 fungal spores per L of nutrient solution (control, AMF1, AMF2, and AMF3, respectively). Root colonization analysis proved that the maximum dose of applied AMF (AMF3) supported colonization to a large extent, succeeding 36.74%. In addition, the highest values of total dry weight (1.386 g), survival rate (94.79%), N content (3.376 mg per 100 g DW) and P content (0.497 mg per 100 g DW) were also observed under AMF3 treatment. In conclusion, the application of high doses of the AM fungus *R. irregularis* in nutrient solutions of float system leads to a substantial improvement in the quality and growth of processing tomato seedlings.

Keywords: arbuscular mycorrhizal fungi (AMF); Dickson's quality index (DQI); Heinz 3402 F_1; root colonization; seedling quality

1. Introduction

Tomato (*Lycopersicon esculentum* Mill.) constitutes the second most widely produced and consumed vegetable crop, after potato, and the worldwide production has been estimated at 186 million tonnes per year from a total cultivation area of around 5.1 million hectares [1]. Due to its high levels of antioxidants, it is suggested that an adult human consumes 25 to 32 kg of tomatoes per year [2]. Tomatoes are ingested in the form of both fresh and processed products. A percentage higher than 80% of the tomatoes cultivated worldwide are processed into products such as sauce, juice, ketchup, canned tomato, stew, and soup [2,3]. Increased productivity and fruit quality are required for successful processing tomato production. In the Mediterranean countries, where tomato growing requirements are large in water and fertilization inputs, cropping practices should be enhanced to improve the sustainability of processing tomato production while retaining high levels of yield to meet the demands of an expanding population [4]. Under the present climate change scenarios, rising temperatures and variations in precipitation intensity and distribution would exacerbate heat and drought related stresses, reducing crop productivity [5,6].

Conventional plant breeding and genetic engineering were used to develop stress tolerant cultivars in research to enhance drought resilience and alleviate the negative impacts of climate change on crop productivity, with little attention paid to the complex ecological interactions, particularly at the soil level [7–9]. Among plant growth promoting microorganisms (PGPM), arbuscular mycorrhizal fungi (AMF) have been frequently recorded to enhance abiotic stress tolerance in plant species. AMF create a mutualistic symbiotic interaction with the roots of most terrestrial plants, including the tomato plant, by forming typical intracellular fungal structures in the root cortex called arbuscules, which are believed to be the location of nutrient transfers among the partners [6,10]. Furthermore, being obligate biotrophs, AMF consume carbon compounds from the host plant in exchange for water and low transportable nutrients, such as phosphorus, hence extending the root depletion zone via their extraradical hyphae [11,12]. The symbiosis of plants with AMF often results in enhanced levels of tolerance to abiotic stress, such as drought, salinity, nutrient deficiency, heavy metals and adverse soil pH, as described in literature [13–16]. In particular, under drought conditions, AMF inoculation in maize plants increased growth and photosynthetic activity by improving chlorophyll content, nutrient uptake and assimilation [17]. In response to a water deficient environment, higher plant heights, root length, and vigor, as well as mineral nutrient leaf concentrations (NO_3^-, PO_4^{3-}, SO_4^{2-}, and Na^+), attributable to key tolerance mechanisms and upregulating antioxidant enzyme activities were found in durum wheat inoculated plants [18]. Enhanced fruit yield of AMF inoculated tomatoes was also found for the most efficient maintenance of leaf water potential and nutritional status with increased nitrogen (N) and phosphorus (P) content [6,13,19].

Currently, contemporary cropping practices have eventuated in a decrease in diversity and frequency of AM fungi in agricultural soils and potting soil substrates, a consequence attributed to tillage methods, mineral fertilizer use as well as nursery substrate sterilization, among other factors [12]. As a result, AM fungal spores have been applied externally, with AMF inoculum added to seedlings' growing medium or into the planting hole at the time of transplanting. Therefore, two major agronomic benefits are anticipated: (a) greater seedling growth in the nursery and (b) increased production of mature plants succeeding field planting [9,20].

