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Growth, yield and fruit quality of tomato under different integrated management options against *Tuta absoluta* Meyrick

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All relevant data are within the paper and its Supporting Information files.

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The authors declare no competing interests.

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Abstract: This study evaluated the effect of entomopathogens and plant extracts, used against *Tuta absoluta*, on growth, yield, and fruit quality of tomato. Two field trials were carried out in a randomised compled block design, replicated thrice. The treatments were *Steinernema* sp. RW14-M-C2a-3, *Steinernema* sp. RW14-M-C2a-3, Metatech®WP (*Metarhizium anisopliae*, Strain FCM Ar 23B3), Beauvitech®WP (*Beauveria bassiana*, Strain J25) as entomopathogens, *Tephrosia vogelii* and *Phytolacca dodecandra* as plant extracts, and azadirachtin 0.03% EC. Imidacloprid and water also were included as positive and negative controls, respectively. The best growth and yield parameters were recorded with the entomopathogens and azadirachtin, which were insignificantly different in most cases. The increase in yied of healthy fruit per plant (average of two trials) compared to the negative control (water spray) was 11.4, 10.8,10.1, 9.6, 3.96, 2.2, 11.7 and 2.4 folds for *Steinernema* sp. RW14-M-C2a-3, *Steinernema* sp. RW14-M-C2a-3, Metatech®WP, Beauvitech WP, *T. vogelii, P. dodecandra*, azadirachtin, and imidacloprid, respectively. There was no significant difference in number of leaves per plant and fruit quality parameters. The entomopathogens and azadirachtin, which exhibited a capacity to enhance tomato growth and reduced yield losses due to *T. absoluta*, are recommended to be included in integrated pest management programme on tomato.

1. Introduction

The increasing world population requires food security, which can be partly achieved by reducing the portion of food lost every year as a result of pests (Kumar and Omkar, 2018). However, yield losses inflicted by crop pests have been observed to increase constantly despite different strategies being implemented globally (Dhaliwal *et al*., 2010).

Tomato (*Solanum lycopersicum* L.) is one of the most popular vegeta-

bles in the world and its fruits are a rich source of nutrients and health-promoting compounds (Luna-Guevara *et al*., 2014; Asensio *et al*., 2019). One average-sized tomato fruit offers 40% and 20% of the recommended daily amount of vitamins C and A, respectively. It also provides a significant amount of dietary fibres and minerals like calcium and potassium (Tigist *et al*., 2013). Furthermore, the antioxidant activity of ascorbic acid, carotenoids, and phenols protects humans against cancers and cardiovascular diseases (Tigist *et al*., 2013; Luna-Guevara *et al*., 2014). Therefore, any technology used on tomato crop has to be investigated not only for its effect on growth and yield but also on fruit quality parameters.

Several pests have been reported to attack tomato throughout its production cycle (Kumar and Omkar, 2018). The tomato leaf miner, *Tuta absoluta* Meyrick (Lepidoptera: Gelechiidae), was recognised among the major pests since 1964 in Argentina from where it invaded the rest of South America (Desneux *et al*., 2010). Following Spain invasion during the year 2006, the pest spread to many other European countries, the Middle East, more than 40 African countries, and almost all Southern West and Central Asian countries neighbouring China, the world's largest tomato producer (Biondi *et al*., 2018; Mansour *et al*., 2018). In only one decade, *T. absoluta* spread drastically and the world tomato production area under its invasion increased from 3% to 60% (Biondi *et al*., 2018). In Rwanda, *T. absoluta* was first recorded in Bugesera District in 2015 (FAO, 2015), after which it quickly spread in all tomato production areas of the country. The damage inflicted by *T. absoluta* affects negatively its growth and development and can lead to total crop failure (Desneux *et al*., 2010; Biondi *et al*., 2018). This calls for concerted efforts from different stakeholders in developing effective management strategies against this devastating pest.

Synthetic pesticides have been observed to be less effective against *T. absoluta* (Roditakis *et al*., 2013) and are associated with various challenges and harmful effects (Brahman *et al*., 2012; Kumar and Omkar, 2018). The concept of integrated pest management (IPM) was developed to address the drawbacks of solely relying on chemical control. In this perspective, alternatives to synthetic insecticides with reduced negative effects have been the object of research in several parts of the world (Biondi *et al*., 2018). A lot has been done on natural enemies, which are used in biological control of *T. absoluta* in some parts of the world (Desneux *et al*., 2010; El-Ghany *et al.*, 2016; Giorgini *et al*., 2019). Different biopesticides based on entomopathogens and botanical insecticides have also been evaluated and shown to be effective against this pest. However, these studies have been limited to specific biocontrol strains/species and also have been carried out mainly in the pest's area of origin (Jallow *et al*., 2019). Besides, many other studies have been limited to laboratory conditions (Youssef, 2015; El-Ghany *et al.,* 2016; Giorgini *et al*., 2019). There is also a scarce information on the effects on different *T. absoluta* management options on growth, yield and fruit quality of tomato.

