



Effects of Mixed Infection of Tomato Chlorosis Virus and Tomato Yellow Leaf Curl Virus on Disease Incidence and Growth of Two Tomato Cultivars When Infected at Different Growth Stages

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The occurrence of mixed infection with tomato chlorosis virus (ToCV) and tomato yellow leaf curl virus (TYLCV), transmitted by the whitefly vectors *Bemisia tabaci* Mediterranean is not uncommon in cultivated tomatoes. Mixed infection of those viruses resulted in increased disease severity and reduced plant growth, as synergistic interactions. However, the impact of ToCV+TYLCV mixed infection at different growth stages on tomato growth and fruit yield has not been examined. Therefore, from September to November 2024, we surveyed the spread of single and mixed virus infections in tomato plants in the region of Docheok-myeon, Gwangju-si, Gyeonggi-do; we also conducted field trials to evaluate quantify damage and yield losses incurred by a susceptible (SuperDotaerang) and resistant (TY Giants) tomato cultivar when ToCV+TYLCV mixed infection at seedling stage (SS) and fruiting stage (FS). We observed that the monthly incidence rate of single ToCV infection remained ranged from 29.7% to 46.1% during the experiments, while the incidence rate of ToCV+TYLCV mixed infection on both cultivars significantly increased to about 50% in October. In SuperDotaerang, ToCV+TYLCV mixed-infected tomato plants at the seedling stage showed more severe symptoms compared with those in ToCV-infected plants in both SS and FS, which led to significant yield losses as plant height and leaf area decreased. Thus, this study provides information on management strategies targeted at preventing mixed infection with ToCV and TYLCV in seedling stage tomato crops and highlights that resistant cultivars should not be relied upon as the sole management practice for viral diseases.

Keywords: *Bemisia tabaci* MED, Growth stage-dependent yield loss, Mixed infection, Tomato chlorosis virus, Tomato yellow leaf curl virus

Received November 27, 2025

Revised December 10, 2025

Accepted December 10, 2025

Introduction

Synergistic interactions resulting from mixed infections with two or more viruses are common in plants. Many reports present that mixed infections among plant viruses are probably a rule rather than an exception in nature (DaPalma et al., 2010; Roossinck et al., 2015). A mixed infection may

result from multiple transmission involve numerous vectors carrying the different viruses, or the same vector carrying the different viruses (Syller, 2014). Recent study demonstrated that viral mixed infections of tomato chlorosis virus (ToCV) and tomato yellow leaf curl virus (TYLCV) frequently occurring in greenhouse tomato crops, and the infection rate was more than 50% (Kwon et al., 2022). ToCV and TYLCV are fundamentally different viruses. ToCV is a typical *Crinivirus* (family *Closteroviridae*) with a single-stranded RNA virus and TYLCV is a *Begomovirus* (family *Geminiviridae*) with a circular single-stranded DNA virus. Because both viruses are very efficiently

Research in Plant Disease

eISSN 2233-9191

www.online-rpd.org

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transmitted by the whitefly *Bemisia tabaci* Mediterranean (MED), it is expected that a favourable outcome to occurring the mixed infection. The outcome of mixed infection interaction between the viruses may be synergistic or antagonistic (Syller, 2012). Viral synergism is caused by often mixed infection of two unrelated viruses, at least one of the viruses benefits from the presence of the other, which is manifested by an increase virus replication and cellular tropism, within host movement, that promotes the virus infection of host plants (Mascia and Gallitelli, 2016; Syller, 2012). Mixed infections of ToCV and TYLCV result in increased virus titer, induced more severe symptoms in tomato plants than single infections, suggesting a synergistic interaction between these two viruses (Li et al., 2021). In addition, it has been reported that mixed infections with ToCV enhance the breakdown of resistance to TYLCV in tomato cultivars with a resistance conferring (Ty-1) gene (Fortes et al., 2023). Mixed infection with the RNA virus, cucumber mosaic virus or potato virus X, compromises the effectivity of resistance conferred by Ty-1, by inhibiting RNA interference in resistant tomato cultivars (Butterbach et al., 2014; Voorburg et al., 2020).

