MAIZE CHLOROTIC MOTTLE VIRUS INDUCES CHANGES IN HOST PLANT VOLATILES THAT ATTRACT VECTOR THRIPS SPECIES

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Abstract - Maize lethal necrosis is one of the most devastating diseases of maize causing yield losses reaching up to 90% in sub-Saharan Africa. The disease is caused by a combination of maize chlorotic mottle virus (MCMV) and any one of cereal viruses in the Potyviridae group such as sugarcane mosaic virus. MCMV has been reported to be transmitted mainly by maize thrips (Frankliniella williamsi) and onion thrips (Thrips tabaci). To better understand the role of thrips vectors in the epidemiology of the disease, we investigated behavioral responses of F. williamsi and T. tabaci, to volatiles collected from maize seedlings infected with MCMVin a four-arm olfactometer bioassay. Volatile profiles from MCMV-infected and healthy maize plants were compared by gas chromatography (GC) and GC coupled mass spectrometry analyses. In the bioassays, both sexes of F. williamsi and male T. tabaci were significantly attracted to volatiles from maize plants infected with MCMV compared to healthy plants and solvent controls. Moreover, volatile analysis revealed strong induction of (E)-4,8-dimethyl-1,3,7-nonatriene, methyl salicylate and (E,E)-4,8,12-trimethyltrideca-1,3,7,11-tetraene in MCMV-infected maize seedlings. Our findings demonstrate MCMV induces changes in volatile profiles of host plants to elicit attraction of thrips vectors. The increased vector contact rates with MCMV-infected host plants could enhance virus transmission if thrips feed on the infected plants and acquire the pathogen prior to dispersal. Uncovering the mechanisms mediating interactions between vectors, host plants and pathogens provides useful insights for understanding the vector ecology and disease epidemiology, which in turn may contribute in designing integrated vector management strategies. **Key Words -** Multi-trophic interactions, maize chlorotic mottle virus, *Frankliniella williamsi, Thrips tabaci,* behavioral assays, induced volatile compounds.

INTRODUCTION

Maize, *Zea mays* L. (Poaceae), is a major staple and cash crop for over 300 million people in sub-Saharan Africa (SSA), covering a production area of over 27 M ha and is mainly grown by smallholder farmers (Sileshi et al. 2010; Cairns et al. 2013). Unfortunately, maize production in SSA is constrained by several indigenous and invasive pests and diseases resulting in significant yield loss (Kifr et al. 2002). The maize lethal necrosis (MLN) disease syndrome recently reported in eastern and central Africa on maize and other cereal crops (Wangai et al. 2012; Adams et al. 2014; Kusia et al. 2015; Mahuku et al. 2015b; Isabirye and Rwomushana 2016) is among the most important viral diseases that can cause up to 90% yield loss and has a devastating impact on food security and livelihoods (Mahuku et al. 2015a). The best strategy to manage the disease is to employ integrated pest management practices encompassing different approaches such as vector control and host-plant resistance (Nelson et al. 2011; Wangai et al. 2012). The disease occurs due to co-infection of cereal crops, such as maize and finger millets, with *Maize chlorotic mottle virus* (MCMV) and *Sugarcane mosaic virus* (SCMV) (Wangai et al. 2012; Kusia et al. 2015).

The maize chlorotic mottle virus (Tombusviridae: Machlomovirus), one of the causative agents ofMLN, has been spreading rapidly to various locations around the world in the past decade (Braidwood et al. 2018; Mahuku et al. 2015a). MCMV single infection in maize leads to yield losses that range between 10 to 15% in natural infection, whereas up to 59% yield loss has been reported in artificially inoculated maize plots (Uyemoto, 1983). More importantly, MCMV interaction with other Potyviridae viruses such as sugarcane mosaic virus causes an aggressive synergistic viral condition - maize lethal necrosis, which often leads to complete crop losses (Braidwood et al. 2018; Mahuku et al. 2015a; Wang et al. 2017; Xie et al. 2011). Recently, rapid spread of such synergistic viral infection has occurred in Africa, China, Taiwan and Ecuador where it has led to severe necrosis and yield losses in maize, sweet corn and finger millets (Degen et al. 2014; Kusia et al. 2015; Mahuku et al. 2015a; Wang et al. 2017; Xie et al. 2011). In Africa, the first MCMVoutbreak was reported from the southern rift valley of Kenya in 2011 (Wangai et al. 2012). MCMVand consequently MLN incidences in eastern and central Africa have been on increase since its first incidence (Adams et al. 2014; Lukanda et al. 2014; Mahuku et al. 2015b). The potential spread of MCMV to maize producing regions across Africa and its synergistic interaction with established potyviruses to cause MLN has been predicted (Isabirye and Rwomushana 2016). MCMV is transmitted mechanically in a semi-persistent manner by several vectors including, maize thrips (Frankliniella williamsi) (Cabanas et al. 2013), Chrysomelid beetles (Oulemamelanopa) and corn rootworms (Diabrotica spp) (Nelson et al. 2011). In eastern Africa, thrips have been observed in high densities in fields affected by MLN and MCMV (Mahuku et al. 2015a; Wangai et al. 2012). Maize thrips (F. williamsi), onion thrips (Thrips tabaci) and the pale form of common blossom thrips (Frankliniella schultzei) are known to transmit MCMV in east Africa and are widely distributed in the region (Mahuku et al. 2015a; Nyasani et al. 2015). Frankliniella williamsi and T. tabaci have narrow host range of Poaceae, Amaryllidaceae and Brassicaceae, while F. schultzei has a much wider host range (Moritz et al. 2013). The attraction of thrips and other insect vectors to virus infected or intact plants has been proposed to be mediated by volatile organic compounds (VOCs) and/or visual cues such as leaf color, which play a crucial role in both pre- and