Hydroponic systems, such as the float system, are commonly used to cultivate seedlings of a large number of cultivated plant species, including vegetables (i.e., tomato), tobacco, and cannabis [21–23]. Cultivation in a typical float system is frequently conducted on Styrofoam sheets that float on top of troughs filled with nutrient solutions [24]. Nutrient solutions, which can be either organic or inorganic in nature, have a significant impact on plant growth [25]. In addition, it should be noted that plants grown on float systems typically have a substantially larger root system [26,27]. As the root length, diameter, and density are mainly related to the plant uptake rates for water and nutrients, the float system seedlings present high-quality attributes [28,29]. Furthermore, Dickson's quality index (DQI) can be utilized to assess seedling quality by evaluating root biomass and other agronomic properties [30].

The inclusion of AMF in nutrient solutions of float systems could be advantageous for processing tomato seedlings. AMF include a variety of fungal species from the Glomaceae family [31]. Particular attention has been paid to the effects of *Rhizophagus irregularis* (syn. *Glomus intraradices*) on tomato plants grown in various cultivation systems [6,9,32,33]. With relevance to these research works, the existence of the previously mentioned fungi on plant roots compensated for the detrimental effects of abiotic stress and enhanced nutritional quality. Although there is research available on the application of the AM fungus *R. irregularis* on tomato plants, there is a paucity of evidence on the effects of *R. irregularis* on processing tomato seedlings produced in a float system. The current research work intends to examine, for the first time to our knowledge, the AM fungus *R. irregularis* effect on the growth and quality of processing tomato seedlings grown on a float system using Dickson's Quality Index.

2. Materials and Methods

An experiment was conducted in a glasshouse at the Agricultural University of Athens (37°58′55.83″ N, 23°42′16.69″ E) from April to May 2018 to assess the influence of the AM fungus *Rhizophagus irregularis* on the growth and quality of processing tomato seedlings. The average lowest and highest recorded temperatures during the experiment was 14.3 °C and 36.1 °C, respectively (average 15.2 °C). The relative humidity (RH) reached from 45% to 81% (average 70%). For the experiment, arranged according to a completely randomized design (CRD), four treatments with three replications per treatment were employed. The treatments included the application of 0, 40, 80, and 120 fungal spores per L of nutrient solution (control, AMF1, AMF2, and AMF3, respectively; Table 1).

Table 1. Experimental treatments and total AM fungus *Rhizophagus irregularis* applied rates.

Treatment	MycoPlant® Polvo Grow Dose (g per L of Nutrient Solution)	Applied Fungal Spores per L of Nutrient Solution	Total Applied Fungal Spores in Nutrient Solution of Each Trough
Control	-	-	-
AMF1	0.1	40	2000
AMF2	0.2	80	4000
AMF3	0.3	120	6000

At first, polystyrene floating trays with 150 cells per tray (individual cell volume 12 cm^3) were filled with a mixture of organic peat and vermiculite 1:1 v/v. On each individual cell, one seed of processing tomato (*Lycopersicon esculentum* Mill. cv. Heinz 3402 F_1) was hand-sown on 9 April 2018 by placing the seed on the surface of the substrate, without additional covering. The trays were then put into 50 L troughs filled with tap water, where two trays were put into each trough. In the current study, twelve troughs of equal size were utilized for the floating system: three for each treatment (4 treatments × 3 troughs). In all troughs, 1 L of organic water-soluble fertilizer Fish–Fert (2–4–0.5 and other trace elements) (Humofert S.A., Athens, Greece) was added and its chemical composition is presented in Table 2. With the exception of the control treatment, the nutrient solution of each trough received various doses of the commercial root inoculant product MycoPlant® Polvo Grow (Tratamientos BioEcológicos S.A., Murcia, Spain), which contained water–dispersible granules of *R. irregularis*. The number of fungal spores added to each trough is presented in Table 1. The choice of the root inoculant product doses to be tested was based on the dosage of 0.15 g per L of nutrient solution recommended by the manufacturer for tomato, adding quantities below and above the recommended. In addition, the nutrient solution in the troughs was aerated with an air pump (EcoPlus 728459; Intertek, Shanghai, China) pumping 3566 GPH and with a diaphragm and filter in order to prevent dust from entering the solution. Aeration was maintained 24 h a day during the duration of the experiment and allowed a dissolved oxygen (DO) concentration of 6.4 mg L^{-1} (Microprocessor Dissolved Oxygen meter HI 9146; HANNA Instruments, Woonsocket, RI, USA). The seedlings emerged 10 days after sowing with a germination percentage of 91% and were transplanted in the field at 30 days after their emergence (DAE).