Entomopathogenic nematodes (EPNs), entomopathogenic fungi (EPFs) and plant extracts (PEs) are among the claimed options for effective management of *T. absoluta* (Mansour *et al*., 2018). Laboratory studies in Rwanda recommended some EPNs, EPFs, and PEs which can be advanced to field evaluation stage (Ndereyimana *et al*., 2019 a, b, c). To this aim, the current study investigated the growth, yield and fruit quality of tomato as affected by entomopathogens and plant extracts against *T. absoluta*.

2. Materials and Methods

Study site

This study was carried out in Bugesera District of Rwanda, in a farmer's field located at 02° 32' 355" South latitude, 30° 26' 963" East longitude and an elevation of 1338 m above sea level. The average annual rainfall and temperature are 854 mm and 21.4°C, respectively (Kabirigi *et al.,* 2017).

Experimental design, trial establishment, and treatments application

The study evaluated nine treatments in a randomised complete block design with three replications. The individual experimental plots were 3 m long and 2 m wide, with 1.5 m wide paths between them. Thirty days old, healthy and uniform tomato cv. Roma seedlings were transplanted into the plots applied with 20 t of organic manure per hectare and mulched with dry grass. Transplanting for trials one and two was carried out on 3rd April 2019 and 28th June 2019, respectively.

The treatments included: two local EPN isolates (*Steinernema* sp. RW14-M-C2a-3 and *Steinernema* sp. RW14-M-C2b-1), two commercial formulations of EPFs [Metatech® WP: *Metarhizium anisopliae* (Metsch.) Sorok, Strain FCM Ar 23B3, 5 x 109 CFUs/g,

and Beauvitech® WP: *Beauveria bassiana* (Bals.) Vuill., Strain J25, 1 x 1010 CFUs/g], two local plant extracts (*Tephrosia vogelii* and *Phytolacca dodecandra*), azadirachtin 0.03% EC (Nimbecidine), imidacloprid (Confidor SL 200) and water. The two last treatments were included as positive and negative controls, respectively. The two EPN isolates used were obtained from Biological Control Laboratory - EPN Production Facility at Rwanda Agriculture and Animal Resources Development Board (RAB) (Yan *et al*., 2016). Mass production of the EPNs was done through *in-vivo* method using *Galleria mellonella* larvae (Kaya and Stock, 1997). For field applications, these EPNs were formulated into sponges and were used at a concentration of 5 x 10^9 IJs/ha (Gözel and Kasap, 2015).

The EPF formulations were obtained from Dudutech Division, Flamingo Horticulture (K) Ltd, Naivasha, Kenya and were used at a concentration of 250 g/ha. The two local plant extracts were prepared from leaves of local plants (*T. vogelii* and *P. dodecandra*). The fine powder was obtained (using an electric grinder) from the leaves dried in a shaded area, mixed with boiled water and kept for 12 hours. The concentration used for field application was 15% weight/volume (w/v) and filtration was done using a muslin cloth. Azadirachtin 0.03% EC (Nimbecidine) and imidacloprid (Confidor SL 200) were used at the rates of 5 ml and 1 ml, respectively, per litre of water. All these treatments were applied weekly using a knapsack sprayer and the application volume was 1000 l/ha (Brusselman *et al*., 2012).

Cultural operations

Apart from the difference in applied treatments, all other cultural operations were uniformly done in all the experimental plots. Fungicide application was done every week by alternating Copper oxychloride 50% WP with fungicides containing Mancozeb 80% or Mancozeb (640 g/kg) + Metalaxyl (80 g/kg). Each tomato plant was fertilised with 10 g of NPK 17-17-17 as basal fertiliser, supplemented with 4 g of Urea 46% on 30th day after transplanting as per RAB recommendation. Other cultural practices like watering, weeding, and pruning were carried out conventionally.

Data collection and analysis

Data were collected on growth, yield, and fruit quality parameters. Plant growth parameters: plant height, stem diameter and number of leaves per plant, were recorded every two weeks. Plant height (cm) was measured from the ground to the tip of each of five randomly selected plants using a metre tape. Stem diameter (mm) was measured from the collar using a digital vernier caliper. The number of leaves arising from the main stem was counted. For yield parameters, the numbers of flower trusses per plant and flowers per truss were recorded 40 days after transplanting, while the number of fruits per truss was recorded 60 days after transplanting. The number and yields of healthy and bored fruits were recorded during the harvesting period, which started 72 and 70 days after transplanting in trials one and two, respectively. All the above parameters were taken from five plants selected randomly in the middle of each plot.

