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Original Research

Potential of Composted Agricultural Wastes to Control Stem Rot and to Promote Growth in Tomato

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Abstract

Stem rot caused by *Sclerotium rolfsii* is one of the most devastating disease in tomato. An integrated management strategy implementing potential biotool is required to control this disease. Thus, five on-farm composts were evaluated for their ability to control tomato stem rot and to promote plant growth. The tested composts, except C_1, were effective in decreasing disease severity from 31.2 to 56.2%, with a significant similarity between pathogen-inoculated plants treated with C_3 and C_4 and disease-free and untreated controls. Treatments with C_2 and C_4 had significantly enhanced most tomato growth parameters: stem diameter, and dry weights of aerial part and roots. A similar effect was noted for C_3-based treatment on the plant height, the stem diameter, and the root dry weight where the recorded increments as compared to control were estimated at 16.9%, 23.8%, and 80%, respectively. Tested on *S. rolfsii*-free plants, compost $C_4$was the most efficient in improving all tomato growth parameters by 28.8, 8.54, 92.2 and 80% in their height, stem diameter and aerial part and root dry weights, respectively. A similar significant effect was observed on tomato plants challenged with composts C_2 and C_3. This work demonstrated the ability of composts to control tomato stem rot and to enhance the plant growth.

Keywords: composts, growth parameters, microbial community, physicochemical traits, *Sclerotium rolfsii*

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Introduction

The amounts of urban, industrial and agricultural wastes are increasing worldwide thereby becoming a threat to the environment and human health [1]. The increasing solid wastes are causing soil pollution and groundwater contamination [2, 3]. Thus, researchers have paid attention to develop new materials by utilizing wastes and by-products [4, 5]. So, composting is considered to be the most efficient treatment in producing an agronomically beneficial organic amendment and environmentally safe. This process is an environmentally safe, efficient and cost-effective treatment to recycle biodegradable materials, generally mixtures of organic materials, leading to a stabilized end-product named compost [6]. Compost is a renewable organic resource that can be widely used in agriculture for its beneficial effects on physical, chemical, biological, and biochemical soil properties, and explored for disease-management and plant health improvement [7-9]. In fact, soil amendment with compost does not only provide macro- and micronutrients to soil [10], but also raises its stock of organic carbon [11], increases its water holding capacity [12], improves its structure [13], and ameliorates crop yield by the suppression of soilborne pathogens [14]. The disease-suppressive ability of composts depends on their microbial consortia and the competitive capacity of their associated beneficial microorganisms against target plant pathogens. Compost microbiota diversity and relative abundance depend on the origin and the quality of raw materials available for composting [15].

Southern blight disease or stem rot, caused by the widespread fungus *Sclerotium rolfsii*, is considered one of the most disease affecting a vast host range of over 500 plant species, including vegetables, leguminous, medicinal, ornamentals, and grass crops in many regions of the world [16, 17]. This fungus survives on decayed plant material in the soil as sclerotia, which are the primary inoculum for disease initiation under conducive conditions and its main dispersal propagule [18]. Sclerotia germinate and attack surrounding host plants, where the pathogen attacks directly healthy plant tissues using various cell-wall degrading enzymes and other metabolites [19]. It infects the stem bases at or near the soil surface and forms dark brown lesions, spreading quickly to girdle the stem [20]. Infected plants may turn into drooped and the whole plants wilted, causing severe economic losses due to plant death [17, 18, 21]. Thus, reported losses attributed to this disease are estimated up to 100% [22]. So, as its broad host range, its ability to survive several years in the soil, and the unavailability of resistant cultivars, disease control relies on the use of fungicides which may have adverse environmental and toxicological effects in addition to the eventual development of resistant strains [23]. Thus, there are increased interests in the investigation of novel eco-friendly and sustainable alternatives for controlling this serious soilborne disease. The effectiveness of composts derived from a combination of agricultural and agro-industrial wastes may vary depending on target plant pathogens [24]. In fact, it has been demonstrated that composts are capable of suppressing soilborne plant pathogens more efficiently than fungicides such as tebuconazole and vinclozolin in controlling the onion white rot induced by *Sclerotinia cepivorum* and the lettuce root rot caused by *Sclerotinia sclerotiorum*, respectively [25, 26]. Many reports have demonstrated the suppressive capacity of organic composts against various soilborne diseases induced by *Fusarium oxysporum*, *Rhizoctonia solani*, *Verticillium dahliae*, *Sclerotinia minor*, *Pythium ultimum* associated to different host plants [16, 24, 27]. However, there have been few studies conducted on the compost ability to control stem rot disease caused by *S. rolfsii*.