Table 2. Chemical composition of organic water-soluble fertilizer Fish-Fert.

Chemical Characteristics	Values
pH	6.70 ± 0.20
Nitrogen (N % w/w)	2.00 ± 0.10
Phosphorus (P_2O_5 % w/w)	4.00 ± 0.02
Potassium (K_2O % w/w)	0.20 ± 0.02
Calcium (CaO % w/w)	0.60 ± 0.04
Magnesium (MgO % w/w)	0.09 ± 0.01
Sulphur (S %)	0.10 ± 0.02
Iron (Fe mg kg^{-1})	26.0 ± 1.05
Copper (Cu mg kg^{-1})	1.0 ± 0.08
Zinc (Zn mg kg^{-1})	13.0 ± 0.05
Manganese (Mn mg kg^{-1})	3.0 ± 0.03
Amino acids (% w/w)	55.00 ± 1.80

The traits that were taken into account in order to assess the processing tomato seedlings were the plant biometric parameters, nitrogen (N) and phosphorus (P) content, as well as the survival rate. Besides the survival rate, all other measurements necessitated destructive sampling. As a result, 20 seedlings from each treatment were collected at 25 DAE, and the following plant biometric parameters were evaluated: plant height, dry weight of the plant aboveground parts (shoot) and roots, stem diameter and total root length. Shoot length was measured from the substrate surface to the apical bud of the plant. For the determination of dry weight, the samples were oven-dried for 72 h at 64 °C. The stem diameter and total root length were measured by placing the collected samples on a high-resolution scanner (HP Scanjet 200 Flatbed Photo Scanner; Hewlett-Packard Inc., Palo Alto, CA, USA) using Delta–T software (Delta–T Scan ver. 2.04; Delta–T Devices Ltd., Burwell, Cambridge, UK) (Figure S1). The current parameters were then applied to define Dickson's quality index (DQI) described by Dickson et al. [34], as follows:

$$\mathrm{DQI} = \frac{\text{Seedling total dry weight (g)}}{\frac{\text{Shoot length (cm)}}{\text{Shoot diameter (cm)}} + \frac{\text{Shoot dry weight (g)}}{\text{Root dry weight (g)}}} \tag{1}$$

The total N content was determined by grinding the dried samples to a fine powder and applying them to the Kjeldahl procedure using a Kjeltec 8400 autoanalyzer (Foss Tecator AB, Höganas, Sweden). Moreover, for the measurement of the P content, ten plants per treatment were also harvested at 25 DAE, dissolved in an $HNO_3H_2O_2$ solution, and heated under pressure in a CEM MDS-2000 microwave digestor oven (CEM Microwave Technology Ltd., Buckingham, UK). The extract was consequently analyzed using an iCAP 6500 DUO inductively coupled plasma emission spectrometer (Thermo Fisher Scientific, Waltham, MA, USA). The survival rate was evaluated by sight at 25 DAE. In addition, the percentage of root length colonized by the arbuscular mycorrhizal fungi (AMF) was also determined microscopically at 5, 9, 13, 17, 21 and 25 DAE with the gridline-intersection method at a 30–40× magnification [35] after cleaning washed roots in 10% (w/v) KOH for 10 min at 90 °C and staining with 0.05% (w/v) trypan blue dissolved in lactophenol [36].

The experimental data were statistically analyzed using the SigmaPlot 12 statistical program (Systat Software Inc., San Jose, CA, USA) according to the completely randomized design (CRD). One-way ANOVA was used to examine the significance of the data, and differences among means were separated using Tukey's honestly significant difference (Tukey's HSD) test. All comparisons were made at the level of probability ($p \leq 0.05$).

3. Results

3.1. Mycorrhizal Functioning

The analysis of root colonization revealed that the untreated seedlings presented the lowest mycorrhizal infection. In particular, the arbuscular mycorrhizal fungi (AMF) colonization on untreated processing tomato seedlings was kept below 8% for the first twenty-five days after the emergence of seedlings (Figure 1). Significant variations were observed among regimes, with the inclusion of the AMF appearing to enhance mycorrhizal colonization in roots. Between the three distinct AMF treatments, the highest dose examined (AMF3) supported colonization to a larger extent, achieving 36.74%. On the other hand, the medium (AMF2) and minimum (AMF1) doses presented statistically lower values in comparison to AMF3, with the values being 28.77% and 24.20%, respectively.