post-alighting stages of host selection (Abdullah et al. 2015; Koschier et al. 2000, 2007). VOCs emitted from virus-infected plants may differ from healthy plants and this could influence the preference of vectors such as thrips for infected plants (Abe et al. 2011; De Vos and Jander 2010). Several studies have revealed that plants infected by pathogens are attractive to insect vectors of the pathogens and support better survival and development of vectors than uninfected plants though the mechanisms underpinning the interactions have not been adequately examined (Belliure et al. 2005; Eigenbrode et al. 2002; Tomitaka et al. 2015).

Plant viruses are known to manipulate their vectors' behavior via host plant nutrients and volatiles to enhance their transmission and spread (Blanc and Michalakis 2016; Mauck et al. 2014; Shalileh et al. 2016; Tomitaka et al. 2015). Information on virus-thrips-host plant interactions is available to some extent for thrips – tospovirus interactions (Abe et al. 2011; Tomitaka et al. 2015), where the mode of virus transmission is persistent circulative (Whitfield et al. 2005). However, there is a scarcity of information on mechanisms mediating multitrophic interactions between host plant–thrips–MCMV, where the mode of virus transmission is semi-persistent and noncirculative (Cabanas et al. 2013). Hence, this study was designed to examine the chemical ecology of MCMV-vectorhost plant interactions. The behavioural responses of two thrips species, i.e. maize thrips (F. williamsi) and onion thrips (T. tabaci), to maize volatiles inoculated with MCMV and healthy maize plants were investigated. Moreover, the volatile profiles from MCMV infected and healthy maize plants were characterized and compared by gas chromatography (GC) and GC coupled mass spectrometry (GC-MS). Information on the underlying mechanism mediating thrips vectors, MCMVand maize plants interactions may help in better understanding of vector ecology and epidemiology of the pathogen.

METHODS AND MATERIALS

Plants and Virus Inoculation. Disease-free maize seeds of variety H6210 were planted singly in pots (21cm in height, 20cm diameter) filled with sterilized (autoclaved) soil in an insect-proof screen house at the International Centre of Insect Physiology and Ecology (*icipe*), Duduville campus, Nairobi. Three weeks-old plants, at principal phenological growth stage one (BBCH-scale, Lancashire et al. 199l) were used in experiments. The plants were artificially inoculated with *Maize chlorotic mottle virus* inoculum consisting of infected leaf sap in 0.01 M potassium phosphate buffer (PH 7.0) and carborundum 100 mesh grit (Wangai et al. 2012). Application to the host plant was done using a soft finger-rubbing technique, i.e. by dipping cheesecloth-tied fingers in the inoculums, and gently rubbing the maize plant leaves and later incubating in a separate screen house for one week before use in the experiments. Concurrently, control plants were treated the same way, but without virus inoculum.