Therefore, the aims of this study include: (1) assess the ability of composts derived from various animal manures and green wastes and/or olive-mill solid waste to control stem rot caused by *S. rolfsii* and to promote tomato growth, (2) evaluate physicochemical and microbiological parameters related to different composts to define intrinsic compost characteristics associated to their potentialities. The flowchart of this study was showed in Fig. 1.

Materials and Methods

Plant Material

Tomato seedlings (cv. Rio Grande) were grown in 77-hole plastic pots (7 cm diameter), filled with horticultural peat (Klasmann-Deilmann, Biosubstrate, Germany). They were maintained in a greenhouse at 25±5ºC air temperature with 60-70% relative humidity and 16 h photoperiod. They were watered at constant day intervals until reaching the two-true-leaf growth stage. Seedlings with relatively similar heights were used for all experiments.

Composts

Bioassays were carried out using five composts produced following an on-farm composting process. The composting system was carried out in five parallel open-windrows with 2.0 m width, 1.5 m height, and 10 m length. Composts were turned mechanically to provide aeration and to improve homogeneity, and water was used as humidifying agent during all the composting period. They were identified as follows: C_1 – 30% Cattle, 30% chicken and 30% sheep manures mixed with 5% green waste and 5% olive-mill solid waste; C_2 – 70% Cattle and 25% chicken manures mixed with 5% olive-mill solid waste; C_3 – 70% Cattle and 25% chicken manures mixed with 5% green waste; C_4 – 70% Cattle and 25% sheep manures mixed with

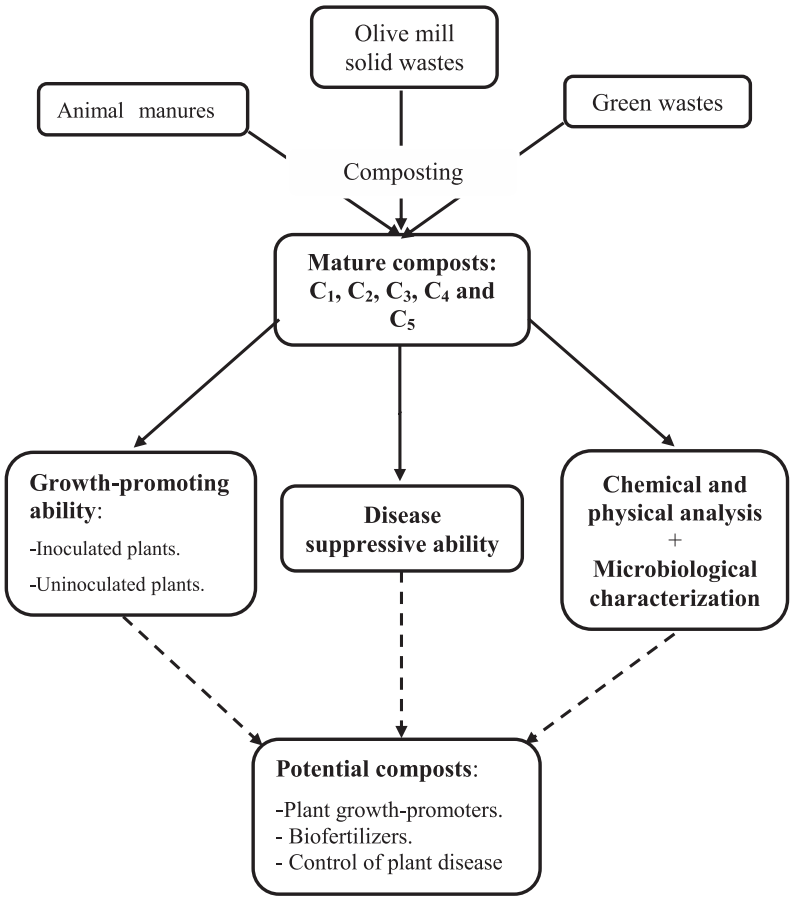

Fig. 1. Flowchart of this study.

5% olive-mill solid waste; C_5 – 70% Cattle and 25% sheep manures mixed with 5% green waste. They were prepared and allowed to mature for eight months using windrow-composting system. The tested composts were mature and stable in terms of microbiological and physico-chemical characteristics with no phytotoxic effect.

Pathogen Culture and Inoculum Preparation

Three *S. rolfsii* isolates, previously isolated from potato and artichoke plants showing typical stem rot symptoms, were used in the current study. Identification and pathogenicity of tested isolates were previously determined [28, 29].