The objective of our study was to evaluate mixed infections of ToCV and TYLCV in tomato plants using TYLCV-resistant or susceptible tomato cultivars in the field conditions. For this, the prevalence of ToCV or ToCV+TYLCV in the major growing areas of tomato were first determined and examined how fruit yield and other plant growth parameters are impacted by viruses infection at different growth stages.

Materials and Methods

Tomato cultivars and virus inoculations. Two tomato cultivars were used in this experiment to evaluate the spread of singly ToCV-, TYLCV-infected and ToCV+TYLCV mixed-infected under field conditions: SuperDotaerang, a cultivar grown commercially in the Republic of Korea, is considered highly susceptible to TYLCV. TY Giants is an experimental hybrid produced by Mifko Seed Company; has high resistance to TYLCV.

The ToCV and TYLCV isolates were obtained from naturally infected tomato plants in a greenhouse of tomato cultivation in Toechon-myeon, Gwangju-si, Gyeonggi-do. Viral cultures maintained on tomato plants were inoculated with viruliferous whiteflies (*B. tabaci* MED) previously fed on tomatoes infected by ToCV, TYLCV, or ToCV and TYLCV.

Colonies of *B. tabaci* MED, reared on tobacco plants (*Nicotiana tabacum* L.), were kept inside a rearing cage (30×30×60 cm) located in a controlled environment room maintained at 23°C to 30°C with cycles of 16 hr of light and 8 hr of darkness.

We established whitefly-mediated transmission methods that were performed inside insect-proof net cages (64×38×38 cm) in natural temperature and light conditions. Three plants infected with ToCV, TYLCV, or ToCV and TYLCV were used as inoculum sources, surrounded by recipient plants ($n=49$). Groups of 500 viruliferous whitefly adults were used for each virus inoculation. Viruliferous whiteflies were obtained using a vacuum hand trap to 100 healthy *B. tabaci* MED adults, providing a 24-hr acquisition access period (AAP) to feed on each virus-infected tomato leaf disc in clip-on cages (35 mm in diameter). Following AAP, each clip-on cage, containing the viruliferous whiteflies, was released inside cages containing the test plant (five-leaf growth stage) to be inoculated. After a 24-hr inoculation access period, whiteflies were eliminated from plants by insecticide spraying (50% pimaja oil).

Field sites and experimental design. Two days after the inoculation was completed, 332 plants were transplanted on 12 August in four rows into a greenhouse located in Docheok-myeon, Gwangju-si, Gyeonggi-do. Plants were placed every 150 cm in rows which were 40 cm apart. Two cultivar trials were set up in a complete randomized block design with three replications. Three weeks after the seedlings were transplanted, plantlets were sprayed at least twice weekly with spirotetramat (active ingredient [a.i.], 22.0%, suspension concentrate [SC]), emamectin benzoate (a.i., 2.15%, emulsifiable concentrate [EC]), fluxametamide (a.i., 9.0%, EC), clothianidin (a.i., 8.0%, SC), cyantraniliprole (a.i., 5.0%, EC) and spinetoram (a.i., 5.0%, SC) to prevent emergence of adults.

Disease ratings and detection of viruses. The severity of symptoms on individual plants was conducted on 10 September, 8 October, 21 October, and 5 November. The disease severity index (DSI) in plants was divided on a scale of 0 to 4 (0, no symptom; 1, mild mosaic; 2, yellowing; 3, leaf curling; 4, stunting). Two leaf discs of 2-3 nodes on a younger portion of the stem were sampled and distinguished by cultivar SuperDotaerang ($n=167$) and TY Giants ($n=165$). Total DNA/RNA were extracted by using TissueLyser II (Qiagen, Hilden, Germany) with the Viral Gene-spin Viral DNA/RNA Extraction Kit (iNtRON Biotechnology, Seongnam, Korea), following the

manufacturer's protocol.

