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Review Article

Survival Mechanisms and Management Challenges Associated with Silver Leaf Whitefly on Tomato in Africa: A Review

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Abstract

Silver leaf whitefly (*Bemisia tabaci* Gennadius) (Hemiptera: Aleyrodidae) is a polyphagous winged insect pest that causes high yield losses in tomatoes and other vegetable crops globally. To combat the infestation by the silver leaf whitefly and other insects, tomato growers use cultural and synthetic chemical-based methods. However, the silver leaf whitefly continues to dominate the tomato production systems. Some of the reasons for such continued dominion by the silver leaf whitefly in tomato include among other reasons; little understanding of the mechanisms for survival of the insect pest by tomato production stakeholders which consequently results in difficulties in making appropriate pest management decisions, presence of diverse hosts, the ability of the silver leaf whitefly to develop resistance to synthetic pesticides and ineffective techniques used by tomato grower in combating the insect. Of these challenges, this review discusses the mechanisms for survival of the insect, current pest management options and recommendations for a way forward concerning the silver leaf whitefly management in Africa.

Keywords: *Bemisia tabaci*; Survival mechanism; Control techniques; Continued dominion; Joint action

Introduction

Silver leaf whitefly (*Bemisia tabaci* Gennadius) is an invasive insect pest that threatens tomato (*Lycopersicum esculentum* L.) and other various cultivated and weed plant species worldwide (Sri and Jha 2018). In Africa, silver leaf whitefly like in other areas of the world has been reported to affect the crops both directly and indirectly. The direct effect occurs when the silver leaf whitefly nymph or its adult pierces and sucks the plant phloem using the stylets to exploit nutrients, consequently reducing its growth vigour (McKenzie *et al.* 2014). The damaged tomato develops chlorosis, stunting and stopping its growth and making the plant wilt (McKenzie *et al.* 2014). The direct effects also include secretion of honeydew by the insect leading to the development of black sooty mould on plant vegetative parts consequently impairing plant's photosynthetic efficiency, leading to low plant productivity (Mugerwa *et al.* 2021). The indirect effects of silver leaf whitefly on a tomato plant are from its ability to vector > 350 pathogenic plant viruses, which cause diseases of economic importance in tomatoes and other crops in the tropical and subtropical regions (Zhang *et al.* 2014; Ochilo *et al.* 2019). The combined effects of the silver whitefly (whether direct or indirect) causes significant yield losses of up to 100% in tomatoes which are equated to worth more than one hundred million dollars each year (Moodley *et al.* 2019).

Efforts for managing silver leaf whitefly are always going on; however, the following challenges affect the effectiveness of the management efforts. The main challenges are; the majority of tomato growers in Africa have little understanding of the mechanisms for survival of the insect pest making then ineffectively managing the pest (Laizer *et al.* 2019), presence of diverse host range (Simmons and Riley 2021) and ability of this pest to develop resistance to synthetic pesticides (Legg *et al.* 2014). Thus, this review discusses the survival mechanisms of silver leaf whitefly, its management options and recommendations for a way forward to control silver leaf whitefly in Africa.

Silver leaf whitefly survival mechanisms

Silver leaf whitefly uses different strategies to colonize and survive in different environments (Jiu *et al.* 2017). The most common mechanisms are discussed below:

Life cycle and small body size

The life cycle of silver leaf whitefly goes through three main stages: egg, four larval stages and the adult (Walker *et al.*

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2009). The average time between laying eggs to the first larval stage is seven (7) days, and that from first to second and second to third, third to fourth and fourth to adult is 3–4, 2–3, 2–3 and 3–5 respectively (Ghelani *et al.* 2020). This style allows the silver leaf whitefly to produce 11–15 generations per year in tropical climate areas, leading to an increase of its population within a short period (Liu *et al.* 2015; Jiu *et al.* 2017).

The body size of the silver leaf whitefly also gives it an easy survival favor. For instance, at emergence, the size is 0.5 mm long and attains a maximum of 2 mm at the adult. This makes the insect feed on a small amount of food. In addition, males are smaller than females making matting easy and the small sizes of the insects allow them to move from place to place unnoticed through wind and human activities (Kliot *et al.* 2016).