S. rolfsii isolates were grown on Potato Dextrose Agar (PDA) medium at 30°C in the dark for 7 days before being used for the antifungal bioassay [29].

For the pathogen inoculum production, 15 mycelial plugs (6 mm in diameter) of each *S. rolfsii* isolate, removed from 7-day-old cultures, were added to 500-ml Erlenmeyer flasks containing 200 g sand corn-meal medium and incubated in the dark at 30ºC for 20 days [30]. The mixed inocula, containing all three isolates, were used for tomato seedling inoculation.

Screening of Disease Suppression Ability

The ability of the five tested composts to control tomato stem rot was evaluated on tomato seedlings. Potting-mixtures were prepared with 80% of commercial peat (v/v) and 20% of the tested compost (v/v) [10]. *S. rolfsii* mixed inocula (20 days old), was mixed thoroughly with additional clean sharp sand at 5% (w/w), and applied to top 2-cm depth of the pot mixture [30].

Seedlings were transplanted into individual pots (14.5 × 12.5 cm) and watered periodically with tap water to avert water stress and guarantee optimal growth. Five replicates were used for each individual treatment. Pots fully filled only with peat were used as non-amended controls (uninoculated control and inoculated control). Tomato seedlings were grown under the same conditions as described above.

At 45 days post-inoculation with *S. rolfsii*, disease severity was rated based on a 1-5 scale [31], where 1 = no stem lesion, 2 = lesions girdled ≤ 25% of the stem circumference, 3 = lesions girdled 26-50% of the stem circumference, 4 = lesions girdled > 51% of the stem circumference, and 5 = stem completely girdled. Plant height, stem diameter, root and aerial part dry weights were also noted. The whole experiment was repeated twice.

Screening of Growth-Promoting Ability

Five different composts were assessed for their plant growth-promoting potential. Tomato seedlings (cv. Rio Grande; two-true leaf stage) were potted in plastic pots (14.5 × 12.5 cm) containing a mixture of commercial peat (80%, v/v) and tested compost (20%, v/v) [27]. They were maintained under the same conditions as described above and periodically watered with tap water to avert water stress. Control seedlings were transferred to individual pots filled only with peat. All bioassays were carried out using five pots per individual treatment. At 45 days post-planting, different growth parameters were recorded for all tomato plants (plant height, stem diameter, and aerial part and root dry weights). The whole experiment was repeated twice.

Chemical and Physical Analyses

Electrical conductivity (EC) and pH were measured on aqueous extracts (1:5 w/v) from the tested composts according to ISO 11265:1994 and ISO 10390:2005, respectively. Water content was determined after desiccation for 24 h at 105ºC according to ISO 17892-1:2014. Organic matter and total organic carbon were analysed by loss-on-ignition at 550ºC during 5 h [32]. Total N was determined according to Kjeldahl method [33]. The content of different elements (K, Na and Ca) was determined using flame photometer [33]. Phosphorus concentration was measured on compost with UV-visible spectrophotometer as described by Milinkovic et al. [34]. Analysis of composts was conducted in triplicate.

Microbiological Characterization

The microbial population in the tested composts was determined using the spread plate and the plate count agar methods of serial dilutions. PDA medium amended with streptomycin sulphate (300 mg/l) and PCA medium were used for the isolation of total fungi and total bacteria, respectively. Each compost was ten-fold diluted (10^{-2}-10^{-10}) and 100 µl of each compost extract dilution were pipetted and spread, using sterilized bent glass rod, on the selective media (PDA for fungi and PCA for bacteria) [35, 36].

All plates were incubated in the dark at 35±2ºC. The number of colonies growing on the culture media was counted after 72 h of incubation. Colonies in plates with 30 to 300 colonies were counted and colony forming units (c.f.u. g^{-1}) were calculated as described in ISO 7218: 2007.

Statistical Analysis

The data were subjected to one-way analysis of variance (ANOVA) using the SPSS (Statistical Package for the Social Sciences) software for Windows (version 20.0). The *in vivo* experiments were performed according to a completely randomized design with one factor (composts) and each individual treatment was replicated five times. Means were compared using Duncan's Multiple Range test at $P \leq 0.05$. Each bioassay was repeated twice yielding similar results. So, one representative trial of each experiment was reported. Correlations between disease severity and tomato plant growth parameters were performed out using bivariate Pearson's test at $P \leq 0.05$.