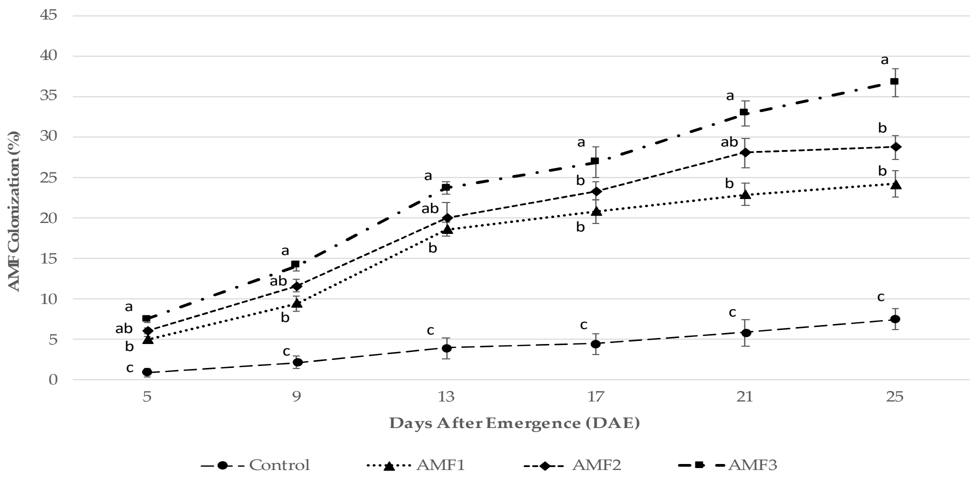

Figure 1. Percentage of arbuscular mycorrhizal fungi (AMF) colonization of processing tomato roots as affected by the different treatments of AM fungus *Rhizophagus irregularis* measured at 5, 9, 13, 17, 21 and 25 days after emergence (DAE). Vertical lines represent standard mean errors. The different lowercase letters in the values of different AMF treatments for each time point of measurement denote statistically significant differences according to the Tukey's HSD test ($p \leq 0.05$).

3.2. Seedlings Growth and Development

The presence of AM fungus *R. irregularis* influenced both the growth of aboveground parts and roots of processing tomato seedlings. After the AMF application, significant variation in total root length was found among treated and untreated plants. Especially, the highest total root length was found in the case of maximum AMF dose (AMF3) with the length increased by 54.72% compared to the control seedlings. In the same manner, the root dry weight of AMF3 treated plants was 54.19% higher in contrast to the non-treated plants (Table 3).

Table 3. Biometric characteristics of processing tomato seedlings as affected by the different treatments of AM fungus *Rhizophagus irregularis*.

	Total Root Length (cm)	Root Dry Weight (g)	Shoot Length (cm)	Stem Diameter (cm)	Shoot Dry Weight (g)	Root/Shoot Ratio	Seedling Total Dry Weight (g)
Control	22.84 ^{c}	0.179 ^{c}	7.89 ^{a}	2.69 ^{a}	0.675 ^{b}	0.267 ^{a}	0.855 ^{b}
AMF1	28.88 ^{b}	0.207 ^{bc}	7.94 ^{a}	2.73 ^{a}	0.892 ^{ab}	0.233 ^{a}	1.097 ^{ab}
AMF2	32.31 ^{ab}	0.251 ^{ab}	8.13 ^{a}	2.71 ^{a}	0.956 ^{ab}	0.264 ^{a}	1.206 ^{ab}
AMF3	35.34 ^{a}	0.276 ^{a}	8.22 ^{a}	2.78 ^{a}	1.113 ^{a}	0.248 ^{a}	1.386 ^{a}
F_{AMF}	12.289 *	13.712 *	2.293 ^{ns}	1.224 ^{ns}	11.570 *	1.993 ^{ns}	12.808 *

F–test ratios are from ANOVA. ns and *: Not significant and significant at 5% probability level, respectively. The different lowercase letters within a column denote statistically significant differences according to the Tukey's HSD test ($p \leq 0.05$).

In terms of the growth of processing tomato aboveground parts, the addition of AMF in nutrient solution had no influence on the shoot length and stem diameter (Table 3). On the contrary, the enhancement of AMF resulted in a considerable increase in shoot dry weight. As a result, tomato plants exposed to the maximum AMF dose (AMF3) had the highest dry weight (1.113 g), whereas untreated (control) plants had the lowest (0.675 g).