Haplodiploid mode of reproduction

The reproduction systems of silver leaf whitefly are in such a way that females are diploid as they develop from the fertilized eggs, while males are haploid as they grow from unfertilized eggs. This mechanism allows females to control the males and or female ratio making their growth difficult to predict and manage (Gill *et al.* 2015). The males lack one of the genome copies, impairing their fitness as they develops less resistance to environmental pressure, including pesticides, than is the case with the diploid insects (Kliot *et al.* 2016). In the case of positive selection of resistant mutations in silver leaf whitefly males, only individuals with resistant alleles will survive the selection pressure when pesticides are applied, whether they are recessive or dominant. Such individuals will pass the resistant allele to their progeny, resulting in a generation resistant to pesticides that becomes irreversible within a few generations in case of equal male: female ratio resistance and increases the difficulties in controlling the pest (Kliot *et al.* 2016).

Hiding and cuticle waxy materials

The female silver leaf whitefly lays eggs in a circular group under the leaf surface (Sri and Jha 2018) and inserts them in the leaf tissues to hide and protect them from enemies (Vashisth *et al.* 2013). Additionally, all other silver leaf whitefly developmental stages continue under the leaf surface to defend themselves against enemies, sunburn and heat stress, rainwater during heavy rains, and pesticides from overhead spraying (Kumar *et al.* 2017). In addition, the waxy cuticle material covering silver leaf whiteflies' bodies protect them from dehydration, natural enemies, mechanical damage and toxic molecules such as pesticides (Schoeller *et al.* 2018).

Adaptation

Silver leaf whiteflies have a high ability to cope with different environmental (abiotic and biotic) stresses such as pesticides molecules and high temperatures (Firdaus *et al.* 2013). The pests survive up to the environmental temperatures of 20–30°C (Xiao *et al.* 2016). The symbiotic association between silver leaf whitefly and some primary and secondary bacteria is the tentative reason for silver leaf whitefly survival under these harsh environments (Lv *et al.* 2018).

The primary symbionts provide silver leaf whitefly with essential nutritional elements, especially in a poor diet, for example, *Portiera aleyrodidarum* that synthesize some amino acids and carotenoids, which silver leaf whiteflies cannot synthesize (Skaljac *et al.* 2017). In addition, some secondary symbionts give silver leaf whitefly immunity and affect their development and reproduction (Ferrari and Vavre 2011), while others especially those localized in the salivary glands and the midgut facilitate virus transmission (Rana *et al.* 2012).

Wide host range

Silver leaf whitefly feeds on more than 900 plant species of different families, both cultivated and wild (Gill *et al.* 2015; Alam *et al.* 2016). Such silver leaf whitefly host plants are present in Africa, where the tropical climatic condition favors massive biodiversity (Primack and Corlett 2011). As such, during the offseason, silver leaf whitefly relies on these alternative host plants while waiting for their favorite hosts in the cropping season, thereby increasing their survival chance and enabling them to colonize a wide range of distribution. Additionally, the global trade of silver leaf whitefly host plant materials widened the spread of silver leaf whitefly (Hadjistylli *et al.* 2016).

High genetic diversity of silver leaf whiteflies

The silver leaf whitefly has high genetic diversity seen from a complex of biotypes called cryptic species (Boykin and Barro 2014). Biotypes of the silver leaf whitefly are differentiated based on molecular polymorphism. Such biotype or species differences are expressed in the ability of a particular biotype to cause plant disorders, attract natural enemies, susceptibility to insecticides and resistance expression, host range and capabilities to transmit plant virus (Hadjistylli *et al.* 2016). Also, different biotypes of silver leaf whitefly respond differently to control measures applied which necessitate the knowledge on the silver leaf whitefly biotypes present in a particular place (Naveen *et al.* 2017).