Insects. Adult maize thrips, *Frankliniella williamsi* and onion thrips, *Thrips tabaci* were obtained from thrips cultures maintained at the Thrips IPM program lab at *icipe*, Duduville campus. The thrips culture was originally initiated through adult thrips that were field-collected from maize and onions fields in the Central Kenya. The field-collected insects were reared on baby corn, *Zea mays* and snow peas, *Pisum sativum*, respectively as described by Nyasani et al. (2013) and maintained in ventilated plastic jars (17 cm in height, 8 cm diameter) at 25±1°C, 50–60% relative humidity (RH) and 12L: 12D photoperiod. The laboratory-reared adult thrips used in various behavioral assays were maintained for more than 30 generations in the lab with intermittent infusion of field collected thrips to keep the original behavioral characteristics of the species. Identification and separation of male and female adult thrips was based on visible external morphological features under a stereomicroscope (Moritz et al. 2013). Female and male thrips of each species were aspirated and transferred separately into ventilated plastic jars.

Collection of Plant Volatiles. Plant volatiles from maize seedlings infected with MCMV (N=6) and healthy plants (N=6) were collected by headspace sampling (Tamiru et al. 2011). Prior to volatile collection, individual maize plants were placed inside odourless polyethyleneterephthalate (PET) bags (volume 3.2L, ~12.5 mm thickness) heated to 100°C for 1 hour before use and fitted with Swagelock inlet and outlet ports. The bottom of each bag was tightened around the plant stem and the upper bag opening closed with a twist-on seal. Charcoal-filtered air was pumped constantly at 500 ml min^{-1} through the inlet port for 24 hrs. Headspace volatiles were simultaneously collected at room temperature on Porapak Q (0.05 g, 60/80 mesh; Supelco) filters inserted in the outlet port through which air were drawn at 300 ml min^{-1}. After entrainment, volatiles retained in the Porapak Q filters were desorbed with 0.5 ml dichloromethane. Each sample was stored at -20°C in individual small glass vials (2 ml, Agilent Technologies) with polytetrafluoroethylene (PTFE) lined screw cap until used in the bioassay and GC and GC-MS analyses.

Four-arm Olfactometer Bioassay. Behavioural responses of the two thrips species to volatiles from MCMV infected and healthy maize seedlings were tested in a Perspex four-arm olfactometer as described in Tamiru et al. (2011) (Figure 1). Headspace samples (10µl aliquots) were applied, using a micropipette (Drummond 'microcap',

Drummond Scientific Co., Broomall, PA, USA), to pieces of filter papers (4×25 mm) placed in the inlet port at the end of each olfactometer arm. A choice-test was carried out where the two opposite arms held the test stimuli (10µl aliquots of headspace sample) and the remaining two arms were solvent controls. Putative non-viruliferous male and female thrips of each species were starved for 24 hrs and acclimatized at a room temperature for 2 hrs. A single adult thrip of specific species and sex was individually transferred into the central chamber of the olfactometer using a soft camel-hair brush. Air was drawn through the four open-ended olfactometer arms towards the centre at 260 ml min^{-1}. The time spent by thrips in each olfactometer arm was recorded with 'Olfa'software (F. Nazzi, Udine, Italy) for 12 min. To avoid directional bias, the position of the treatments was randomly allocated between each replicate and the olfactometer arms were gently rotated 90^{o} after every 3 min during the test. Each olfactometer was used only once per replicate and scrupulously cleaned before the next bioassay run. The olfactometers were washed with an aqueous solution of Teepol, 80% ethanol and rinsed with distilled water and air-dried; whereas, the glass arms were further cleaned with acetone and sterilized in an oven at 150°C for 2 hrs. The experiment was replicated 12 times (each insect representing a replicate). Test insects were discarded when they remained motionless for more than 2 uninterrupted minutes and replaced with new ones.