The root to shoot ratio was not significantly affected by AMF treatments during the experiment. The higher *R. irregularis* rates favored the seedling total dry weight with the highest value (1.386 g) obtained in the maximum AMF dose (AMF3) followed by AMF2 (1.206 g) and AMF1 (1.097 g) treatments, while the lowest value (0.855 g) was observed in the untreated plants (Table 3). Consequently, the findings of the current investigation support the hypothesis that AMF colonization stimulates plant development.

The experiment results indicated that the medium and maximum AMF doses (AMF2 and AMF3, respectively) had a favorable effect on the plant's nitrogen (N) content, with values being 24.39% and 16.61% greater than the control treatment (Table 4). Furthermore, the phosphorus (P) content of the tomato seedlings was also increased with the AMF augmentation, and the greatest value (0.497 mg 100 g^{-1} DW) recorded in AMF3 treatment followed by AMF2 and AMF1 (0.463 and 0.434 mg 100 g^{-1} DW, respectively) treatments.

Table 4. Dickson's quality index (DQI), survival rate, and nitrogen (N) and phosphorus (P) content of processing tomato seedlings as affected by the different treatments of AM fungus *Rhizophagus irregularis*.

	Dickson's Quality Index (DQI)	N Content (mg 100 g^{-1} DW)	P Content (mg 100 g^{-1} DW)	Survival Rate (%)
Control	0.128 ^{c}	2.714 ^{c}	0.373 ^{c}	89.87 ^{b}
AMF1	0.152 ^{bc}	2.883 ^{bc}	0.434 ^{b}	90.91 ^{b}
AMF2	0.177 ^{ab}	3.165 ^{ab}	0.463 ^{ab}	93.74 ^{a}
AMF3	0.198 ^{a}	3.376 ^{a}	0.497 ^{a}	94.78 ^{a}
F_{AMF}	16.034 *	21.189 **	20.828 **	32.307 **

F–test ratios are from ANOVA. * and **: Significant at 5% and 1% probability levels, respectively. The different lowercase letters within a column denote statistically significant differences according to the Tukey's HSD test ($p \leq 0.05$).

Similarly, Dickson's quality index (DQI) was significantly affected by the increased rates of *R. irregularis*, and the highest values were observed in maximum (0.198) and medium dose (0.177) of AMF (Table 4). Moreover, statistically significant differences were observed for the survival rate, where the highest values observed in AMF3 (94.78%) and AMF 2 (93.74%) treatments.

4. Discussion

AMF colonization has been shown to play an essential role in stimulating plant development and seedling quality [37,38]. AMFs' ability to promote plant growth can be shown in a variety of parameters and plant tissues, such as biomass accumulation [39,40]. In the current study, the impacts of AMF colonization on plants were clearly demonstrated after the inoculation with *R. irregularis* on processing tomato seedlings.

Rhizophagus irregularis promoted processing tomato root growth by enhancing total root length and dry weight. The inoculated seedlings with the highest AMF dose (AMF3) presented almost 50% higher total root length as compared to the non–inoculated seedlings, which might probably enhance nutrient uptake and better growth in the field. Previous studies confirm the present results, describing a beneficial effect of *R. irregularis* on the root development and biomass of tomato plants [6,9,13,19,32]. In general, it is well accepted that inoculation during the early stages of plant development can promote AM symbiosis, resulting in enhanced plant growth in the nursery and improved field performance after planting [9,37,38,41].

Plant growth parameters, including stem length, stem diameter as well as biomass production, are the external indicators of internal plant metabolism. Throughout the study period, the abovementioned parameters of inoculated seedlings remained consistently higher than those of non–mycorrhizal seedlings (Table 3). These results are in accordance with Fracasso et al. [6] and Kakabouki et al. [23], who observed significantly increased shoot length, stem diameter, and shoot dry weight upon inoculation with *R. irregularis* in tomato and cannabis plants, respectively.

In addition, the application of AMF increased the root to shoot ratio in inoculated plants. This revealed that AMF-inoculated seedlings divided more biomass to the roots than to the shoots, implying that AMF inoculation may have increased the nutritional absorption area in AMF–colonized seedlings. According to Begum et al. [38], a higher root to shoot ratio indicated a high level of mycorrhizal efficacy. A betterment in seedling quality seen in terms of growth characteristics when compared to the control further endorsed the notion that the infected seedlings enhanced their vigor, robustness, and development, and hence transplanting performance. AMF was found to be beneficial to tomato seedlings inoculated with *R. irregularis* [9,13]. Moreover, mycorrhizal inoculation has been found to promote crop uniformity, reduce transplant mortality, and increase the production of many horticultural crops in soilless substrates lacking AM fungi [15,37].