Results

Growth-Promoting Potential of Tested Composts on *S. rolfsii*-Inoculated Tomato Plants

Variance analysis revealed that tomato growth parameters (height, stem diameter, aerial part and root dry weights), noted 45 days post-inoculation with *S. rolfsii*, varied significantly depending on tested compost treatments. Overall, all tested composts exhibited similar effectiveness in enhancing the stem diameter by 20.2-23.8%, compared to *S. rolfsii*-inoculated (IC) and untreated control (UC) (Table 1). As for their ability to promote plant height, C_3-based amendment induced the highest increase estimated to 16.9% and 14.3% over the inoculated and uninoculated controls, respectively. Nevertheless, the other tested composts did not induce a significant enhancement in this parameter.

A significant improvement in the aerial part dry weight, by 43.2-67.4% over pathogen-inoculated control, was recorded on plants amended with all tested composts, except C_1. The highest increments (52.8 and 67.4%) were recorded following C_2 and C_4 treatments, respectively, compared to inoculated control. An interesting effect was also observed on C_3 and C_5 treatments showing, respectively, an increase of 45.9 and 43.2% (Table 1). Furthermore, the root dry weight was significantly improved by 40.3 to 91.2% over the inoculated control following treatments with the five tested composts with C_2, C_3 and C_4 being the most active leading to 79, 80 and 91.2% increase of this parameter, respectively. C_5 had also significantly enhanced the root weight by 61% and 28.4%, versus inoculated and uninoculated controls, respectively (Table 1).

Disease Suppression Potential of Tested Composts

Stem rot severity noted on tomato plants, 45 days post-inoculation with *S. rolfsii*, varied significantly (at $P \leq 0.05$) depending on tested treatments. As shown in Figure 2, a significant decrease by 31.2 to 56.2% versus inoculated control was noted on tomato plants infected with *S. rolfsii* and amended with the majority of tested composts (except C_1). The highest reductions in disease severity by 37.5, 43.7, 56.2, and 31.2% compared to pathogen-inoculated control, were achieved using composts C_2, C_3, C_4 and C_5, respectively. It should be

Table 1. Growth-promoting potential of the tested composts on tomato plants cv. Rio Grande inoculated with *Sclerotium rolfsii* noted 45 days post-inoculation as compared to controls.

Composts	Plant height (cm)	Stem diameter (mm)	Aerial part dry weight (g)	Root dry weight (g)
UC	35.7±0.5 bc	5.8±0.19 ab	4.28±0.06 c	2.25±0.06 c
IC	34.9±1.9 bc	5.08±0.14 b	3.83±0.17 c	1.8±0.03 d
C_1	36.9±1.1 bc	6.16±0.22 a	4.31±0.10 c	2.53±0.17 c
C_2	36.44±0.9 bc	6.1±0.18 a	5.85±0.24 ab	3.22±0.05 ab
C_3	40.8±1.2 a	6.29±0.44 a	5.59±0.17 b	3.24±0.08 ab
C_4	37.2±1.2 b	6.23±0.26 a	6.41±0.35 a	3.44±0.15 a
C_5	33.4±0.7 bc	6.16±0.21 a	5.49±0.40 b	2.89±0.10 b

UC: Uninoculated and untreated control; IC: Inoculated with *S. rolfsii* and untreated control.
Results are presented as means±SE (n = 5, $P \leq 0.05$).
For each column, values followed by the same letter are not significantly different according to Duncan's Multiple Range test (at $P \leq 0.05$).

highlighted that disease severity noted on tomato plants inoculated with *S. rolfsii* and treated with C_3 and C_4composts was significantly comparable to that of the untreated and disease-free control (Fig. 2).

Correlation between Stem Rot Severity and Growth Parameters

Pearson's correlation analysis indicated that the decline in stem rot severity, estimated based on a necrosis index, was associated with an increment in the majority of measured growth parameters. In fact, this analysis revealed that the stem diameter (r = -0.368; n = 35; $P = 0.03$), the aerial part dry weight (r = -0.338; n = 35; $P = 0.047$), and the root dry weight (r = -0.358; n=35; $P = 0.035$) were negatively correlated to the necrosis index. Nevertheless, no significant correlation was reported between plant height and disease severity (r = -0.202; n = 35; $P = 0.246$).