Fruit quality parameters, namely fruit firmness (Kg F/cm^2), total soluble solids (TSS) (°Brix), beta-carotene (mg/100 g of fruit), lycopene (mg/100 g of fruit), and ascorbic acid (mg/100 g of fruit), were recorded. To determine fruit firmness, tomatoes were harvested at the pink stage and stored at room temperature until the uniform red ripe stage. Then, five fruits were randomly selected from each treatment lot and fruit firmness measured in the equatorial zone of each tomato using a penetrometer (Ritenour *et al*., 2002). Total soluble solids were determined on the same fruits used for the determination of fruit firmness using a refractometer (RHW Refractometer, Optoelectronic Technology Company Limited, UK) (Majidi *et al*., 2011). Beta-Carotene was obtained following the method described by Delia *et al*. (2004). Lycopene was extracted using acetone and analysed in a spectrophotometer at 503 nm. Lycopene content was then calculated using the formula given by Ranganna (1997) as follows:

$$\text{Lycopene content} = 3.1206 \times A \times V \times D \times \frac{100}{(W \times 100)}$$

where A = Absorption, V = Volume made up, D = Dilution, W = Weight of Sample. Ascorbic acid was determined by titration with 2,6-dichlorophenolindophenol dye (AOAC, 1990).

The distribution of the collected data was assessed and the appropriate transformation was undertaken, where necessary, before subjecting them to analysis of variance. In both trials, the numbers of healthy and bored fruits per plant were square-root transformed, while the yield of healthy and bored fruits per plant were log-transformed. The number of fruits per truss was log-transformed in trial one, and arcsine-transformed in trial two; while the number of flowers per truss was arcsine-transformed in trial two. All other parameters were

analysed without transformation. To determine the effect of the treatments on tomato fruits yield and quality, analysis of variance was carried out; and the means for significantly different treatments (at P≤0.05) were separated using Tukey's honestly significant difference test. The data analysis was carried out using the Statistical Analysis System package, SAS software version 9.2 (SAS Institute, 2010).

3. Results

Tomato growth parameters

Plant height was significantly (P≤0.05) influenced by the studied treatments from 30 days after transplanting (DAP) (Fig. 1). In both trials, the plant height was not significantly different at 15 DAT; with an average of 14.9 and 15.3 cm for trials one and two, respectively. Plant height increased with time but became almost constant at 45 DAT. In trial one, there was no significant difference among the entomopathogens (EPNs and EPFs) and azadirachtin on all days of observation. *Tephrosia vogelii* was not significantly different from all the above at 30, 45, and 60 DAT, except *Steinernema* sp. RW14-M-C2a-3. Lower plant height was recorded with *P. dodecandra* and the controls, which were insignificantly different. In trial two, plant height did not significantly differ among the treatments, except *P. dodecandra* and the controls which had lower plant height than others.

Stem diameter did not significantly differ among the treatments at 15 and 30 days after transplanting (DAT) in trial one and at 15 DAT in trial two (Fig. 2). In addition, only the stem diameter in the negative control was significantly lower as compared to the other treatments at 45 DAT in trial one. *Phytolacca dodecandra* and imidacloprid were similar to the negative control, with significantly lower stem diameter (P≤0.05) compared to the other treatments at 60 DAT. For trial two, *P. dodecandra* and negative control had significantly lower stem diameter as compared to the other treatments at 30 DAT; but at 60 DAT it was only the negative control which had significantly lower stem diameter as compared to azadirachtin and all entomopathogens except Beauvitech® WP.

The number of leaves per plant was not significantly affected by the evaluated treatments in both