For detection of TYLCV, a polymerase chain reaction (PCR) was performed, using primer pairs *tylcv* 1f (5'-GTCAACCAATCAAATTGCATCCTCAA-3') and *tylcv*1-2r (5'-GTCCAAAATC-CATTGGGC-3') were designed according to Won et al. (2019). The PCR reaction was performed in a total volume of 20 µl containing 10.0 µl of 2× Taq buffer with 0.5 µl of 2 mM dNTPs, 10 µM of each forward and reverse primers, 0.025 units of KOD Fx Taq polymerase (TOYOBO, Osaka, Japan), 2 µl of cDNA and sterile distilled water to make up the final volume. The thermal cycling conditions were performed with initial denaturation at 95°C for 10 min, followed by 35 cycles of denaturation at 95°C for 30 sec, annealing at 55°C for 40 sec, extension at 72°C for 45 sec, and final extension at 72°C for 5 min.

For detection of ToCV, a reverse transcription (RT)-PCR was performed, using primer pairs ToCV-M-4F (5'-AGAA-GATCCGCGCTAATGCTAA-3') and ToCV-M-4R (5'-GGT-CATCTTCCCAAACACGA-3') were described by Won et al. (2019). The final RT-PCR reaction volume was 20 µl, and the reaction was performed using SuPrimeScript RT-PCR Premix (GeNet Bio, Daejeon, Korea) according to the manufacturer's protocol. The RT-PCR conditions were performed with a cDNA synthesis step at 50°C for 30 min, an initial denaturation at 95°C for 10 min followed by 35 cycles (denaturation at 95°C for 30 sec, annealing at 55°C for 40 sec, and an extension at 72°C for 45 sec), and a final extension at 72°C for 5 min. The PCR and RT-PCR were performed using a C1000 Touch™ Thermal Cycler (Bio-Rad Laboratories, Hercules, CA, USA). All the amplified products were run on 2.0% agarose gels stained with Midori Green Advance (NIPPON Genetics, Co., Ltd., Tokyo, Japan) and gel images were documented in a gel documentation unit (Bio-Rad Laboratories).

Growth and yield analysis. The growth and yield performance were evaluated after 90 days of transplanting the tomato plant seedlings. The main crop growth parameters like plant height, leaf length, leaf width, and the number of fruits, and fruit weight were measured. The plant height was measured from the soil surface to the highest tip (apical bud). Leaf length was measured from the petiole to the terminal leaf tip using a ruler for tomato plants. Leaf width was determined by measuring the longest width of the leaves perpendicularly to the midrib. The number of fruits per plant was counted while the fruit weight of the first cluster was

weighed and recorded at harvesting. Statistical data analysis was performed using one-way ANOVA following Tukey's HSD (honestly significant difference) test with SPSS software (IBM Corp., Armonk, NY, USA).

Results

ToCV and TYLCV infections in tomato cultivars. The results of viral detection from 167 tomato samples in the TYLCV-susceptible cultivar (SuperDotaerang) indicated that 80 (47.9%) in September, 161 (96.4%) in October, and 163 (97.6%) of them showed a positive ToCV or TYLCV band, exhibiting an amplification of 442 bp and 238 bp, respectively. In this study, we confirmed the detection of ToCV and TYLCV, with single and mixed infections. The incidence of single infections of ToCV was maintained at similar levels throughout the growing period: 32.9% in September, 35.3% in October, and 35.9% in November. Whereas the rate of TYLCV single infection was significantly lower than that of ToCV alone: 6.6% in September, 9.6% in October, and 6.0% in November. The mixed infection rate of ToCV and TYLCV significantly increased in October and November: 8.4% in September, 51.5% in October, and 55.7% in November (Fig. 1A).

Among the 165 tomato samples collected from the TYLCV-resistant cultivar (TY Giants), 76 samples (46.1%) in September, 149 samples (90.3%) in October, and 161 samples (97.6%) in November were infected with viruses. The rate of ToCV infection was high from September: 46.1% in September, 29.7% in October, and 46.1% in November. However, TYLCV infection rate was low at 3.6% in September, 13.9% in October, and 1.2% in November. However, the mixed infection rate of ToCV and TYLCV increased rapidly in October, reaching more than 50%, showing a similar trend to that in the susceptible tomato cultivars (Fig. 1B).