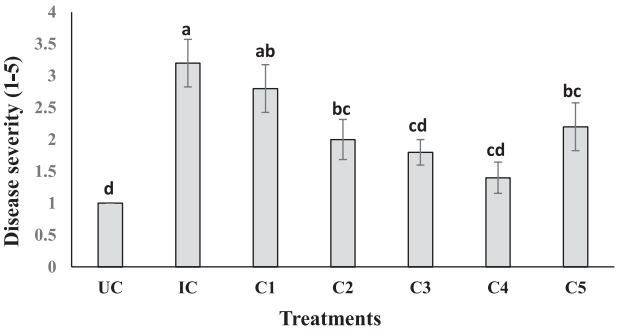

Fig. 2. Effect of various composts on stem rot severity noted on tomato cv. Rio Grande plants 45 days post-inoculation with *Sclerotium rolfsii* as compared to controls.
UC: Uninoculated and untreated control; IC: Inoculated with *S. rolfsii* and untreated control. Results are presented as means±SE (n = 5, $P \leq 0.05$). Bars sharing the same letter are not significantly different according to Duncan's Multiple Range test (at $P \leq 0.05$).

Growth-Promoting Potential of Tested Composts on Pathogen-Free Tomato Plants

ANOVA analysis revealed a significant variation (at $P \leq 0.05$) in tomato growth parameters (plant height, stem diameter, aerial part dry weight, and root dry weight), noted 45 days post-planting, depending on tested treatments. In fact, as shown in Table 2, plants amended with composts C_2, C_3, and C_4 were significantly 24.4%, 22.1% and 28.8% taller than control, respectively.However, $C_1$and C_5 had no significant effect on plant height compared to the control. Composts C_3, C_4, and C_5 had enhanced the stem diameter by 8.8, 8.5, and 9.7% over control. C_4 led to the highest increment in the aerial part dry weight by 92.2%. A significant effect was also observed on tomato plants challenged with composts C_2, C_3, and C_5, which had significantly improved the aerial part dry weight by 49.5, 56.7, and 45.2%, respectively. An interesting enhancement of root dry weight, by 75.2 to 94.4% over control, was reported on plants treated with tested composts (except C_1), as compared to the uninoculated and untreated control. However, C_1 did not exhibit any significant effect on all plant growth parameters when compared to the untreated control (Table 2).

Physicochemical Characteristics

Physicochemical characteristics and nutrient contents of tested composts are reported in Table 3. The type of compost had a significant effect (at $P \leq 0.05$) on the average pH and EC values (Table 3). The pH was relatively neutral and was stabilized at 6.9-7.4. Compost C_5, produced from cattle manure with sheep manure and green waste, had the highest pH value but C_2, issued from cattle and chicken manures associated to olive-mill solid waste, had the lowest pH value at maturity. The EC of 5% green waste-based composts C_1, C_3 and C_5 was significantly greater than the EC of the composts C_2 and C_4 based on 5% olive-mill solid

Table 2. Plant growth-promoting potential of the tested composts noted on pathogen-free tomato cv. Rio Grande plants, 45 days post-planting, compared to the untreated control.

Composts	Plant height (cm)	Stem diameter (mm)	Aerial part dry weight (g)	Root dry weight (g)
UC	35.7±0.54 c	5.79±0.19 bc	4.28±0.06 d	2.25±0.06 b
C_1	39.9±1.7 bc	5.27±0.19 c	5.36±0.44 cd	2.55±0.16 b
C_2	44.4±0.4 a	6.27±0.14 ab	6.39±0.32 bc	3.94±0.36 a
C_3	43.6±1.0 ab	6.5±0.16 a	6.70±0.37 b	4.37±0.35 a
C_4	46±2.2 a	6.48±0.12 a	8.22±0.49 a	4.05±0.36 a
C_5	39.7±2.4 bc	6.55±0.24 a	6.21±0.47 bc	4.17±0.45 a

UC: Uninoculated and untreated control. Results are presented as means±SE (n = 5, $P \leq 0.05$).
For each column, values followed by the same letter are not significantly different according to Duncan's Multiple Range test (at $P \leq 0.05$).

waste. However, moisture contents [F(4, 10) = 1.458; P = 0.286] and organic matters [F(4, 10) = 0.590; P = 0.678] did not vary significantly depending on the tested composts (Table 3).

Sheep manure-based composts, C_4 and C_5, had the highest total N contents with 1.82% and 1.85%, respectively. Nevertheless, N becomes less available in composts C_1 (1.05%) and C_2 (0.92%). The concentrations of P and K were significantly higher (at $P \leq 0.05$) in the composts C_1 (0.104%) and C_2 (0.102%) and in C_1 (1.32%) and C_3 (1.29%), respectively. However, these constituents were low in compost C_5. The Na concentration ranged between 0.4 and 0.45%. The most important Ca level was recorded in compost C_4 (3.39%), followed by C_1 (2.94%) and C_5 (2.99%) (Table 3).

