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Tomato nutrition with the application of *Trichoderma* spp. on different soils

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Abstract. The present work aimed to evaluate the effect of *Trichoderma* spp. on the nutrition and development of tomato plants in three soil types under protected environments. One experiment was conducted with ferralsol and acrisol soil (conducted in pots in a greenhouse), and another used cambisol soil (conducted in beds in a commercial greenhouse). The experiments were carried out in a randomized block design with twelve replications. The treatments consisted of a control (no application of *Trichoderma* spp.), an application of *Trichoderma* spp. before seedling transplantation, and monthly *Trichoderma* spp. applications in tomato plants cv. Itaipava®. The evaluations included plant nutrition at full flowering, development (height and fresh and dry mass of shoots), crop yield components of number, weight, and diameter of fruits, and average yield per plant. A second nutritional evaluation was repeated in the cambisol. The application of *Trichoderma* spp. in the soil did not modify the nutrition parameters of plants until flowering. However, at the end of the cycle in cambisol, the treatment increased the available contents of N, P, Cu, and Mn. The application of *Trichoderma* spp. did not affect the development and yield of tomato plants in the conditions tested.

Key words: acrisol, bioinputs, cambisol, ferralsol, *Solanum lycopersicum*.

INTRODUCTION

The cultivation of vegetables in Brazil, in general, is carried out with intense soil disturbance and with high use and dependence on inputs (Lima et al., 2014). Vegetables are productive and have high nutrient demand, so they extract and export more nutrients from the soil than grain crops, requiring more extensive fertilization. As a result, mineral fertilization has been applied in horticulture at higher levels than in other crops (Filgueira, 2008).

The tomato crop (*Solanum lycopersicum*) is among the vegetables with the highest fertilizer demand, especially in protected cultivation, where yield tends to be higher than in unprotected cultivation (Rusu et al., 2023). Although the application of chemical fertilizers drives agricultural production in Brazil (Oliveira et al., 2019), the excessive use of these compounds can cause soil pollution, especially in protected cultivations, contributing to the increase in salinity levels, eutrophication, and surface and groundwater contamination (Silva et al., 2013). In addition, the large consumption of fertilizers associated with exhaustible reserves has increased the search for alternatives to supply nutrients to plants and increase fertilization efficiency.

Natural systems, such as forests and native grasslands, are self-sustaining, without the addition of synthetic fertilizers, and with low nutrient availability (Gamage et al., 2023). Plant nutrition occurs in a complex system of plant, substrate/soil, and many microorganisms, encompassing bacteria and fungi. The relationship between crops and soil microorganisms, including plant growth-promoting fungi such as *Trichoderma* spp., makes them natural biostimulants (López-Bucio et al., 2015). *Trichoderma* is a fungal genus with a cosmopolitan distribution and high biotechnological value. Several species are used as biological control agents (Hermosa et al., 2013). These microorganisms help plants withstand environmental stresses, such as salinity and water imbalances and can help plant defense against pathogenic bacteria and fungi (López-Bucio et al., 2015; Smolińska et al., 2016; Kowalska et al., 2017; Di Vaio et al., 2021).

The control of phytopathogens by fungal inhibition and induction of resistance in tomato induced by *Trichoderma* spp. is well reported (Jayaraj et al., 2006; Lee et al., 2006; Lisboa et al., 2007; You et al., 2016; Patel & Saraf, 2017; Kuzmanovska et al., 2018; Li et al., 2020). However, plant nutrition can interfere with biological disease control (Abro et al., 2014). Furthermore, there is evidence that using *Trichoderma* spp. can increase the bioavailability of nutrients and their absorption by plants (Yedidia et al., 2001). Divergent results are found in the literature, where *Trichoderma* spp. may compete with plants for nutrient absorption (Santiago et al., 2011) and negatively affects the development of tomato and other crops (Souza et al., 2018). Li et al. (2015) observed that tomato seedlings inoculated with *Trichoderma* spp. and grown under copper (Cu) deficient hydroponic conditions exhibited an increase in the dry biomass of plants and Cu uptake compared to control plants. However, the same authors demonstrated that *Trichoderma* spp. competed for phosphorous (P) and zinc (Zn) with tomato seedlings, suppressing root development and releasing phytase and/or chelating minerals. The authors suggested that growth induction directly affects root development, combined with indirect mechanisms such as mineral solubilization (including solubilization via acidification, redox, chelation, and hydrolysis mechanisms). Thus, these effects can be influenced by the soil or substrate, growing conditions, among other factors.