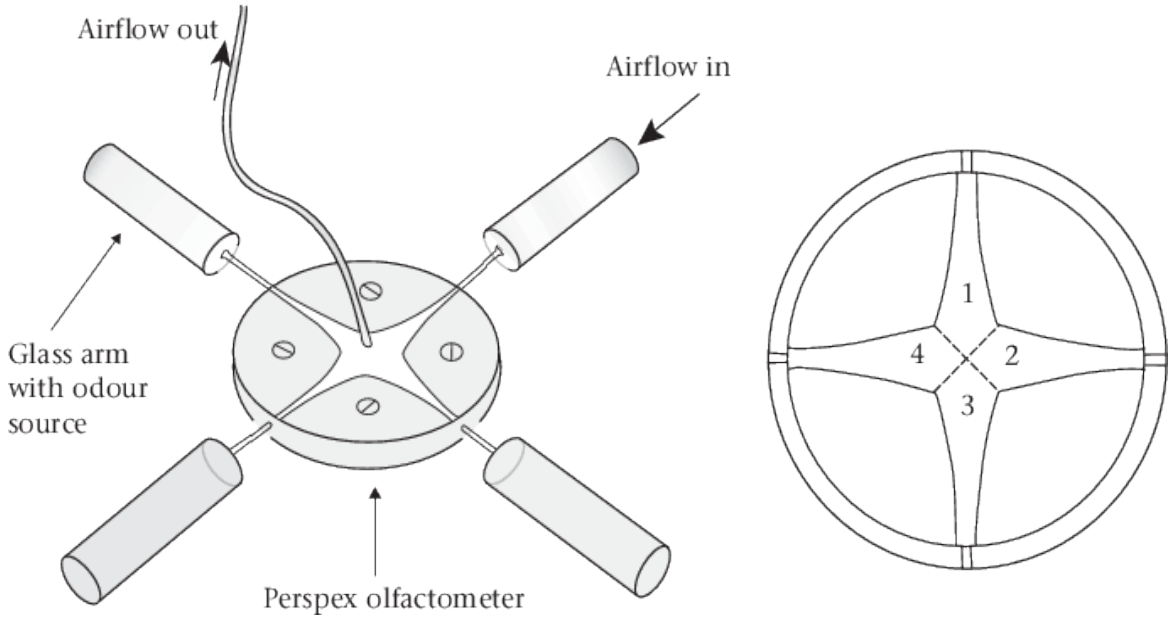

FIG. 1 A schematic diagram representing the four-arm olfactometer (120 mm diameter) with cylindrical glass arms (90 mm × 20 mm internal diameter with 50 mm × 3mm internal diameter connecting arms) used to contain odour sources alongside diagram showing division of regions within the olfactometer.

Gas Chromatographic (GC) Analysis. GC analysis was carried out by injecting 2 µl of headspace sample onto an Agilent 6890 GC equipped with a cross-linked methyl silicone capillary column (HP-1, 50 m, 0.32 mm i.d, 0.52 µm film thickness) fitted with a cool-on-column injector and a flame ionization detector (FID). The carrier gas was hydrogen. The oven was maintained at 30 ^{o}C for 1 min and then programmed at 5 ^{o}C min^{-1} to 150 ^{o}C and 10 ^{o}C min^{-}

^{1} to 250 ^{o}C with a total run time of 55.1 min. Quantification of the volatile compounds was performed with a multiple point external standard calibration method using GC traces peak area data acquired from nine different concentrations (0.001, 0.005, 0.01, 0.05, 1, 5, 10, 25, 50 ng μl^{-1}) of authentic standards.

Coupled GC-Mass Spectrometry (GC-MS) Analysis. Aliquots of headspace volatile samples (1µl) from MCMV infected and healthy plants were analysed with VG AutoSpec mass spectrometer (Fisons Instruments, Manchester, UK) coupled to a Hewlett Packard 5890 GC equipped with a cool-on-column injector. Ionization was performed by electron impact (70 eV, 220^{0}C). To separate the volatiles, non-polar column (HP-1, 50 m, 0.32 mm i. d., 0.52 µm film thickness) was used with Helium as carrier gas at constant flow. The oven temperature was maintained at 30ºC for 1 min, then programmed at 5^{0}C min^{-1} to 150 ^{o}C and 10 ^{o}C min^{-1} to 250 ^{o}C with a total run time of 70 min. The volatiles were then identified by comparison of retention times and mass spectra with those of authentic standards, reference library (NIST05) and with MS data published in the literature. Identifications were confirmed by peak enhancement with authentic samples (Tamiru et al. 2011).

Data Analyses. Statistical analyses were performed using R statistical software, version 3.2.3 (R Core Team 2015). Time spent in each arm of the four-arm olfactometer bioassay was compared by analysis of variance (ANOVA) after conversion of the data into proportions and a log ratio transformation. Significant means were separated using Student Newman Keul (*SNK*) test. All tests were performed at 5% significance level.

RESULTS

Behavioral Responses of Frankliniella williamsi: Both female and male *F. williamsi* spent significantly more time in the olfactometer arm containing volatiles from plants inoculated with MCMV in comparison to those containing volatiles from healthy plants and solvent controls (Male: F=7.67, P=0.0014; Female: F=13.52, P<0.0001) (Figure 2). The time spent by males in areas with volatiles from MCMV infected plants was 1.69 and 1.78 times higher than in areas with volatiles from uninfected plants and solvent control, respectively. On the other hand, females spent 1.47 and 2.02 times more time in areas with volatiles from MCMV infected plants compared to areas with volatiles from uninfected plants and solvent control, respectively.