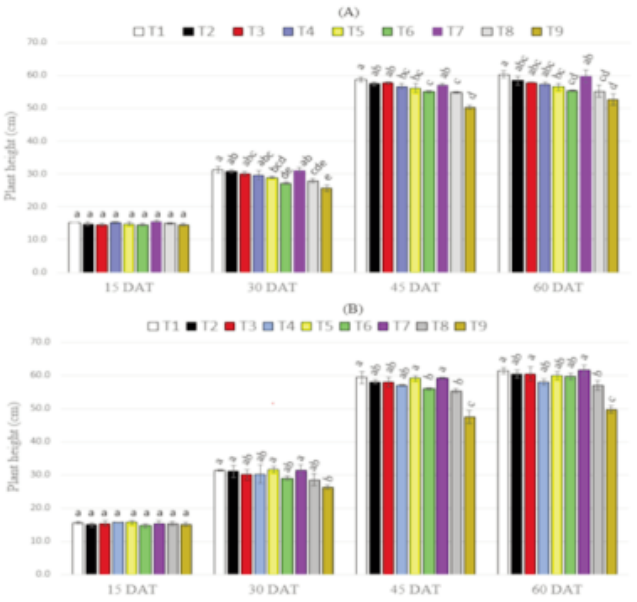

Fig. 1 - Plant height of tomato cv. Roma under different treatments against *Tuta absoluta* in trials one (A) and two (B). T1: *Steinernema* sp. RW14-M-C2a-3, T2: *Steinernema* sp. RW14-M-C2b-1, T3: Metatech®WP (*Metarhizium anisopliae*, Strain FCM Ar 23B3), T4: Beauvitech® WP (*Beauveria bassiana*, Strain J25), T5: *Tephrosia vogelii*, T6: *Phytolacca dodecandra*, T7: azadirachtin 0.03% EC, T8: imidacloprid, T9: Water; DAT: Days after transplanting; Different letters above the bars indicate significant difference according to Tukey's test (P≤0.05).

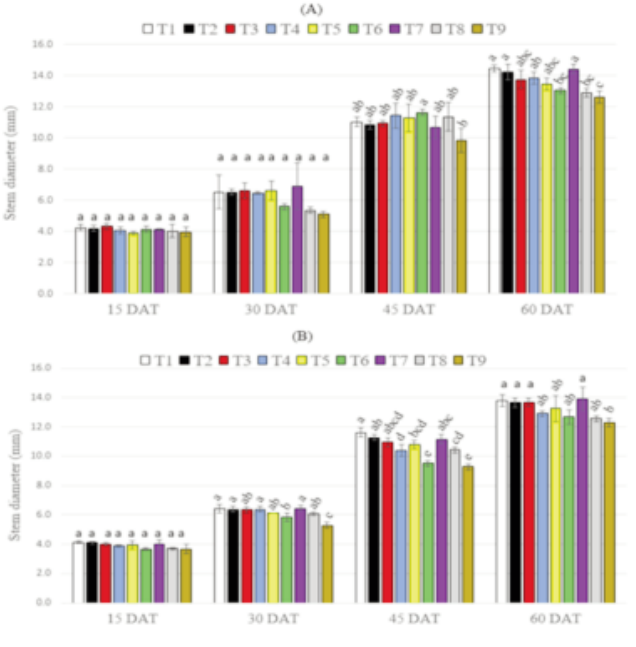

Fig. 2 - Stem diameter of tomato cv. Roma under different treatments against *Tuta absoluta* in trials one (A) and two (B). T1: *Steinernema* sp. RW14-M-C2a-3, T2: *Steinernema* sp. RW14-M-C2b-1, T3: Metatech®WP (*Metarhizium anisopliae*, Strain FCM Ar 23B3), T4: Beauvitech® WP (*Beauveria bassiana*, Strain J25), T5: *Tephrosia vogelii*, T6: *Phytolacca dodecandra*, T7: azadirachtin 0.03% EC, T8: imidacloprid, T9: Water; DAT: Days after transplanting; Different letters above the bars indicate significant difference according to Tukey's test (p≤0.05).

trials. However, the general trend observed in both trials was that slightly higher (but not significantly different) number could be obtained in plots treated with Metatech® WP (*M. anisopliae*, Strain FCM Ar 23B3) and azadirachtin in trial one; and with *Steinernema* sp RW14-M-C2a-3 and Beauvitech® WP (*B. bassiana*, Strain J25) in trial two (Fig. 3). The average numbers of leaves per plant recorded at 60 DAT in trial one were 13.0, 12.8,14.0, 12.5, 12.8, 12.6, 13.3, 11.9, and 12.6; while in trial two they were 11.8, 11.6, 11.7, 11.9, 11.1, 11.1, 11.5, 11.2, and 11.3, in plots treated with *Steinernema* sp. RW14-M-C2a-3, *Steinernema* sp. RW14-M-C2b-1, Metatech®WP (*M. anisopliae*, Strain FCM Ar 23B3), Beauvitech® WP (*B. bassiana*, Strain J25), *T. vogelii, P. dodecandra*, azadirachtin, imidacloprid, and water, respectively.

Effect of entomopathogens and plant extracts on tomato yield

The evaluated treatments significantly (P<0.001) influenced tomato yield parameters in both trials (Table 1). Generally, plots treated with the entomopathogens or azadirachtin had higher performance as compared to those with plant extracts or controls. A similar number of flower trusses per plant was recorded by *Steinernema* sp. RW14-M-C2a-3, *Steinernema* sp. RW14-M-C2a-3, Metatech®WP,