Microbiological Characteristics

The Counts of the culturable microbial populations in the tested composts are given in Table 4. The bacterial and fungal populations varied significantly much across the five composts (at $P \leq 0.05$). Populations of total culturable bacteria were statistically larger in C_3 (10.8×10^5 c.f.u. g^{-1}) followed by C_4(3.92×10^5 c.f.u. g^{-1}) but C_5 exhibited lower value with 1.65×10^5 c.f.u. g^{-1}. They were moderate in C_1 and C_2 with 2.92×10^5 c.f.u. g^{-1} and 2.45×10^5 c.f.u. g^{-1}, respectively. Most culturable fungi were recorded in C_2 cultures (11.6×10^4 c.f.u. g^{-1}), whereas the lowest population level was noted in C_4 with 6.6×10^4 c.f.u. g^{-1}. However, composts C_1 and C_3 had significantly the lowest fungal counts estimated at 4.0×10^4 and 4.7×10^4 c.f.u. g^{-1}, respectively (Table 4).

Discussion

Composts, produced from animal and plant debris, are perceived as potential alternatives to agrochemicals for improving plant growth and health by enhancing the soil physico-chemical properties and their nutriactive effects and nutrient content [37, 38]. In addition to their high agronomic values, several studies reported their potential exploration and use as biopesticide and their suppressive abilities against various soilborne and airborne plant diseases [35, 39]. This study highlights

Table 3. Analytical characterization of composts used in the current experimental study.

Parameters	C_1	C_2	C_3	C_4	C_5
pH	7.1±0.06 b	6.9±0.06 c	7±0.1 b	7.1±0.08 b	7.4±0.06 a
Moisture (%)	26.83±0.21 a	28.8±0.20 a	28.33±1.42 a	29.87±4.45 a	26.13±1.22 a
Organic matter (%)	41.3±4.72 a	40.13±2.72 a	43.4±2.16 a	42.8±2.11 a	42.37±1.87 a
Electrical conductivity (mS/cm)	4.47±0.73 ab	3.92±0.22 bc	5.22±0.03 a	3.6±0.49 c	4.8±0.12 a
Total N (%)	1.05±0.11 c	0.92±0.06 c	1.43±0.05 b	1.82±0.02 a	1.85±0.04 a
P (%)	0.104±0.01 a	0.102±0.002 a	0.052±0.006 b	0.06±0.004 b	0.061±0.009 b
K (%)	1.32±0.02 a	1.2±0.003 b	1.29±0.002 a	1.2±0.01 b	1.15±0.011 c
Na (%)	0.41±0.042 ab	0.4±0.007 b	0.45±0.003 a	0.44±0.003 a	0.41±0.009 ab
Ca (%)	2.94±0.07 bc	2.53±0.06 d	2.76±0.09 cd	3.39±0.07 a	2.99±0.03 b

Results are expressed on dry matter as means±Standard Error.
For each parameter, values followed by the same letter are not significantly different according to Duncan's Multiple Range test (at $P \leq 0.05$).

Table 4. Microbial population density in the tested composts noted after 72 h of incubation at 35°C in the dark.

Composts	Microbiological features	
	Bacteria (10^5c.f.u. g^{-1})	Fungi (10^4c.f.u. g^{-1})
C_1	2.92 c	4.0 d
C_2	2.45 c	11.6 a
C_3	10.8 a	4.7 cd
C_4	3.92 b	6.6 b
C_5	1.60 d	5.2 c

Compost was 10-fold diluted (10^{-2}-10^{-10}) and 100 µl of each dilution spread on PDA medium for fungi and on PCA medium for bacteria.

the efficiency of five composts, produced from different raw materials, to promote growth and to control stem rot of tomato plants.