Based on these characteristics, more than 44 silver leaf whitefly cryptic species are reported globally (Acharya *et al.* 2020). However, a recent study found the addition of three silver leaf whitefly species in Uganda, where they were named Sub Saharan Africa 14–16 (Mugerwa *et al.* 2021). In Africa, the Sub Saharan Africa 1–5, Sub Saharan Africa 6 or Uganda 3, Sub Saharan Africa 7, Indian Ocean and East

African 1, the Mediterranean species (MEM) and the Middle East Asia Minor I (MEAM I) are present (Mugerwa *et al.* 2018). Studies show silver leaf whitefly of Sub Saharan Africa species to be the most widely distributed occurring in West, East and South Africa, on contrary, Sub Saharan Africa 4 and 5 occasionally occur in Cameroon and South Africa, respectively (Legg *et al.* 2014). The Middle East Asia Minor I (MEAM I) and Mediterranean silver leaf whitefly species (MEM) are the most invasive and globally distributed, while the Mediterranean species is the most spread (Shadmany *et al.* 2019; Kriticos *et al.* 2020).

Silver leaf whitefly management options and their associated advantages and challenges

Some control methods and challenges associated with silver leaf whitefly are summarized in Table 1. Nevertheless, the insect is very difficult to control since besides its role as a pest, it carries and transmits viruses that cause economically critical viral diseases (Satar *et al.* 2018). Therefore, the management of silver leaf whitefly as a pest and as a vector for various diseases is essential. Tomato growers apply different Pest Management options globally to reduce infestation by silver leaf whitefly as discussed hereunder:

Integrated pest management (IPM)

IPM is a long term, economical and eco-friendly silver leaf whitefly control strategy of mitigating the adverse effects of pesticides resulting from extensive use of synthetic pesticides during the green revolution (Lamichhane *et al.* 2016; Wilson and Daane 2017; Horowitz *et al.* 2018). The method employs a combination of control methods of silver leaf whitefly such as biological control, modification of cultural practices, the use of resistant varieties and, when needed, judicious and timely use of chemical pesticides (Flint and Bosch 2012).

IPM focuses mainly on monitoring, pest avoidance and practical chemical usage to ultimately develop the most effective and cost-effective solution to silver leaf whitefly management (Legg *et al.* 2014). As such IPM reduced pesticides usage and sustained the reduction of the silver leaf whitefly population with economic benefits of more than $US 200 million. In Burkina Faso, pyriproxyfen as a growth regulator was used and proved to be effective in controlling silver leaf whitefly and conserving the natural enemies in cotton (Horowitz *et al.* 2018). Planting the tomato associated with aromatic plants reduced silver leaf whiteflies, unlike the case with tomatoes grown as a mono-crop because the volatiles disrupts the silver leaf whitefly development while promoting the development of the host plants in Burkina Faso (Son *et al.* 2018). In South Africa, a mixture of fermented plant extract from neem leaves and wild garlic reduced Silver leaf whiteflies and aphids on tomatoes (Nzanza and Mashela 2012).

Biological control

Biological pest control involves the use of other living organisms such as predators, insect pathogens and parasitoids to reduce the population of another organism such as the silver leaf whitefly (Lenteren *et al.* 2018). The method has been in use for over 2000 years when the augmentative release of *Encarsia* species (Hymenoptera: Aphelinidae) in 1027 successfully controlled greenhouse silver leaf whitefly *Trialeurodes vaporariorum* (Westwood) (Speyer 1927). Biological silver leaf whitefly control can be conservation, natural, augmentative or classical (Cock *et al.* 2010).

Conservation of biological silver leaf whitefly control includes human actions aiming at protecting and stimulating the functioning of naturally occurring natural enemies in the environment, and it is currently receiving much attention (Mendes *et al.* 2011). Natural biological silver leaf whitefly control is an ecosystem service where naturally occurring beneficial organisms reduce the pest population with no human intervention. In contrast, classical biological silver leaf whitefly control through humans collecting the natural enemies from the area of origin and releasing them to the places where the pest is invasive to permanently reduce the problem (Cock *et al.* 2010).

Finally, augmentative biological silver leaf whitefly control can either be inundative or inoculative. In the inundative control, the natural enemies are mass-reared and released in large numbers to have immediate pest control on crops with a short production cycle. In contrast, in inoculative control, the natural enemies are mass-reared and released in large numbers to control pests in several generations in crops with a long production cycle (Lenteren 2012). Below is the review of some biological agents used in controlling silver leaf whitefly.

The use of natural enemies (Parasitoids and Predators)

Parasitoids are insects whose larvae live as parasites that eventually kill their hosts. About 115 species of silver leaf whitefly parasitoids from 23 genera in the family Anatidae, Aphelinidae, Signiforidae, Platygastridae, Pteromalidae, Encyrtidae, Eupelmidae and Eulophidae, are widely used to control silver leaf whitefly in the tropics (Lahey and Stansly 2015; Ramos *et al.* 2018).