In southern Brazil, particularly the Serra Gaúcha, Campos de Cima da Serra, and Vale do Caí regions, the predominant soils are of the cambisol, ferralsol, and acrisol types (Streck et al., 2008), which are often used in the production of vegetables. Cambisol is a soil in a transformation process with insufficient characteristics to be included in other soil classes. On the other hand, ferralsol is clayey, deep, homogeneous along with the profile, and suffers from high weathering. In addition, it has high acidity, low nutrient reserve, and aluminum (Al) toxicity for plants. Finally, acrisol has a sandy surface horizon and a more clayey subsurface horizon (Santos et al., 2018). These soils can vary in depth, texture, drainage, and organic matter content but typically have high acidity, aluminum saturation, and low natural fertility (Streck et al., 2008). According to Rodrigues (2010), the response of *Trichoderma* spp. relative to soil characteristics is little known, which may cause oscillation in its performance. Therefore, research is needed so that the beneficial biostimulant potential of *Trichoderma* spp. can be translated to crops grown in different soil types. Based on the influence of soil characteristics and interaction with microbial communities, this work aimed to evaluate the effect of the application of *Trichoderma* spp. in the nutrition and development of tomato plants in three soil types grown under a protected environment.

MATERIALS AND METHODS

Site and soil description

The experiments were conducted in two locations from October 8, 2018 to February 11, 2019. Experiment 1 was carried out in a greenhouse used for research located at UCS Campus Vacaria (geographical coordinates of 28°31'02" S; 50°54'27" W, and an altitude of 960 m above sea level) with Ferralsol and Acrisol (IUSS, 2015), stored in pots with a capacity of 8 L. Experiment 2 was performed in a greenhouse used for commercial production located in the municipality of Caxias do Sul (geographical coordinates of 28°52'58" S; 51°02'38" W, and an altitude of 690 m above sea level) in Cambisol (IUSS, 2015). The temperature during the experiment varied between the minimum of 11.2 °C registered in October 2018 and the maximum of 29.0 °C registered in January 2019 (Embrapa Uva e Vinho, 2023).

The soils used in experiment 1 were collected at a 0–20 cm depth in Campos de Cima da Serra, and Vale do Caí regions, corresponding to a ferralsol and an acrisol, respectively. Experiment 2 was carried out on the ground in Cambisol in an area with a three-year history of tomato cultivation. The three soils were sampled (0–20 cm deep) and had their fertility parameters evaluated according to the methods described by Tedesco et al. (1995). Clay was determined by the densimeter method. Organic matter was determined using sulfochromic solution followed by colorimetry. Ca, Mg, Mn, and Al were extracted with KCl 1 $mol \cdot L^{-1}$. Al and H + Al contents were assesed by titration; and Ca, Mg, and Mn were determined by atomic absorption spectroscopy (AAS). S was extracted with 500 mg L^{-1} $Ca(H_2PO4)_2$, and assessed by turbidimetry with $BaCl_2$. B was extracted with hot water and determined by colorimetry with azomethine-H. K, P, Cu, and Zn were extracted with Mehlich-1 solution; K was determined by flame photometry; Cu and Zn by AAS; and P by the molybdenum blue method. Cation exchange capacity (CEC) was calculated by the summation of cations (K, Ca, and Mg), and base saturation was calculated based on the percentage of CEC composed of the cations other than Al (Susin et al., 2023).

The fertility parameters of the three soils tested in the experiment are compiled in Table 1.

Before the experiments, the soils were corrected for fertility and acidity (pH 6.0) following the recommendations of the Manual of Fertilization and Liming for the Soils of Rio Grande do Sul and Santa Catarina for tomato crops (CQFS, 2016).