Five composts were tested for their capacity to suppress stem rot disease induced by *S. rolfsii*. Thus, all composts, except C_1, were shown effective in controlling the plant disease where $C_3$and C_4 exhibited the highest suppressive potential. Their incorporation to the growing substrate had significantly decreased disease severity and treated plants were significantly comparable to the unamended and uninoculated control ones. The present results confirmed earlier reports on the suppressive effects of composts, based on orange fruit waste, grass clippings and grape marc, against *S. rolfsii* in turfgrass [40]. Moreover, Danon et al. [41] demonstrated that the disease incidence on bean germination was decreased by 65 to 70% using compost compared to the inoculated and untreated controls. The disease-suppression ability of composts was also reported in many previous studies focused on many soilborne pathogens associated to various crops [35, 39, 42]. The tested composts also exhibited growth-promoting effects on inoculated and uninoculated tomato plants. All composts had significantly similar effect on the stem diameter compared to *S. rolfsii*-inoculated and untreated plants. A significant enhancement in the aerial part dry weight was noted on plants challenged with all tested composts, except C_1, with the highest increase recorded following C_2 and C_4 amendments. Moreover, composts C_2, C_3 and C_4 showed the highest growth-promoting potential as measured by their effects on the root dry weight. Similar effects were induced by C_2, C_3 and C_4 treatments on the plant height, the stem diameter, and the root dry weight of uninoculated plants. In the current study, the decrease in disease severity was associated with an increase in the growth parameters (stem diameter, aerial part and root dry weights). These results are in agreement with those of Ntougias et al. [43] and Tubeileh and Stephenson [24] who demonstrated the highest disease suppression potential of olive pomace-based-composts against *Phytophthora nicotianae* and *Verticillium dahliae*. Moreover, Shafique et al. [44] reported that vermicompost is a best-suited growing media, which not only improved the soil health but also promoted Marigold (*Tagetes erectus*) plant growth.

This disease-suppression ability depends mainly on the physiology and the biology of target pathogens, pathosystems, and plant responses to infection [45]. Variability may be further due to intrinsic compost characteristics [27]. In fact, Scheuerell et al. [46] tested 36 different composts against three distinct pathosystems and Termorshuizen et al. [47] compared the effect of 18 composts on 7 pathosystems. These studies demonstrated that disease suppressiveness varied rather across composts and target pathogen species. The disease-suppressive properties of composts can be affected by their physicochemical characteristics either directly on plant pathogens and associated microbial communities, and/or indirectly on plant systems through the improvement of soil structure, the supply with soluble nutrients, the increase of water retention and porosity, and other factors [48-50]. Siddiqui et al. [51] showed that the improved nutritional status following compost amendments may protect the plant against diseases.

In the present investigation, the compost C_4 being the most effective in enhancing the plant growth, had the highest contents of N, Na and Ca with a moderate K concentration. C_2, having a similar effect on inoculated tomato plants, had only an important P concentration with reasonable K content. However, these composts had the lowest electrical conductivity (3.92 mS/cm for C_2 and 3.6 mS/cm for C_4) which may be involved in the growth-promoting effect recorded on pathogen-inoculated tomato plants. These results confirmed other studies reporting that media amended with compost with EC values in the range of 1 to 5 mS/cm are suitable for plants [52]. Therefore, the suppressive effect of olive-mill solid waste compost, such as C_2 and C_4, seems to be largely due to the diversity of their microbial populations. Such results were consistent with other studies reporting the suppressive effectiveness of specific active microbial group in the composted solid olive mill against plant pathogens such as *Verticillium dahliae*, *Fusarium oxysporum* f. sp. *lycopersici*, *Sclerotinia sclerotiorum*, *Pythium ultimum*, and *Phytophthora infestans* [16, 39].

Mature composts were reported to be suppressive towards sclerotial germination of *S. rolfsii* only when they were weakened at the higher pH level in the presence of NH_3 [53]. Pugliese et al. [54] showed that the most appropriate parameters to predict plant disease suppression varied on target pathogens i.e.*O*-aryl C, extractable carbon, and C:N ratio for *Pythium ultimum*; *N*-acetyl-glucosaminidase, alkyl/*O*-alkyl ratio, and chitobiosidase enzymatic activities for *Rhizoctonia solani* and electrical conductivity for *Sclerotinia minor*. Composts with high levels of ammonium-N and a low C:N ratio are shown able to increase Fusarium wilt

whereas composts with a high C:N ratio are more efficient in decreasing Fusarium wilt severity [49]. According to Coelho et al. [35], the physicochemical properties of composts (pH, electrical conductivity, organic matter, and nitrogen content) are more involved in the development of their microbiota. The organic matter of the compost contributed to the rise of bacterial, fungal, and actinomycetes populations [55].