For example, the use of aphelinid (tiny parasitic wasp) from the genus Eretmocerus, especially *E. melanoscutus* and *E. Mundus*, proved successful in controlling silver leaf whitefly in Southern America (Navas-Castillo *et al.* 2011). Chalcidoid wasp (*Encarsia Formosa)*, a parasitic wasp, is also used in controlling the silver leaf whitefly. The adult lay eggs inside the silver leaf whitefly larvae, and on hatching, the young Encarsia feed on the larvae from inside out.

On the other hand, predators are organisms that kill and eat other organisms (Roda *et al.* 2020). However, their

Table 1: Framework of the silver leaf whitefly Control Measures and their Applicability in Africa Farming context

Silver leaf whitefly control Method	Method Description	Applicability	Afford-ability	Reasons for method applicability
Biological Methods: Entomopathogens, parasitoids Predators EPNs	Specific to target pest. Work better in screen houses/greenhouses Less developed in Africa Great opportunity to reduce synthetic pesticide uses	** *	*	Expensive and not common in the Africa farming context African small-scale farmers do not manage greenhouse production (dominate the sector) Require non-contaminated environment for their survival Lack of identity, selection, preparation and application knowledge Rectifies synthetic pesticides problems
Management of fertilizer and irrigation	Crops become succulent and prone to silver leaf whitefly attack	*	*	Africa soils are fertile and with farm yard manure (FYM) from domestic animals, farms have enough Nitrogen. Agriculture in Africa is mostly rain-fed or conducted near water bodies and so a possibility of crops becoming succulent and so attractive to silver leaf whitefly
Fallowing/host free period	The period between successive planting is left in-between seasons- break the host life cycle	**	*	Require communal efforts to create host free period-Require big land and there is a scarcity of fertile land Require knowledge to know alternative host plants to the pest to avoid them
Trap crops	Alternative host crops that attract and hold the pest to reduce the attack to the main crop	***	***	Available and affordable in the Africa farming context Planted as border rows-attract the pest Gives soil organic matter/ animal feed
Reflectance mulch	reflectance created by coloured mulch scares silver leaf whitefly from the host plant	***	*	Poor availability and affordable of mulch materials by most African farmers Suitable for greenhouse crop production as it covers a small area Crops with reflectance characteristics that can be used as mulch are not known to farmers.
Intercropping and companion farming	Different crops planted on the field at the same time pests move from crop to crop-spend less time/ crop	***	***	Applicable in Africa where farmers grow different crops in their fields as a means of diversification unlike mono-cropping in the developed world Farmers have narrow selection of the best plants to be intercropped to reduce the silver leaf whitefly population due to lack of knowledge.
Sticky traps	They are coloured cards with glue. The colour attracts insect pest and the glue stick them on the card to death	***	*	Used for monitoring pest presence and population to alert the farmer before the pest population reaches the economic threshold level Useful in all farm settings.
Screen houses/greenhouses	Constructed by nets or glasses are used to exclude silver leaf whitefly from the crops	***	*	Construction materials are expensive and so not affordable to resource-poor small-scale farmers
Use of resistant crop varieties	Few resistant crop varieties are available and their development requires high investment in terms of funds and knowledge	***	*	Lack of resistant crop varieties There is a lack of knowledge and fund in their development
Chemical Synthetic	Their use is increasing year after year Adopted as first option control means	*	*	Contaminate the environment, non-target organisms, producers and consumers Pesticides residues in crop produces-trade barrier especially in the EU markets Higher production costs-regular purchase of pesticides Silver leaf whitefly develop pesticides resistance Lack of spraying equipment's and techniques burdened by silver leaf whitefly hiding under the leaf surface Poor instruction as most pesticides' container labels is in a foreign language Less available in rural areas Disposing empty containers and remaining pesticides is tricky

*= Less applicable; **= Applicable; ***= Very applicable

effectiveness is influenced by predators and parasitoids number, release rate, intra- and inter-specific competition, stage, size and density of silver leaf whitefly nymph, environmental factors and host plants that influence the performance of silver leaf whitefly pest (Shah *et al.* 2015). For example, releasing *C. carnea* at different rates leads to a substantial reduction of aphids and silver leaf whiteflies in various vegetable crops. Also, the release of *Chrysoperla carnea* at the rate of five larvae per plant effectively controlled the silver leaf whiteflies and aphids in sweet pepper. In comparison, the release of ten larvae per squash plant was adequate in managing the two pests in Saudi Arabia (Alghamdi *et al.* 2018).