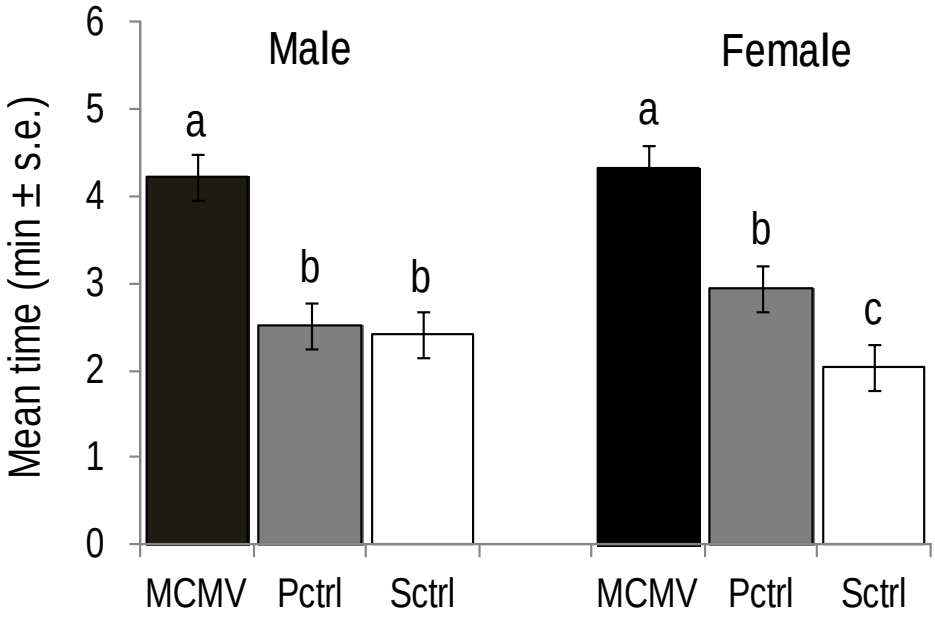

FIG. 2 Behavioral responses of maize thrips, *Frankliniella williamsi*, to maize volatiles from *Maize chlorotic mottle virus* (MCMV) infected plants, healthy plants (Pctrl) and solvent control (Sctrl) in a four-arm olfactometer bioassay. Each insect was observed for 12 min (N = 12). Mean time spent ± *SE* (minutes) by *F. williamsi* in each part of the olfactometer is shown. Different letters above the bars indicate statistically significant differences based on the Student–Newman–Keuls (*SNK*) test ($P < 0.05$).

Behavioral Responses of Thrips tabaci. Male *T. tabaci* were significantly attracted to volatiles from MCMV inoculated plants compared to healthy plants and solvent controls (F=3.98, P=0.027) (Figure 3). The male preference for volatile for MCMV infected plants was 1.58 and 1.62 times higher than for volatiles from healthy plants and solvent control, respectively. However, there was no significant difference between time spent by females in olfactometer arms containing volatiles from MCMV inoculated plant and non-inoculated plants and solvent controls (F=0.79, P=0.4590) (Figure 3).