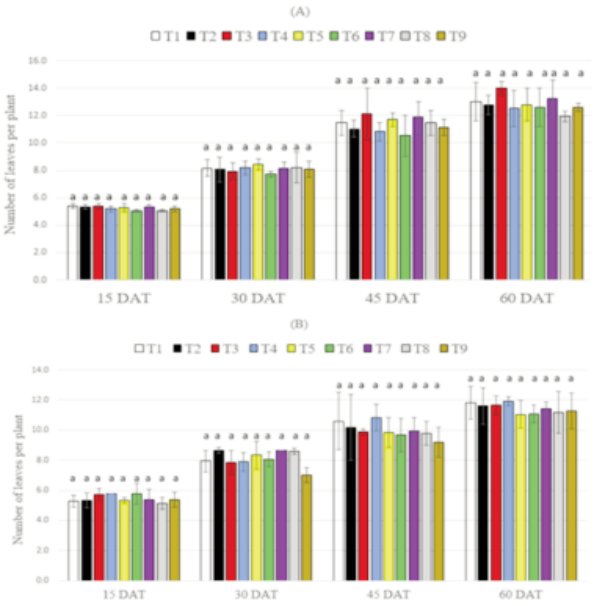

Fig. 3 - Number of leaves per plant for tomato cv. Roma under different treatment against *Tuta absoluta* in trials one (A) and two (B). T1: *Steinernema* sp. RW14-M-C2a-3, T2: *Steinernema* sp. RW14-M-C2b-1, T3: Metatech®WP (*Metarhizium anisopliae*, Strain FCM Ar 23B3), T4: Beauvitech® WP (*Beauveria bassiana*, Strain J25), T5: *Tephrosia vogelii*, T6: *Phytolacca dodecandra*, T7: azadirachtin 0.03% EC, T8: imidacloprid, T9: Water; DAT: Days after transplanting; Similar letters above the bars indicate non-significant difference according to Tukey's test (P≤0.05).

Table 1 - Yield parameters (mean ± SD) of tomato under different entomopathogens and plant extracts treatments

Treatments	Number of flower trusses/plant	Number of flowers/truss	Number of fruits/truss	Number of healthy fruits/plant	Number of bored fruits/plant	Yield of healthy fruits (g/plant)	Yield of bored fruits (g/plant)
Trial one							
T1	11.9 ± 0.2 a	9.7 ± 0.4 a	4.1 ± 0.3 a	5.9 ± 0.2 a	5.8 ± 0.2 a	406.3 ± 10.9 a	333.3 ± 33.4 a
T2	11.6 ± 0.4 abc	8.5 ± 0.1 bc	4.0 ± 0.1 a	5.6 ± 0.2 a	5.1 ± 0.4 a	381.0 ± 22.3 a	286.8 ± 8.8 a
T3	11.7 ± 0.2 ab	7.7 ± 0.2 cd	4.1 ± 0.1 a	5.5 ± 0.3 a	6.1 ± 0.4 a	374.4 ± 23.5 a	328.8 ± 34.9 a
T4	11.4 ± 0.1 abc	7.3 ± 0.3 de	3.8 ± 0.5 a	5.4 ± 0.2 a	5.6 ± 0.4 a	335.0 ± 34.5 a	313.9 ± 17.3 a
T5	10.9 ± 0.2 bc	7.4 ± 0.1 de	3.0 ± 0.3 b	2.5 ± 0.3 b	3.2 ± 0.2 b	151.0 ± 12.3 b	161.7 ± 9.7 b
T6	10.8 ± 0.3 c	6.4 ± 0.2 ef	2.9 ± 0.2 b	1.5 ± 0.1 c	2.6 ± 0.2 cb	81.5 ± 12.5 b	126.2 ± 10.1 b
T7	12.7 ± 0.1 a	9.4 ± 0.6 ab	4.3 ± 0.2 a	6.5 ± 0.2 a	4.9 ± 0.6 a	402.9 ± 12.7 a	275.7 ± 29.5 a
T8	10.8 ± 0.3 c	6.5 ± 0.3 ef	3.0 ± 0.4 b	1.7 ± 0.2 c	2.3 ± 0.5 cb	86.6 ± 9.0 b	109.9 ± 26.2 bc
T9	10.8 ± 0.5 c	5.6 ± 0.7 f	2.5 ± 0.3 b	0.7 ± 0.4 d	1.9 ± 0.5 c	32.5 ± 8.2 c	83.7 ± 22.1 2 b
CV	2.5	4.89	6.53	4.39	5.76	4.2	2.23
P	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
Trial two							
T1	9.0 ± 0.2 a	7.7 ± 0.3 a	3.8 ± 0.3 a	5.5 ± 0.2 a	4.6 ± 0.7 a	367.8 ± 5.2 a	249.5 ± 22.1 a
T2	9.0 ± 0.2 a	7.4 ± 0.2 a	3.7 ± 0.2 a	5.4 ± 0.2 a	4.7 ± 1.0 a	350.9 ± 12.1 a	255.9 ± 38.1 a
T3	8.8 ± 0.2 ab	5.6 ± 0.2 cb	3.8 ± 0.4 a	4.9 ± 0.4 a	5.6 ± 0.8 a	309.7 ± 26.3 a	302.4 ± 45.9 a
T4	8.8 ± 0.5 ab	5.5 ± 0.2 cb	3.6 ± 0.2 a	4.9 ± 0.4 a	5.3 ± 1.0 a	319.4 ± 33.5 a	273.6 ± 64.8 a
T5	8.8 ± 0.2 ab	5.9 ± 0.2 b	2.8 ± 0.1 b	2.0 ± 0.4 b	4.4 ± 0.4 a	113.1 ± 13.4 b	220.9 ± 18.2 a
T6	8.1 ± 0.2 b	5.2 ± 0.3 cb	2.4 ± 0.4 b	1.4 ± 0.2 b	2.1 ± 0.1 b	67.0 ± 8.5 c	114.8 ± 17.0 b
T7	9.3 ± 0.2 a	8.0 ± 0.3 a	4.0 ± 0.2 a	6.0 ± 0.4 a	4.7 ± 0.1 a	392.5 ± 38.1 a	266.6 ± 19.6 a
T8	8.7 ± 0.1 ab	5.5 ± 0.3 cb	2.7 ± 0.2 b	1.6 ± 0.3 b	1.9 ± 0.5 b	74.7 ± 8.1 c	96.7 ± 22.5 b
T9	8.1 ± 0.2 b	5.0 ± 0.2 c	2.2 ± 0.3 b	0.8 ± 0.2 c	1.7 ± 0.2 b	35.7 ± 6.7 d	80.0 ± 10.10 b
CV	3.02	2.31	4.17	5.11	7.94	2.3	3.05
P	0.0004	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001