Experimental design and treatments

The experiments were carried out in randomized blocks with four blocks containing three plants per treatment, totaling 12 plants per treatment. In experiment 1, all plants in the pots were evaluated. In experiment 2, the plots were composed of 5 plants, and each plot's two lateral plants/borders were discarded.

The treatments consisted of a control (without application of the fungus *Trichoderma* spp.), an application of *Trichoderma* spp. before seedling transplantation and monthly applications (one application per month) of *Trichoderma* spp. in tomato crops. The commercial product used in this experiment was a liquid produced with propagules of *Trichoderma harzianum*, *T. asperellum*, and *T. koningiopsis* at 1×10^{11} CFU·mL^{-1}, with the concentration checked before application.According to the manufacturer's recommendation, the product was applied at 300 mL·ha^{-1} on the surface of the soil/pots. Transplantation of tomato seedlings cv. 'Itaipava'® were carried out using seedlings grafted onto the TD1 rootstock, produced by the Hidroceres nursery (São Paulo, Brazil).

Table 1. Fertility parameters of the three soils used in the experiments

Parameter	Unit	Ferralsol	Acrisol	Cambisol
pH	-	6.1	5.0	5.1
pH-SMP	-	5.9	5.6	5.7
Organic matter	% w/v	5.6	1.0	1.1
Ca	cmol$_c$·dm^{-3}	9.4	0.5	6.9
Mg	cmol$_c$·dm^{-3}	6.5	0.5	2.0
Al	cmol$_c$·dm^{-3}	0.6	38.9	0.4
H+Al	cmol$_c$·dm^{-3}	4.9	6.9	6.7
P	mg·dm^{-3}	5.0	2.9	242.0
K	mg·dm^{-3}	287.0	27.0	252.0
S	mg·dm^{-3}	8.7	3.1	101.0
Zn	mg·dm^{-3}	4.0	4.0	7.9
Cu	mg·dm^{-3}	13.2	0.7	9.6
Mn	mg·dm^{-3}	15.7	9.7	12.5
B	mg·dm^{-3}	0.5	0.1	1.6
Na	mg·dm^{-3}	6.0	4.0	19.6
Effective CTC	cmol$_c$·dm^{-3}	16.7	1.8	9.9
CTC at ph 7	cmol$_c$·dm^{-3}	21.5	8.0	16.2
Saturation of Bases	%	77.7	13.4	59.9

CTC: cation exchange capacity.

In experiment 1, manual watering was performed daily to reach each soil's field capacity. The fertilization regime followed the recommendations of the Manual of Fertilization and Liming for the Soils of Rio Grande do Sul and Santa Catarina for tomato crops (CQFS, 2016), applied by fertigation. In experiment 2, fertigation was carried out according to the management adopted by the producer and using two drip strips with a 20 cm spacing between drippers placed on each side of the plant row.

Sampling procedures and evaluations

Plant nutrition (plant tissue nutrient content), development (height, fresh and dry mass of shoots), and tomato yield components of plant yield, number of fruits, and average fruit mass and diameter were evaluated. The test was carried out for 120 days after transplanting in experiment 1 and 180 days in experiment 2. In experiment 1, the cycle was reduced because of the higher temperatures (> 35 °C) inside the greenhouse, considering that it did not allow the opening of the side walls.

The nutritional evaluation of the plants was carried out at full flowering, collecting the fourth leaf from the tip of three plants per repetition and five repetitions per treatment. A second nutritional evaluation was repeated after 180 days, with the collection criterion being the removal of the leaf opposite the last bunch with full flowering. This evaluation was carried out only in experiment 2 because, in experiment 1, the plants did not reach this cultivation stage. Nutrient content in plant tissue was determined following the methods described by Malavolta (2006).

Relative to biometric parameters, plant height was measured from the insertion of the soil to its apex. Fresh plant mass was determined by cutting at the plant insertion in soil and weighting on a digital scale. To determine the dry mass, the plants were dried in an oven for 15 days at 50 °C, and the mass was weighed on a digital scale.

For yield components, during the entire production phase, the fruits were collected harvest point and weighed with a digital scale. Fruit diameter was measured using a digital calliper, and the number of fruits per plant was determined by counting.