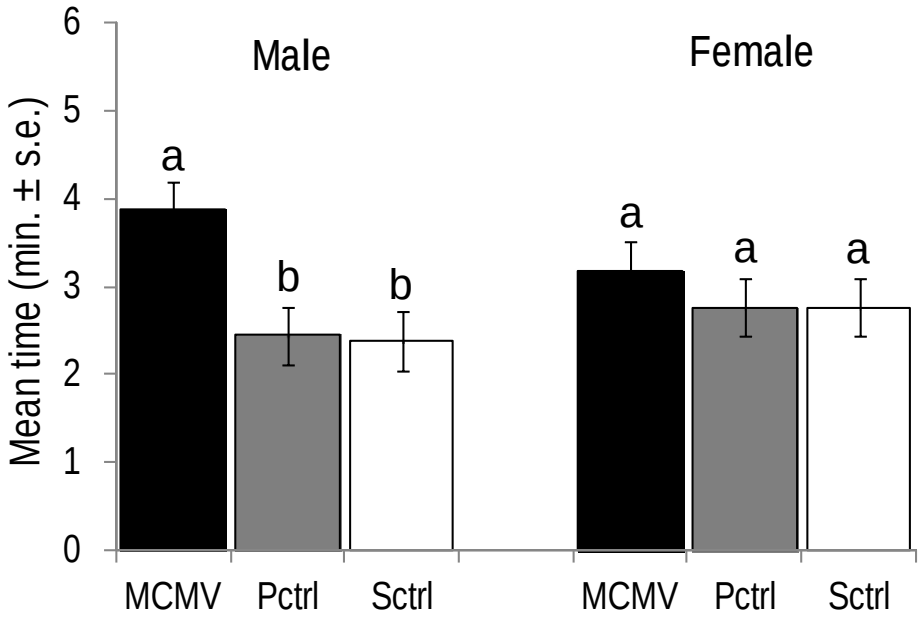

FIG. 3 Behavioral responses of onion thrips, *Thrips tabaci*, to maize volatiles from *Maize chlorotic mottle virus* (MCMV) inoculated plants, healthy plants (Pctrl) and solvent controls (Sctrl) in a four-arm olfactometer bioassay. Each insect was observed for 12 min (N = 12). Time spent (min; mean ± *SE*) by *T. tabaci* in each part of the olfactometer is shown. Different letters above the bars indicate statistically significant differences based on the Student–Newman–Keuls (*SNK*) test ($P < 0.05$).

Volatile Analysis. Chemical analysis of headspace samples revealed qualitative and quantitative changes in the volatile profiles of MCMV infected and uninfected (healthy) maize plants (Figure 4). There was strong induction of (*E*)-4, 8-dimethyl-1,3,7-nonatriene (DMNT), methyl salicylate (MeSA) and (*E*,*E*)-4,8,12-trimethyltrideca-1,3,7,11-tetraene (TMTT) on maize plants inoculated with MCMV compared to healthy plants (Figure 4). MCMV inoculated maize plants emitted significantly higher amounts of the bioactive compounds DMNT, MeSA and TMTT compared to healthy plants. Mean emission rates (ng kg^{-1} fresh weight hr^{-1}) of the major volatile compounds in MCMV infected and healthy plants are presented in Table 1.