T1: *Steinernema* sp. RW14-M-C2a-3, T2: *Steinernema* sp. RW14-M-C2b-1, T3: Metatech®WP (*Metarhizium anisopliae*, Strain FCM Ar 23B3), T4: Beauvitech® WP (*Beauveria bassiana*, Strain J25), T5: *Tephrosia vogelii, T6: Phytolacca dodecandra*, T7: azadirachtin 0.03% EC, T8: imidacloprid, T9: Water. Means followed by the same letter (s) are not significantly different (Tukey's test, P≤0.05)

Beauvitech WP, and azadirachtin. These values were significantly (P<0.001) higher than *T. vogelii*, *P. dodecandra*, imidacloprid, and water spray in trial one. In trial two, the effect of *T. vogelii* and imidacloprid was similar to all the treatments but the plot treated with EPNs and azadirachtin recorded a significantly higher number of flower trusses per plant than the negative control. The number of flowers per truss was significantly higher with *Steinernema* sp. RW14-M-C2a-3 and azadirachtin in trial one, and with all entomopathogenic nematodes and azadirachtin in trial two. Higher numbers of fruits per truss, healthy and bored fruits per plant were recorded with all entomopathogens and azadirachtin, in both trials. A similar trend was observed in the yield of healthy and bored fruits per plant.

Effect of entomopathogens and plant extracts on tomato fruit quality

Tomato fruit quality parameters were not significantly influenced by the applied treatments against *T. absoluta*. The results obtained were so close to each other that it is not easy to find any trend amongst the treatments (Fig. 4). The overall average values obtained were 3.2 and 3.3 kg F/cm^2 for fruit firmness, 4.2 and 4.4°Brix for TSS, 8.3 and 8.1 mg/100 g of fruit for beta-carotene, 5.4 and 5.5 mg/100 g of fruit for lycopene, 14.36 and 14.6 mg/100 g of fruit for ascorbic acid in trials one and two, respectively.