Virus symptoms of TYLCV-susceptible and resistant. At 90 days after transplant, over 90% of the plants in both cultivars were infected with ToCV or TYLCV, and tomatoes had severity indexes of 0, 1, 2, 3, and 4. For SuperDotaerang infected singly with ToCV, more than 40% of the infected plants had yellowing (DSI, 2) and more than 40% had no symptoms (DSI, 0). Symptom severity for TY Giants infected with ToCV was relatively similar to those observed in SuperDotaerang infected, 50% of the infected plants had yellowing (DSI, 2) and more than 30% remained asymptomatic (DSI,

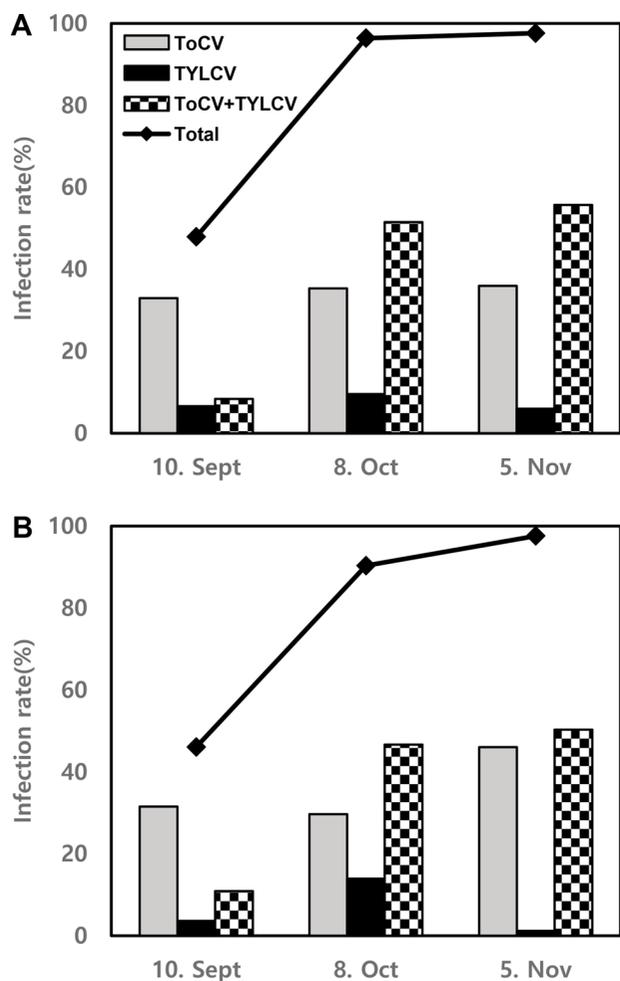


Fig. 1. Comparison of infection rate changes of tomato chlorosis virus (ToCV) and tomato yellow leaf curl virus (TYLCV) in tomato cultivars. (A) SuperDotaerang ($n=167$) and (B) TY Giants ($n=165$) plants over time.

0). In mixed infected with ToCV and TYLCV tomato plants, while 45.2% of SuperDotaerang had yellowing (DSI, 2), about 25% had more severe symptoms of yellowing accompanied by leaf curling (DSI, 3), and about 20% with yellowing, leaf curling, and stunting (DSI, 4) (Fig. 2A). While more than 70% of mixed-infected TY Giants had yellowing symptoms (DSI, 2), and about 10% had mild mosaic symptoms (DSI, 1) (Fig. 2B).

Severity of symptoms of mixed infection time-point trial. In SuperDotaerang, out of 167 samples tested, ToCV was shown positive to 23 samples and ToCV+TYLCV was shown positive to eight samples, in September. In October, ToCV and ToCV+TYLCV additionally showed positive in 31 and 41 samples, respectively. Under field conditions, the singly TYLCV-infected plants at both cultivars were first observed with marked yellowing and severe size reduction