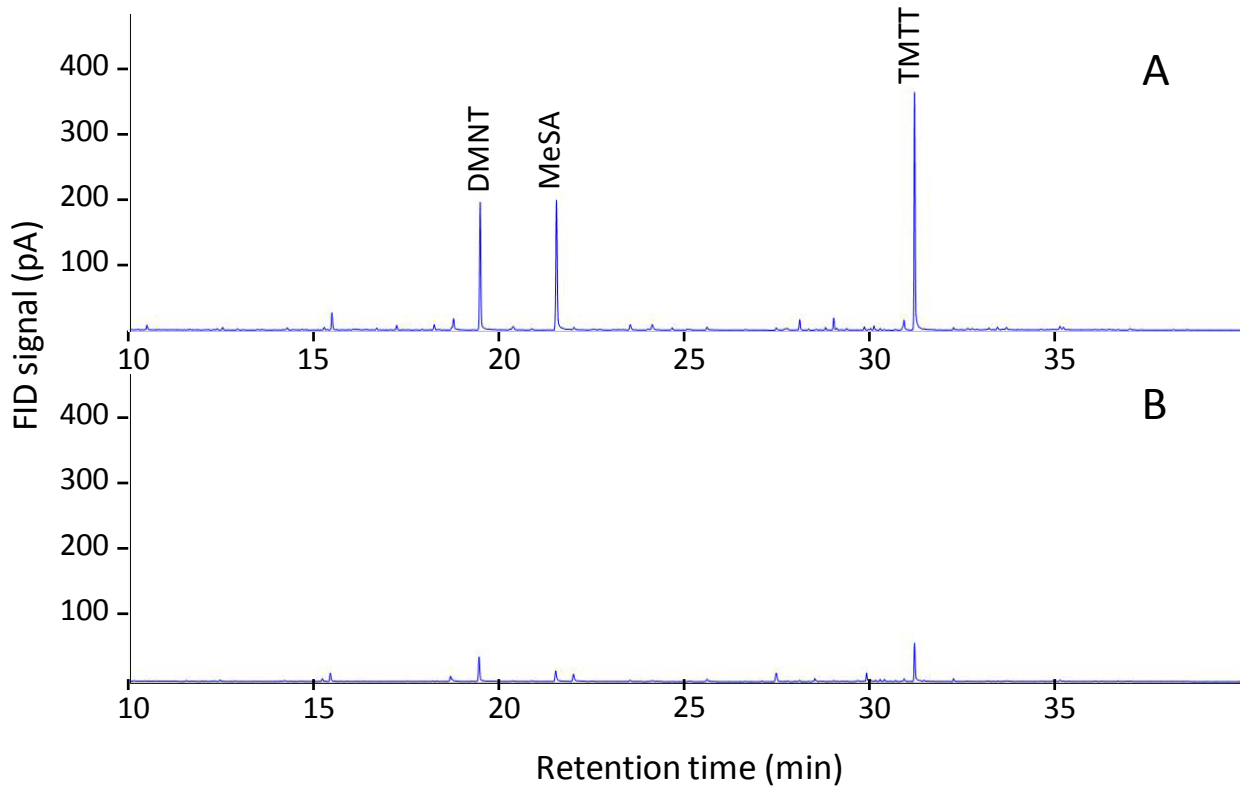

FIG. 4 GC profiles of headspace volatiles from (A) *Maize chlorotic mottle virus* infected and (B) healthy maize seedlings. There was strong induction of (*E*)-4,8-dimethyl-1,3,7-nonatriene (DMNT), methyl salicylate (MeSA) and (*E*,*E*)-4,8,12-trimethyltrideca-1,3,7,11-tetraene (TMTT) in maize plants infected with MCMV. The X-axis represents retention time in minutes (min) while Y-axis gas chromatography–flame ionization detector (GC–FID) signal in pico-ampere (pA).

TABLE 1. Emission rates of strongly induced volatiles compounds from maize plants inoculated with the *Maize chlorotic mottle virus* (MCMV) and healthy plants

Volatiles compounds	Mean volatile emission rates (ng kg fresh weight^{-1} hr^{-1}) (±*SE*)		*F*	*P*
	MCMV infected Plants	Healthy Plants		
(*E*)-4,8-dimethyl-1,3,7-nonatriene (DMNT)	18.70 (±1.09) a*	4.13 (±1.34) b	59.28	0.0046
Methyl salicylate (MeSA)	58.29 (±9.35) a	4.20 (±1.45) b	79.25	0.0030
(*E*,*E*)-4,8,12-trimethyltrideca-1,3,7,11-tetraene (TMTT)	26.84 (±4.33) a	6.33 (±1.73) b	27.54	0.0135

*Means followed by different letters, within a row, are significantly different (N=6, *SNK* test $P < 0.05$)

DISCUSSION

Our results revealed that infection of maize plants with the maize chlorotic mottle virus (MCMV) induces changes in volatile profiles of plants leading to significant attraction of thrips vectors F. williamsi, and T. tabaci to the infected plants. There was a strong induction of volatile compounds (E)-4,8- dimethyl-1,3,7-nonatriene (DMNT), methyl salicylate (MeSA), (E,E)-4,8,12-trimethyltrideca-1,3,7,11-tetraene (TMTT) on maize seedlings inoculated with MCMV. The significant increase in the release of these compounds corresponded with the attractiveness of the headspace samples from MCMVinoculated plants to the thrips vectors. Previous studies have shown that plant viruses induce changes in plant volatile profiles which, in turn, may affect the behavioral responses of their vectors (Eigenbrode et al. 2002; Mauck et al. 2014; Oluwafemi et al. 2011). For example, the level of MeSA has been shown to increases dramatically on tobacco (Nicotiana tabacum) after inoculation with the tobacco mosaic virus (Seskar et al. 1998). Similarly, high levels of bioactive compounds such as linalool and DMNT were observed in cucumber mosaic virusinfected chilli plants (Capsicum annuum) and on tomato plants infected with tomato spotted wilt virus (Maris 2004; Saad et al. 2017). However, there is paucity of information about induction of changes in the host plant volatile profiles due to MCMVinfection or other viruses belonging to the family Tombusviridae. Results from our study demonstrated induction of changes in volatile profiles of maize plants due to MCMV infection which elicited positive behavioral responses in the thrips vectors. We have also characterized the key volatile semiochemicals mediating thrips vectors-MCMV-host plant interactions. Understanding the underlying mechanism mediating thrips vectors, MCMV and maize plants interactions will help to better understand vector ecology and epidemiology of the MCMV. This, in turn, may provide useful inputs towards designing semiochemical based integrated vector management strategy (Cook et al. 2007; Mfuti et al. 2017; Niassy et al. 2012).