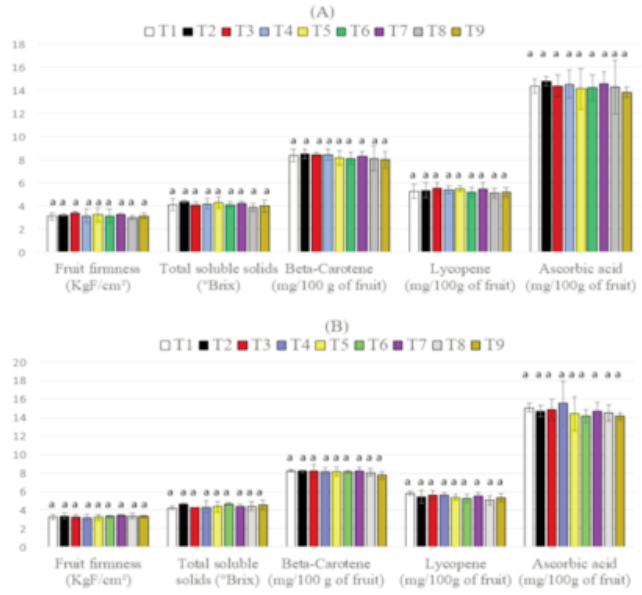

Fig. 4 - Fruit quality parameters of tomato cv. Roma under different treatment against Tuta absoluta in trials one (A) and two (B). T1: Steinernema sp. RW14-M-C2a-3, T2: Steinernema sp. RW14-M-C2b-1, T3: Metatech®WP (Metarhizium anisopliae, Strain FCM Ar 23B3), T4: Beauvitech® WP (Beauveria bassiana, Strain J25), T5: Tephrosia vogelii, T6: Phytolacca dodecandra, T7: azadirachtin 0.03% EC, T8: imidacloprid, T9: Water; Similar letters above the bars indicate non-significant difference according to Tukey's test (P≤0.05).

4. Discussion and Conclusions

Scarce studies have been conducted on the effects of entomopathogens and plant extracts on growth, yield and fruit quality of tomato. The significant differences observed in plant height and stem diameter could be due to the differences in the efficacy of studied treatments against *T. absoluta*. The damages inflicted by *T. absoluta* larvae my have affected the physiological and biochemical reactions of tomato plants, so that plant growth was consequently affected (Desneux *et al*., 2010). *Beauveria bassiana* which was reported to exhibit endophytic activity by colonising vascular tissues would be expected to impair the normal plant growth. However, different researchers reported that *B. bassiana* does not impede tomato growth (Klieber and Reineke, 2016; Allegrucci *et al*., 2017). On the other hand, since *T. vogelii* is a rich source of nitrogen, fixed through biological nitrogen fixation (Stevenson *et al*., 2012), more growth would be expected in this treatment compared to the others because nitrogen is more involved in plant growth and biomass production (Larbat *et al*., 2016). This was, however, not observed in this study and could be explained by the fact that the amount sprayed as an insecticide was too little to have a direct significant effect on plant growth. Finally, the insignificant difference in the number of leaves per plant despite the treatments could be because this parameter is associated with the genetic makeup of the plant (Kaushik *et al*., 2011) and not with cultural practices including pest management.

The significant difference in flower-related parameters could also be due to the difference in the efficacy of the studied treatments. By attacking the floral parts, *T. absoluta* larvae might have damaged some of them before they differentiate into flowers and caused others to drop; which could be the explanation for the flower abortion observed in this study. These results are in agreement with Cherif *et al*. (2013) who reported that *T. absoluta* larvae can damage tomato flower parts and cause flower drop.

The observed significant difference in yield parameters may also have arisen from the indirect effect of *T. absoluta* larvae through their feeding

activity in leaf mesophyll (Biondi *et al.*, 2018), which might have slowed down the process of assimilates synthesis and partitioning for their utilisation by different plant organs, including flower parts and fruits. In agreement with the above observation, Desneux *et al*. (2010) and El-Ghany *et al.* (2016) also reported that a tomato attack by *T. absoluta* disturbs its normal growth, development and the subsequent yield. Thus, higher numbers of flower trusses per plant, flowers per truss and fruits per truss recorded with entomopathogens and azadirachtin suggest that these treatments can reduce tomato yield loss as compared to the plant extracts and the controls (imidacloprid and water spray).

In their study, Rab and Haq (2012) found that the number of flowers per truss varied from 17.1 to 30.8 while the number of fruits per cluster was 4.1-6.4 for tomato cv. Roma. However, in the present study, a range of 5.6-9.7 flowers per truss and 2.2-4.3 fruits per truss was obtained. This indicates the ability of *T. absoluta* to negatively affect the flower and fruit-bearing capacity of tomato plant. This is one of the reasons for high yield losses frequently observed with *T. absoluta* infestations (Cherif *et al*., 2013; Biondi *et al*., 2018).

The higher numbers and yield of healthy fruits that were obtained with EPNs, EPFs, and azadirachtin support our earlier findings in laboratory experiments (Ndereyimana *et al*., 2019 a, b, c). In line with the findings of this study, Braham *et al*. (2012), Gözel and Kasap (2015), Youssef (2015), and El-Ghany *et al.* (2016) reported that EPNs, EPFs, and azadirachtin result in better control of *T. absoluta*. The performance of plant extracts and imidacloprid (positive control) remained low as it was in our previous laboratory studies (Ndereyimana *et al*., 2019 a, b). Negative control also recorded very low yield, which was consistent with Desneux *et al*. (2011) and Biondi *et al*. (2018) who emphasized that if there are no serious pest management strategies that are meticulously implemented, the yield loss might reach 100%.