These findings show a substantial positive relationship between AMF root colonization and plant biometric characteristics including the development of roots and whole-plant dry biomass of processing tomato seedlings (Table 5). Considering the rate of AMF root colonization, this feature may become increasingly apparent. In cases with greater amounts of *R. irregularis*, the colonization rate was actually higher, resulting in a more intensive symbiotic relationship among AMF and the host plant. The abovementioned mechanism promotes root system reinforcement and, as a result, enhances plant growth [42].

Remarkably, the mycorrhizal symbiosis reported in this study seems to have a significant influence on seedling nutrient uptake. Concerning the phosphorus (P), *R. irregularis* increased the availability of this mineral in the rhizosphere and improved its uptake by processing tomato seedlings, with the greatest results detected in seedlings inoculated with the highest AMF dose (AMF3) (Table 4). Although P is not readily available to plants due to its low solubility, processes such as extracellular phosphatase mineralization as well as mycorrhizal fungus solubilization make P available to seedlings [43,44]. As a result, P, as a required component for plant metabolism and growth, has the potential to play a key role in critical physiological functions. [23,45]. P sufficiency is even more important in plant species such as processing tomatoes, where P deficiency may have a deleterious impact on reproductive organs and inflorescence initiation [45].

As for the nitrogen (N) accumulation, increasing the AMF dose had also a favorable effect. The N content in processing tomato seedlings with AMF inoculation might be related the AMF extraradical mycelium's ability to control N uptake into intra-mycelium and, ultimately, to the host plant [46]. Several studies have demonstrated that the AMF can transfer approximately 20–75 percent of the total N uptake to their hosts' plants [47–50].

The inoculation with AM fungus *R. irregularis* has been demonstrated to induce a higher photosynthetic ability of seedlings of diverse plant species [37,38]. Enhanced photosynthesis might be one of the elements that accounts for the reported increased total dry mass production of processing tomato seedlings. The enhanced N uptake and content related to AMF colonization clearly results in increased levels of chlorophyll (the primary pigment used in photosynthesis), since chlorophyll molecules can effectively trap N [51]. In addition, induced P availability in plants related to AMF colonization may have an indirect effect on photosynthesis by changing the ratio of ATP to ADP or the activity of the enzyme ribulose 1,5-bisphosphate (RuBP) carboxylase [52]. The present explanation is consistent with the higher P content in the plant seedlings, which the current data additionally revealed. Furthermore, *R. irregularis* has the ability to increase PEPCase activity, an enzyme involved in malate production [53,54]. Malate constitutes the final product of the photosynthetic carbon reduction (PCR) cycle in C_3 plants such as tomato, proving that *R. irregularis* has a fundamental effect on photosynthesis.

Table 5. Correlation matrix among evaluated traits.

Trait	Coefficient of Correlation (*r*)										
	AMF Colonization 25 DAE	**Total Root Length**	**Root Dry Weight**	**Shoot Length**	**Stem Diameter**	**Shoot Dry Weight**	**Root/Shoot Ratio**	**Seedling Total Dry Weight**	**Dickson's Quality Index (DQI)**	**N Content**	**P Content**
Total Root Length	0.9590 ***										
Root Dry Weight	0.8916 **	0.9588 ***									
Shoot Length	0.7287 *	0.8881 **	0.9226 **								
Stem Diameter	0.5631 ^{ns}	0.5666 ^{ns}	0.5312 ^{ns}	0.4831 ^{ns}							
Shoot Dry Weight	0.8995 **	0.9143 **	0.9358 ***	0.7916 *	0.6598 ^{ns}						
Root/Shoot Ratio	–0.2465 ^{ns}	–0.1209 ^{ns}	–0.0622 ^{ns}	0.1319 ^{ns}	–0.5313 ^{ns}	–0.4068 ^{ns}					
Seedling Total Dry Weight	0.9071 **	0.9322 ***	0.9577 ***	0.8249 *	0.6416 ^{ns}	0.9977 ***	0.3442 ^{ns}				
Dickson's quality index (DQI)	0.9080 **	0.9558 ***	0.9917 ***	0.8877 **	0.6036 ^{ns}	0.9717 ***	0.1846 ^{ns}	0.9854 ***			
N content	0.9077 **	0.8946 **	0.9028 **	0.7412 *	0.5585 ^{ns}	0.8581 **	0.0716 ^{ns}	0.8754 **	0.9084 **		
P content	0.9239 **	0.8816 **	0.9061 **	0.6880 ^{ns}	0.5493 ^{ns}	0.9595 ***	0.3692 ^{ns}	0.9589 ***	0.9381 ***	0.8680 **	
Survival Rate	0.8672 **	0.9053 **	0.9702 ***	0.8369 **	0.5549 ^{ns}	0.9189 **	0.0849 ^{ns}	0.9381 ***	0.9711 ***	0.9474 ***	0.9136 **