Statistical analysis

Data were analysed for normality using the Shapiro-Wilk test. In the case of normality, the comparison of means was performed using the t-test ($p \leq 0.05$) and analysis of variance (ANOVA), and Tukey's test ($p \leq 0.05$) according to the number of treatments compared. In the case of non-normality, the variables were analysed using the U-Mann-Whitney test ($p < 0.05$) and the Kruskal-Wallis test ($p \leq 0.05$). All statistical analyses were performed using SPSS version 21.0 (IBM, USA).

RESULTS AND DISCUSSION

Results

The application of *Trichoderma* spp. application did not significantly impact the plant tissue contents of macro and micronutrients in tomato plants, regardless of the soil class. The plant tissue analysis results are compiled in Table 2.

Table 2. Contents of macro and micronutrients in the plant tissue of 'Itaipava'® tomato plants at full flowering stage, with different application regimes of Trichoderma spp. under protected environment, in Ferralsol, Acrisol, and Cambisol soils. Caxias do Sul, University of Caxias do Sul, 2021

Trichoderma spp.	N	Ca	Mg	P	K	S	Zn	Cu	B	Mn	Fe
application	$g \cdot kg^{-1}$						$mg \cdot kg^{-1}$				
Ferralsol (pot)											
Without	20.9 ^{ns}	22.9 ^{ns}	8.0 ^{ns}	4.0 ^{ns}	40.0 ^{ns}	5.2 ^{ns}	31 ^{ns}	16 ^{ns}	32 ^{ns}	71 ^{ns}	207 ^{ns}
With	19.7	21.8	7.2	4.2	32.6	5.6	28	17	37	68	209
CV (%)	27.4	29.3	20.8	12.2	21.0	17.3	1.0	18.5	16.4	55.4	9.5
Acrisol (pot)											
Without	29.0 ^{ns}	32.3 ^{ns}	5.3 ^{ns}	4.7 ^{ns}	50.6 ^{ns}	7.2 ^{ns}	33 ^{ns}	13 ^{ns}	42 ^{ns}	165 ^{ns}	228 ^{ns}
With	33.3	29.4	6.0	4.7	43.9	6.0	34	13	37	225	212
CV (%)	18.7	29.3	16.8	10.2	15.1	17.1	11.9	16.3	15.3	25.8	9.6
Cambisol (soil)											
Without	42.1^{ns}	52.7 ^{ns}	9.0 ^{ns}	5.4 ^{ns}	42.0 ^{ns}	6.1 ^{ns}	87 ^{ns}	110 ^{ns}	88 ^{ns}	154 ^{ns}	152 ^{ns}
With	43.9	54.0	9.6	5.9	42.5	5.9	80	129	90	141	161
CV (%)	7.8	14.3	8.1	8.3	18.6	7.2	15.6	15.2	5.2	13.7	13.5

Macronutrients (N, P, K, Ca, Mg, and S) are shown in $g \cdot kg^{-1}$, while micronutrientes (Cu, Zn, Mn, Fe, and B) are shown in $mg \cdot kg^{-1}$. ^{ns}: not significant by the statistical analysis at a 5% error probability. CV: Coefficient of variation.

In the evaluation of leaf nutrient contents at the end of the tomato crop cycle (180 days after transplanting) conducted in cambisol, it was observed that a single application of *Trichoderma* spp. increased the contents of N, P, and Cu. The monthly application increased the plant tissue contents of N, Cu, and Mn, as shown in Table 3.

Table 3. Contents of macro and micronutrients in the plant tissue of 'Itaipava'® tomato plants 180 days after transplanting with different application regimes of *Trichoderma* spp. under a protected environment, grown in a cambisol. Caxias do Sul, University of Caxias do Sul, 2021