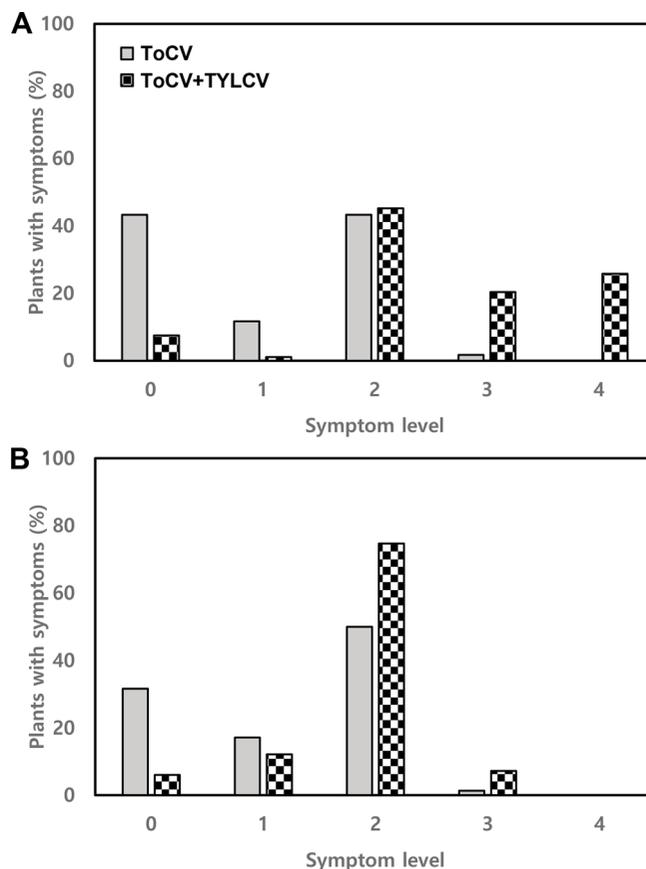


Fig. 2. Severity of symptoms in two tomato cultivars. (A) SuperDotaerang and (B) TY Giants infected with singly tomato chlorosis virus (ToCV) or ToCV and tomato yellow leaf curl virus (ToCV+TYLCV) mixed showing the percentage of plants by different symptom severity at; no symptom (0), mild Mosaic, and lower leaf chlorosis (1), yellowing Mosaic, and upper leaf chlorosis (2), leaf curling (3), and stunt (4).

symptoms in the top leaves at about 14 days after transplanting. Whereas, the ToCV alone or ToCV+TYLCV mixed-infected SuperDotaerang plants began to show symptoms 58 days after transplanting. Tomato plants infected with ToCV alone at two infection time points (seedling stage and fruiting stage) or ToCV+TYLCV at fruiting stage exhibited symptoms of mild mosaic and lower leaf chlorosis with a rating <1. However, Tomato plants infected with both ToCV and TYLCV at seedling stage exhibited significantly severe symptoms, with indexes of about 3, including upper leaves chlorosis, curling, yellowing, and stunting (Fig. 3A).

In TY Giants, out of 165 samples tested, ToCV was shown positive to 23 samples and ToCV+TYLCV was shown positive to eight samples, in September. In October, ToCV and ToCV+TYLCV additionally showed positive in 21 and 44 samples, respectively. Symptoms of TY Giants infected with