ns, *, ** and ***: Not significant and significant at 5%, 1% and 0.1% probability levels, respectively.

However, it is worth highlighting that greater nutrition and higher photosynthetic rates may not be the only causes for the seedlings' overall enhanced the survival rate as well as the seedlings' quality. In addition to their effects on plant nutrient uptake, AMF has been reported to increase the production of phytohormones [55]. Specifically, the application of two AMF species (*Glomus mosseae* and *Glomus intraradices*) on tomato plants substantially increased salicylic acid levels in mycorrhizal roots compared to nonmycorrhizal controls [56]. In addition to its role in stress-relieving pathways, salicylic acid has been shown to affect seed germination and seedling establishment [57].

In addition, literature has shown that *R. irregularis* helps minimize transplanting shock on seedlings. [37,38,58]. In a research study that investigated the influence of several AMF species (including *Glomus* sp.) on micropropagated grapevine plantlets, it was found that AMF colonization was an efficient technique to reduce the shock of transplantation [59]. Specifically, it was observed that mycorrhizal plants produced more proline, a nonprotein amino acid that forms in the majority of plant tissues experiencing stress conditions [60]. Various surveys on the importance of proline in osmotic adjustment and protein protection under stress conditions support this claim [38,61]. Irrespectively of proline quantities, transplanting shock endurance is greatly assigned to a well-developed root system that is capable of supporting the plant, facing environmental changes, and absorbing adequate nutrients and water [62].

Although the accumulation of biochemical compounds, such as salicylic acid and proline, was not assessed in the present study, AMF actually improved root growth and development. The possibility of AMF–induced phytohormones, proteins, and other biological substances influencing processing tomato seedling quality should not be disregarded. More research is required on the reciprocal influence of *R. irregularis*, its metabolites, and the processing tomato metabolic pathways that they may activate, resulting in robust seedlings.

Considering Dickson's quality index (DQI), the strong relationship between this index and AMF recorded in the current research (Table 4) is consistent with the majority of the literature. Researchers have previously utilized DQI to investigate the influence of AMFs on seedling quality in a variety of plant species [30,63–65]. Moreover, DQI as an indicator of robustness and plant biomass [66], presented a significant and strong correlation with biometric characteristics of processing tomato seedlings (Table 5). However, the total N and P concentration in the seedlings appears to alter DQI (Table 5), showing that nutrition may affect the index values. Finally, despite the present interaction, the research findings show that DQI can be used to impartially assess the quality of processing tomato seedlings.

5. Conclusions

In the current study, the inoculation with AM fungus *R. irregularis* as a PGPM influenced the biometrical characteristics of the above and belowground processing tomato tissues. Specifically, the total root length, as well as the seedling total dry weight of processing tomato were significantly increased. Moreover, the mycorrhizal symbiosis positively affected nutrient uptake by the seedlings with the highest accumulation of nitrogen and phosphorus recorded in the AMF3 treatment. Furthermore, *R. irregularis* improved the stress resistance of seedlings, resulting in a significant increase in survival rate. In conclusion, the application of high doses of the AM fungus *R. irregularis* in nutrient solutions of float system leads to a substantial improvement in the quality and growth of processing tomato seedlings. In addition, more research into the mechanisms and biochemical pathways is needed to underline the beneficial interaction between *R. irregularis* and processing tomato seedlings grown in a float system.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su14159001/s1, Figure S1: Images of the working window of the Delta–T Scan software.

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