Trichoderma spp. application	N	Ca	Mg	P	K	S	Zn	Cu	B	Mn	Fe
	$g{\cdot}kg^{-1}$						$mg{\cdot}kg^{-1}$				
Without	36.4 b	26.7 ^{ns}	5.0 ^{ns}	2.8 b	35.8 ^{ns}	7.0 ^{ns}	317 ^{ns}	17 b	47 ^{ns}	157 b	256 ^{ns}
Single	45.3 a	30.1	5.9	3.8 a	40.8	7.6	455	24 a	46	212 ab	243
Monthly	43.9 a	35.0	5.9	3.4 ab	34.0	7.6	414	26 a	56	228 a	334
CV (%)	14.1	23.1	13.1	15.9	15.8	8.3	27.3	19.4	17.5	24.4	58.4

Macronutrients (N, P, K, Ca, Mg, and S) are shown in $g{\cdot}kg^{-1}$, while micronutrientes (Cu, Zn, Mn, Fe, and B) are shown in $mg{\cdot}kg^{-1}$. Means in columns followed by the same lowercase letter do not differ statistically by Tukey's test at a 5% error probability ($p \leq 0.05$). ^{ns}: not significant by the statistical analysis at a 5% error probability. CV: coefficient of variation.

Among the macronutrients, N had the highest concentration in the tissues of the aerial part, and P had the lowest concentration. At the same time, among the micronutrients, the decreasing order of accumulation was Zn>Fe>Mn>B> Cu, regardless of the treatments.

According to Table 4, plant height and fresh and dry matter production at the end of the tomato cycle were not influenced by the application of *Trichoderma* spp. in the evaluated soils and conditions.

The parameters related to tomato production were also not influenced by the application of *Trichoderma* spp. in the soil, regardless of the soil and form of cultivation used, as compiled in Table 5.

It is important to note that the differences in the crop yield components observed in Table 5 regarding the cambisol and the other two soil types occurred because cambisol was tested in a field experiment. In contrast, acrisol and ferralsol were conducted in pots.

Table 4. Plant height and fresh and dry matter of aerial part of tomato cv. 'Itaipava'® plants at the end of the cycle (120 days for ferralsol and acrisol and 180 days for cambisol) with different *Trichoderma* spp. application regimes on the soil surface in a protected environment grown in ferralsol, acrisol, and cambisol soil types. Caxias do Sul, University of Caxias do Sul, 2021

Trichoderma spp. application	Plant height (m)	Fresh plant mass (g)	Dry plant mass (g)
Ferralsol (pot)			
Without	1.10 ^{ns}	178.84 ^{ns}	34.89 ^{ns}
Single	1.13	151.94	31.01
Monthly	1.13	170.34	34.89
CV (%)	12.80	21.74	19.05
Acrisol (pot)			
Without	0.91^{ns}	165.76 ^{ns}	30.59 ^{ns}
Single	0.90	146.91	29.60
Monthly	0.88	123.01	24.01
CV (%)	13.97	34.44	28.29
Cambisol (soil)			
Without	3.68 ^{ns}	2,283.33 ^{ns}	366.00 ^{ns}
Single	3.88	2,340.00	409.33
Monthly	3.95	2,210.67	406.00
CV (%)	7.91	19.15	18.3

^{ns}: not significant by the statistical analysis at a 5% error probability. CV: coefficient of variation.

Table 5. Crop yield components of tomato cv. 'Itaipava'® grown in ferralsol, acrisol, and cambisol with different *Trichoderma* spp. application regimes on the soil surface in a protected environment. Caxias do Sul, University of Caxias do Sul, 2021

Trichoderma spp. application	Number of fruits per plant	Fruit diameter (cm)	Average fruit mass (g)	Fruit yield (g·plant^{-1})
Ferralsol (pot)				
Without	13.00 ^{ns}	4.92 ^{ns}	62.11 ^{ns}	803 ^{ns}
Single	14.58	4.98	62.88	909
Monthly	13.75	5.08	66.42	873
CV (%)	19.17	6.69	18.25	18.94
Acrisol (pot)				
Without	14.67 ^{ns}	5.06 ^{ns}	65.95 ^{ns}	940 ^{ns}
Single	14.45	5.07	66.00	945
Monthly	14.17	4.89	61.86	876
CV (%)	25.57	5.90	14.38	22.41
Cambisol (soil)				
Without	63.93 ^{ns}	7.34 ^{ns}	181.28 ^{ns}	6,392 ^{ns}
Single	69.33	7.32	179.62	7,176
Monthly	65.47	7.42	180.20	6,803
CV (%)	13.04	7.8	22.44	18.71

^{ns}: not significant by the statistical analysis at a 5% error probability. CV: coefficient of variation.