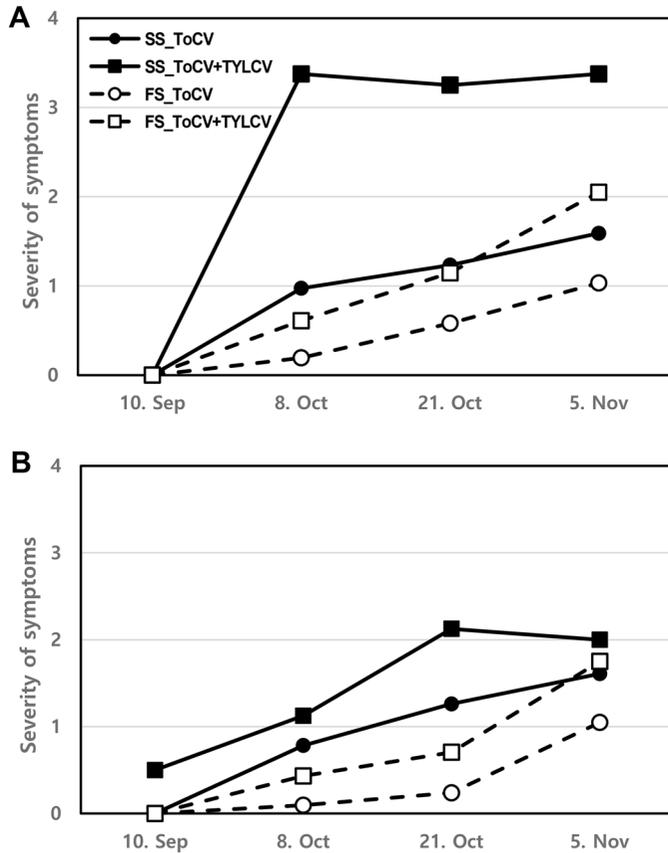


Fig. 3. Progression of symptom severity in (A) SuperDoterang and (B) TY Giants tomato plants naturally infected with tomato chlorosis virus (ToCV) alone or co-infected with tomato yellow leaf curl virus (ToCV+TYLCV). Comparisons were made between two infection time points: seedling stage (SS) and fruiting stage (FS).

both ToCV and TYLCV at seedling stage appear earlier compared to those of SuperDotaerang, at 30 days after transplanting. However, after 58 days of transplanting, TY Giants had delayed symptom development compared with SuperDotaerang and exhibited only slight symptoms of mild mosaic with indexes of about 1. At later stages, the symptoms become moderate with indexes of about 2, such as yellowing mosaic and upper leaf chlorosis, not developing further symptoms. In November, no major differences in symptoms were observed between the infection time point of single ToCV and mixed ToCV+TYLCV (Fig. 3B).

Effect of growth of mixed infection time-point trial. In SuperDotaerang, the plant height of ToCV+TYLCV mixed-infected plants (73.6 cm) at seedling stage was significantly lower than that of the plants in other treatments. However, it did not vary between non-infected controls, and plants infected singly with ToCV at both seedling and fruiting stage. With regards to the effects on leaf area, mixed-infected plants with ToCV+TYLCV at seedling stage had significantly shorter leaf length (29.8 cm) and range (26.8 cm) than the plants in other treatments. In TY Giants, although mixed-infected plants at seedling stage had shorter plant heights, leaf lengths, and widths than non-infected controls and another infected one, there was no significant difference (Table 1).

Table 1. Growth and yield parameters of TYLCV-resistant (TY Giants) and -susceptible (SuperDotaerang) tomato cultivars singly infected with tomato chlorosis virus (ToCV) or co-infected with tomato yellow leaf curl virus (ToCV+TYLCV) at two different infection stages

Cultivar	Treatment ^a	Plant height (cm)	Leaf length (cm)	Leaf range (cm)	Number of fruits per plant	Fruit weight (g)
SuperDotaerang	SS_ToCV	111.8 a ^b	45.4 a	44.6 a	3.4 a	395.3 a
	SS_To+TY	73.6 b	29.8 b	26.8 b	2.1 a	222.4 a
	FS_ToCV	114.0 a	50.8 a	47.9 a	2.7 a	345.6 a
	FS_To+TY	96.5 c	48.6 a	46.7 a	3.7 a	500.4 a
	Control	106.2 ac	49.3 a	46.8 a	2.5 a	394.0 a
TY Giants	SS_ToCV	144.5 a	45.5 a	46.2 ab	4.5 a	539.6 a
	SS_To+TY	113.5 b	35.9 b	38.1 a	3.4 a	373.6 a
	FS_ToCV	133.8 ab	46.5 a	45.6 ab	3.2 a	351.0 a
	FS_To+TY	140.1 a	45.5 a	46.3 b	4.1 a	526.0 a
	Control	151.4 a	46.8 a	49.8 b	5.3 a	613.3 a

TYLCV, tomato yellow leaf curl virus; ToCV, tomato chlorosis virus; SS, seedling stage; FS, fruiting stage.

^aViruses detected at different time points in September 10th (SS) and October 8th (FS).

^bValues followed by the same letter in row are not significantly different at $P=0.05$ by Tukey's HSD (honestly significant difference) test.