Higher number and yield of bored fruits obtained from plots treated with entomopathogens and plant extracts, as compared to plant extracts and controls, might have resulted from the reduced number of aborted and damaged flowers by *T. absoluta* in the plots where these treatments were applied. Although these fruits survived from early abortion and the dropping of progenitor flowers, they were more exposed to *T. absoluta* because they were many, and thus a group of them was later bored by the pest that spoiled their quality. Compared to the negative control, the yield of healthy fruits obtained with *Steinernema* sp. RW14-M-C2a-3, *Steinernema* sp. RW14-M-C2a-3, Metatech®WP, Beauvitech®WP, and azadirachtin increased 12.5, 11.7, 11.5, 10.3 and 12.4 folds, respectively. While compared to the positive control, it was 4.8, 4.5, 4.2, 4.1 and 5.0 folds, respectively. This confirms that, despite the invasive nature of *T. absoluta*, different management options can reduce significantly its negative impact on the crop. However, dependence on synthetic insecticides should be discouraged as evidenced by the results of this study, which are consistent with several other researchers (Desneux *et al*., 2010; Roditakis *et al*., 2013; Biondi *et al*., 2018).

The commercial value of bored fruits is lost because they are not preferred by customers as external appearance and absence of defects are among the factors determining consumer preference (Asensio *et al.,* 2019). In addition to the larvae that enter inside the fruits, also some pathogens like fungi often get inside through the created holes and cause fruit decaying before or after harvest (Desneux *et al*., 2010). The findings of this study are supported by previous researchers who worked on other pests and reported that crop pests are among the main factors reducing the yield and quality of field horticultural produce by direct feeding or by favouring several diseases (Kumar and Omkar, 2018). Thus, implementation of IPM is worth to ensure better yield and quality of tomato crop.

Since the damage inflicted by *Tuta absoluta* on the leaves of tomato plants negatively affects its physiological processes (Desneux *et al*., 2010; Biondi *et al*., 2018) and fruit total soluble solids are translocated from the photosynthetic activities in the leaves (Beckles, 2012), significant difference in fruit quality parameters was expected among treatments with different *T. absoluta* infestation levels. Similarly, the entomopathogens and azadirachtin that exhibited better *T. absoluta* control would have also resulted in higher quality fruits as compared to the plant extracts and the controls´ treatments. The observed non-significant difference in tomato fruit quality parameters: firmness, total soluble solids, beta-carotene, lycopene, and ascorbic acid among treatments against *T. absoluta*, therefore may be attributed to other factors such as variety, crop nutrition, climatic conditions, fruit ripening stage, and storage period (Marsic *et al*., 2011; Rab and

Haq, 2012; Tigist *et al.*, 2013; Asensio *et al*., 2019).

Fruit firmness results obtained in this study fall in the range of the values obtained by Rab and Haq (2012). Fruit firmness is an important quality parameter that determines fruit shelf-life and resistance to mechanical damage (Tigist *et al*., 2013). In line with the current study, Parmar *et al.* (2018) also obtained a TSS value of 4.8 °Brix for tomato cv. Roma under organic management system. Also, TSS values obtained by Rab and Haq (2012) ranged from 4.08 to 6.10 °Brix under different rates of calcium chloride and borax. The values of beta-carotene and lycopene recorded in this study are close to what was obtained by Parmar *et al.* (2018) (8.34 mg/100 g and 5.38 mg/100 g of fruit, respectively) for the same variety (Roma) produced organically. The ascorbic acid results obtained in this study agree with the earlier findings of Tigist *et al*. (2013) who obtained the values of 13.2 and 14.8 mg/100 g after four and eight days of room temperature storage, respectively, for Tomato cv. Roma fruits harvested at the green mature stage.

According to Tigist *et al*. (2013), these quality parameters develop into fruit during the pre-harvest period and they do not get improved after harvesting. However, they can be maintained by proper post-harvest handling and storage. Since pre-harvest activities are responsible for the development of quality parameters in tomato fruits, any technology used to improve its production should also be assessed for its effect on fruit quality.

As a conclusion, the studied entomopathogens and plant extracts significantly affected tomato growth and yield but not the fruit quality parameters. Better yield performance can be obtained with the entomopathogenic nematode isolates (*Steinernema* sp. RW14-M-C2a-3 and *Steinernema* sp. RW14-M-C2a-3), commercial formulations of entomopathogenic fungi (Metatech®WP: *Metarhizium anisopliae*, Strain FCM Ar 23B3 and Beauvitech®WP: *Beauveria bassiana*, Strain J25) and azadirachtin 0.03% EC, which were not significantly different. These biorational control agents are recommended to be included in the IPM of *Tuta absoluta*. The results of this study will guide producers to select the best control options that can result in higher comparative growth and yield without compromising fruit quality. Further studies should be conducted to confirm the effects of the studied entomopathogens and plant extracts under varied agro-climatic conditions.

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