Discussion

The nutritional content of macronutrients in plant tissue found in the full flowering stage in each soil was considered adequate according to Malavolta (2006), except for N and K in Ferralsol, which were below sufficient levels (30 g kg^{-1} and 40 g·kg^{-1}, respectively). According to Mello Prado et al. (2011), the elements whose nutritional requirements are highest for tomato plants are K, N, and Ca.

Regarding the micronutrients, B and Zn presented mean values below the adequate range for ferralsol and acrisol. Fe and Mn contents were considered insufficient in all soils, and Cu had excess values in Cambisol and Ferralsol. The observed results indicated that the nutrients provided via mineral fertilization were sufficient for most plant requirements until this stage of development. However, even in those below adequate values, the application of *Trichoderma* spp. did not affect the absorption of nutrients in any soil and growing conditions assessed.

Li et al. (2015) observed that the inoculation of *Trichoderma harzianum* (strain SQR-T037) significantly improved tomato seedlings' biomass and nutrient uptake. However, in this respective study, the seedlings were grown in nutrient-limited soil with a high pH (8.1) and packed in pots. In the present study, the soils were corrected to pH 6.0, and the nutrient contents were provided according to the official recommendation in force for each evaluated soil (CQFS, 2016). It should be noted that soil turning over and packaging in pots accelerates the decomposition of organic matter, and some nutrients may be temporarily immobilized by microbial biomass (Brandani & Santos, 2016). That can explain the lower contents of nutrients in plant tissue, especially in the ferralsol, whose organic matter content is higher than the other soil types (Table 1).

The increase observed in the concentration of foliar nutrients at the end of the tomato cycle with *Trichoderma* spp. in cambisol indicates that the fungus was efficient in helping plant absorption of nutrients through biochemical mechanisms or by root development, facilitating nutrient absorption. According to Samolski et al. (2012), qid74-induced modifications in root architecture increased the total absorptive surface, facilitating nutrient uptake and translocation of nutrients in the shoots and efficient use of NPK and micronutrients by the plants.

The increase in the absorption of N, P, Cu, and Mn observed in the cambisol using *Trichoderma* spp. was not reflected in the development of tomato plants. According to Sani et al. (2020), *Trichoderma* increased the plant growth and yield of tomatoes with half of the recommended NPK dose for the crop, unlike the present experiment in which the entire NPK fertilizer recommendation was provided. According to Li et al. (2015), the mechanisms by which *Trichoderma* regulates plant growth and mineral solubilization partially depend on the absence of a specific nutrient. This situation probably did not occur significantly in the present experiment because of the fertilizer dose.

Furthermore, according to Szczech et al. (2017) and Conte et al. (2022), the complexity of the relationships between the soil's chemical, physical, and biological components influence the efficiency of biological products and vice-versa. In this respective study, the resulting balance between the effects on chemical and biological soil parameters affected by the application of *Trichoderma* spp. provided an absence of effect in the development and productivity of the soybean crop.

Information about the adaptation and efficiency of applying *Trichoderma* spp. in field conditions and its interaction with the soil's chemical, physical, and biological quality and the resulting balance among them are scarce. Therefore, it is imperative to better understand the interaction dynamics of *Trichoderma* spp. with the soil and plant to allow for greater applicability and more confidence in the field dynamics of interaction (Smolińska et al., 2014; Mahfudz et al., 2019). Thus, further studies are needed to reduce the application of fertilizers and/or establish novel and corroborate already observed applications of *Trichoderma* spp. at longer intervals before planting. This is necessary to clarify further its potential for use and applicability in tomatoes and other horticultural crops in different soil types.

CONCLUSIONS

The application of *Trichoderma* spp. did not interfere with the production and development of tomato plants using mineral fertilizers following current recommendations and the absence of phytopathogens, regardless of the soil type, indicating its potential use without prejudice to tomato development and productive capacity in different soil types.

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