The disease-suppressive effect displayed by composts is principally related to the biological activity of their associated microbial populations colonizing their organic matter [56, 57], but also to their capacity to enhance plant nutrition status and growth [58]. In fact, resident microbial community has been reported to be the main component for compost-based biological control of plant diseases through different mechanisms related to the ecological relationships among the associated microorganisms [53]. Large and diverse microbiata including filamentous fungi (*Gliocladium*, *Trichoderma*, *Fusarium*, *Penicillium*, *Aspergillus*), bacteria (*Bacillus*, *Paenibacillus*, *Pseudomonas*, *Enterobacter*, *Arthrobacter*), actinomycetes (*Streptomyces*), *Oomycetes* (*Pythium*), yeasts (*Saccharomycetes*), and *Zygomycetes* (*Rhizopus*) is crucial to an effective disease control displayed by composts. They are potentially capable to efficiently control Sclerotium, Pythium and Rhizoctonia damping-off, Phytophthora root rot and Fusarium and Verticillium wilts [39, 58, 59]. Mechanisms of disease control have been reviewed and recalled: microbiotasis and fungistasis, competition for the infection site and for nutrients, antibiosis, hyperparasitism and predation, activation of induced systemic resistance, improvement of plant vigor and nutrition, induction either separately or in combination of disease resistance [16, 50]. The first three mechanisms affect directly the pathogen and reduce its survival, but the remaining mechanisms act indirectly through the plant and disturb the disease cycle [53, 57]. Fungistasis and microbiostasis inhibit plant pathogens development in the soil without killing them, owing to nutrient deficiency caused by an expanded microbial biomass [60]. Competition for nutrient and/or space in the rhizosphere can be related to metabolic activity of plant pathogen being controlled by the nutrient availability uptake surrounding roots [61]. The availability and concentration of nutrients and carbon compounds (such as lignin, sugars, lipids, cellulose, chitin, etc.) within compost plays a critical role in the regulating activities of these microorganisms [62]. Antibiosis involved the production of non-specific and/or specific metabolites and antibiotics due to the involved microbial activity such as volatile compounds, lytic enzymes, or other toxic substances [60]. Antibiotic production by various strains of *Gliocladium virens*, *Trichoderma harzianum*, *Bacillus subtilis*, *Pseudomonas* sp. and *Streptomyces* sp. has been implicated in the suppression of *S. rolfsii*, *Pythium ultimum*, *Fusarium oxysporum*, *F. solani* and *R. solani* [23, 63]. Unlikely to microbiostasis, microbial hyperparasitism has mostly been recorded for plant pathogens with propagule diameter more than 200 µm such as *R. solani* and *S. rolfsii* [60]. Phytopathogens can be attacked and colonized by microbiota resulting in the lysis of their cells or their death (hyperparasitism), and/or they can be killed by phagocytosis [16, 64]. The parasitic effect consists of four phases: chemotropic growth, recognition, attachment, and degradation of the host cell walls through the lytic enzyme production [65]. These stages are influenced by the decomposition level of organic matter and the presence of glucose and other nutrients, which inhibit the production of lytic enzymes used to kill pathogens [64].

It is important to emphasize that plants grown in disease-suppressive compost media are colonized by high variety of microorganisms from which numerous strains were able to induce systemic resistance in plants [59]. In addition to that, microbiota can contain plant growth-promoting rhizobacteria (PGPR) and various endophytes which are also able to improve the vegetative vigor and plant growth rending the host more tolerant or resistant to plant disease through the production of microbial metabolites like siderophores, salicylic acid, lipopolysaccharides, and antibiotics [66]. Plant protection by inducing systemic resistance against phytopathogens like *S. rolfsii*, *Alternaria solani*, *Stemphyllium solani*, *Xanthomonas campestris*, *Oidium lycopersici* and *Corynespora cassiicola* by beneficial microbes has been reported [67, 68]. The strengthening of plant tissue by induced resistance activation might be protected from the hydrolytic enzymes produced by the pathogen [69, 70]. There are some studies demonstrating that the lignin accumulation was effective in suppressing *Phomaexigua*, *Botrytis cinerea* and *F. oxysporum* in flax [71]. Enhanced expression of PR genes in tomato plants against *S. rolfsii* has been reported to have co-linear relations with resistance [67].

Conclusion

The present study emphasized the importance of organic composts, from agricultural and agro-industrial wastes, to control the tomato stem rot disease, caused by the soilborne fungal pathogen *S. rolfsii*, and to promote tomato growth. A significant reduction in the disease severity was observed after the application of the composts, based on cattle manure, chicken or sheep manure and olive-mill solid or green wastes, with an average decrease ranging between 37.5 and 56.2%, compared to untreated and inoculated control. Additionally, these composts are potential sources acting as plant growth-promoters on both pathogen-free and *S. rolfsii*-inoculated tomato plants. These effects may be attributed to the diversity of their microbial community and the availability of some nutrients. Thus, the efficient composts displaying biocontrol and growth-promoting abilities may be valorized for the control

of several other soilborne plant pathogens infecting tomato or other crops and could be implemented in an integrated disease management program. Further work is needed to isolate and identify the beneficial bioagents from disease-suppressive and growth-promoting composts.

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Conflict of Interest

The authors declare that they have no conflict of interest.

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