Yield losses of mixed infection time-point trial. Samples for measurement of the number of sets and weight of the fruits on a first cluster at harvest were taken for all treatments. In SuperDotaerang, the average number of edible fruits as at first harvest was 2.1 in mixed-infected plants at seedling stage. This was not significantly different from those of each, which had an average of 2.5-3.7 in other virus-infected plants. As also shown in Table 1, although the average weight of fruits was the lowest in the mixed-infected plants at seedling stage than in other groups, was essentially not different for those of the ToCV-only or fruiting stage-infected plants. This group, also, had the lowest weights, which had a mean value of 222.4 g. However, there was no significant difference in fruit weights of the first cluster between ToCV singly infected and infection time-point trial ($P>0.05$). Similarly, in TY Giants, the single and mixed infection with ToCV and TYLCV did not affect the growth performance and yields of the tomatoes, regardless of the time of infection.

Discussion

This study was conducted to evaluate the effect of single and mixed infections with ToCV and TYLCV on disease severity, plant growth, and yield in tomatoes. We aimed to explore the impact of mixed infections on tomato health and productivity, by analyzing the changing patterns of virus diseases for infection time points between the resistant (TY Giants) and susceptible (SuperDotaerang) tomato cultivars. The results showed that the ToCV singly infected plants did not show any distinct symptoms, whereas the ToCV+TYLCV mixed-infected plants manifested significantly severe synergistic disease symptoms. Mohamed (2010) also reported that mixed infection with other viruses can increase the severity of disease symptoms and significantly reduce the yield of cultivated tomatoes, compared to infection with TYLCV alone. In this study, it was shown that ToCV+TYLCV mixed-infected plants for the susceptible cultivar SuperDotaerang had significantly decreased growth indices such as plant height, leaf length, and width. This suggests that mixed infections may have a significant negative impact on plant growth, demonstrating that interactions between viruses negatively affect host morphology and physiology. In TY Giants, the impact of mixed infection was relatively less than in the susceptible cultivar, which may be because the TYLCV resistance gene (Ty-1) provides resistance to the virus

by restricting viral accumulation and tolerance to TYLCV by inhibiting disease symptoms (Michelson et al., 1994). However, mixed infections of TYLCV-associated viruses can lead to an increase in the potential for the breakdown of Ty-1 gene resistance, thus it is necessary to apply disease management practices to prevent mixed infections even in resistant cultivars. In this study, field experiments revealed the impact of ToCV+TYLCV mixed infection on tomato growth and yield of a TY Giants and SuperDotaerang cultivar when infected at two different growth stages. The susceptible cultivar, SuperDotaerang infected at seedling stage had significantly decreased plant height, leaf length, and width, which may be ultimately leading to a reduction in yield. This suggests that mixed infection significantly affected growth and yield in tomatoes of early viral mixed infection. Especially, as the mixed infection rate increased rapidly after October, virus interaction has become increasingly evident, and the yield tended to decrease significantly. These findings highlight the need for efforts to manage the two viruses' infection at early growth stages. The results presented in this study intend to contribute to a better understanding of the mixed infections in tomato plants that could lead to more effective control strategies. In particular, the fact that mixed infections of tomatoes can also adversely impact resistant cultivars leads to reconsider selecting cultivars and virus management strategies. Thus, it is important to recognize that resistant cultivars should not be relied upon as the sole management practice for viral diseases. Therefore, it should be discussed that the efficient ways to block the entry of viruses, thereby providing protection against viral infection and lowering the force of infection by managing the density of whitefly vector populations. In summary, this study demonstrated that mixed infections result in different severity of symptoms and damage depending on the tomato cultivar. We have shown that mixed infections can have a severe impact on tomato growth and yield, especially even more drastic damage during infection at the early stages of the growth (seedling stage). The fact that mixed infections can promote a breakdown of resistance in resistant cultivars in tomatoes highlights the need for sustainable management practices including appropriate control of insect vectors of virus at seedling stage. We believe that our results might be useful in developing effective strategies to manage viral mixed infections in agriculture.

Conflicts of Interest

No potential conflict of interest relevant to this article was reported.

Acknowledgments

This work was supported by the Cooperative Research Program for Agriculture Science & Technology Development (Project No. RS-2025-02305032), Rural Development Administration, Republic of Korea.

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