In the behavioral study, both sexes of F. williamsi and male T. tabaci were significantly attracted to maize volatiles infected with MCMV compared to healthy plants. This concurs with previous studies on other thrips and insect species which showed preference of insect vectors for plants infected with virus (Mauck et al. 2014; Tomitaka et al. 2015). Host plant location by insects involves detection of specific compounds and/or blends of volatile semiochemicals in specific ratios (Bruce and Pickett 2011; Tamiru et al. 2015). Studies have shown that DMNT, MeSA and TMTT are produced in higher quantities after insect infestation on plants and elicitspotent attraction of pests' natural enemies individually and/or as a blend (de Boer and Dicke 2004; Mallinger et al. 2011; Tamiru et al. 2011, 2015; Turlings et al. 1998). In western flower thrips, F.occidentalis, DMNT and MeSA have been shown to elicit behavioral responses (Chermenskaya et al. 2001; Koschier et al. 2007; Maris 2004). The strong induction of the bioactive compounds DMNT, MeSA and TMTT onMCMV inoculated plants and preference of both thrips species to virus induced volatiles from infected plants compared to volatiles from healthy plants suggests that MCMV alters emission of maize volatiles to enhance attraction of thrips vectors. If the thrips vectors subsequently feed on the infected plants for sufficient time to acquire the pathogen prior to dispersal, this attractive phenotype may lead to enhanced virus spread. Adult thrips transmit MCMV for up to 6 days after acquisition with no need for latent periods (Cabanas et al. 2013). Increasing number of evidences suggested the advantages of vector attraction to

virus infected plants in promoting disease transmission and spread (Belliure et al. 2005; Eigenbrode et al. 2002; Shapiro et al. 2012; Sisterson, 2008).

Interestingly, differences in behavioral responses between male and female T. tabaci were observed in this study. Unlike the males, female T. tabaci did not show preference to volatiles from MCMV infected plants. The low female T. tabaci response to MCMV infected maize plants compared to F. williamsi could be attributed to the fact that maize is not the primary host for T. tabaci although the pest is polyphagous (Moritz et al. 2013). Moreover, T. tabaci was reared on a different host plant, i.e. snow peas, which could influence the choices that the insect makes when experiencing new odor. Silva et al. (2013) reported context dependent behavioral responses of two congeneric thrips, Frankliniella schultzei (Trybom) and F. occidentalis (Pergrande), to induced plants volatiles. Furthermore, feeding behavior of thrips vectors to virus infected plants is known to differ between the sexes and viruliferous nature of the pests. For example, males of western flower thrips, F. occidentalis, transmit tomato spotted wilt virus more efficiently than females (Stafford et al. 2011; Van De Wetering et al. 1999). This could be due to more robust virus infection of males and sexually dimorphic feeding behaviors (Rotenberg et al. 2009; Van De Wetering et al. 1999). Our present study provides additional evidence on sexually dimorphic behavioral responses of onion thrips, T. tabaci, towards MCMV infect maize plants.

Transmission efficiency of a virus in the field is determined, among other factors, by the number of viruliferous vectors in the population and their sex ratio (VanDeWetering et al. 1999), their interaction with the host plant at different phases of infectionBlua and Perring, 1992) and spatial distribution of infected plants (McElhany et al. 1995). Hence, a better understanding on the chemical ecology of thrips vectors, MCMV and host plants interactions could provide valuable insight into developing environmentally sustainable and effective thrips vectors monitoring and management tools by exploiting plant derived volatile semiochemicals mediating the interactions. This, in turn, will greatly contribute towards disease management efforts by mitigating virus transmission and spread while maintaining ecologically integrity. For example, studies have shown that addition of semiochemical attractants to monitoring tools like sticky cards increases capture of thrips species such as western flower thrips and onion thrips (Abdullah et al. 2015; Koschier 2008; Teulon et al. 2014). Similarly, semiochemical-baited autoinoculation devices treated with fungal-based biopesticides e.g. Metarhizium anisopliae have been used to control thrips (Niassy et al. 2012). Evaluating and improving the efficacy of such control strategies through the addition of optimally attractive semiochemicals into the pest's monitoring and management tools is one of the goals for improving IPM. Multi-trophic interactions between insect vectors, host plants and viruses causingMLNis a complex pathosystem. Our current findings established that MCMV, one of the causative agents of MLN, infection induces changes in volatile profiles of maize plants to attract thrips vectors and characterized the main volatile compounds mediating the interactions. Examining the role of individual volatile components and their blends in influencing thrips behavior and vector competence including their effects on insects settling, virus acquisition and dispersal under laboratory and field condition is an important goal for future research. This will provide further clarity on the Maize-MCMV-thrips interactions and virus epidemiology and aid in designing integrated thrips and MCMV management strategies.

Exploiting plant volatile semiochemicals has been shown to present novel and ecologically sustainable pest management opportunities (Tamiru and Khan 2017; Teulon et al. 2014).

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COMPLIANCE WITH ETHICAL STANDARDS

Conflict of Interest - The authors declare that they have no conflict of interest.

Ethical Approval - Experiments were performed in accordance with relevant guidelines and regulations on studies on live animals.

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