The fact that natural enemies such as predators are affected by the environmental conditions in the season challenge the use of these organisms to control silver leaf whiteflies (Pérez-Hedo *et al.* 2021). Another limitation of using natural enemies is that they can become herbivores and feed on the target crop especially when the target insect pest (prey) population is reduced (scares) or limited by confinement (Urbaneja-Bernat *et al.* 2019; Roda *et al.* 2020). Also, in most cases, natural enemies like parasitoids perform better when applied in greenhouse conditions and combination with other methods. Consequently, selecting suitable individuals for successful silver leaf whitefly control require knowledge that is lacking in most small-scale African farmers. Also, most small-scale African farmers carry tomato production in the open fields. These attributes challenge African crop producers making this method of pest control to have low applicability in Africa (Lenteren 2012). In addition,

Table 2: Key Tomato Production stakeholders and their Inclusive Action in Silver leaf whitefly Management for Increased Tomato Production in Africa

Factor	Challenge	Inclusive action needed
Host plants	Lack of resistant cultivars and wide host range (Gill *et al.* 2015)	Policymakers: Making policies that emphasize on investing in researching resistant plant materials against insect pests Encourage nations to pool resources and efforts to invest on development of resistant plant materials against silver leaf whitefly to safeguard the crops and the environment. Formulating policies that emphasize on extension services provision to educate farmers on selecting planting materials that withstand pests and disease attacks. Researchers: Developing resistant cultivars through researching on wild plant relatives with resistant genes Growers: Use seeds and planting materials from reliable sources, practising good agricultural practices Practice mixed planting that and intercropping increases biodiversity along the field margins to raise the number of natural enemies (Andrew and Hill 2017)
Environmental	The increased drought accelerates silver leaf whitefly invasiveness (Xiao *et al.* 2016).	Policymakers: Formulating policies that advocate the effects of climate change and support research on amelioration/restoration of the ecosystem Researchers: Researching on crops that suit new agro-ecological zones Research and promotion of good agricultural practices to increase resilience to climate change Carrying pest risk surveillance frequently to monitor the climate, pest appearance and abundance and keep up to date pest list Developing and using modelling prediction tools to forecast short- and long-term pest populations Researching on appropriate production, processing, storage and distribution technologies that reduce crop pest infestation (Crawford and Terton 2016). The most commonly mentioned strategies are modified IPM practices, monitoring climate and insect pest populations and the use of modelling predictions tools (Raza *et al.* 2015) Growers: Using production technologies that are produced and approved by research to be appropriate for a specific agro-ecological zone.
Insect pest level	Tricky infestation strategies -hiding under leaf surface (Kumar *et al.* 2017). Pesticide resistance development (Moodley *et al.* 2019) Resisting climate variations (Xiao *et al.* 2016).	Policymakers To advise governments to invest in research on the development of new strategies for pest management such as the development of new pesticides formulations, repellents and attractants (Gomez-Zavaglia *et al.* 2020) Advice governments across Africa to invest in research to develop more non-chemicals tomato pest control means to reduce the use of synthetic pesticides to protect the environment and the people involved in agricultural production. Researchers: Development of new pest pesticides formulations that will reach the pest (stick on the pest for contact pesticides). Research on best pesticides application techniques for effective results Research on newer and efficient biological control agents Research on conventional breeding methods like genetic engineering to come up with resistant plant varieties (Gomez-Zavaglia *et al.* 2020) Growers: Use the approved pesticides and best application methods for best pest control Rely on non-chemical pest control methods and use the chemical pest control method as the last option while well informed on the details of the particular pesticide underuse (Gollin 2018).
Pest control methods	Some pest management options exist although the pest continues to dominate agricultural production systems.	Policymakers: Making policies that put in place pesticides management systems that promote safe, efficient and responsible pesticides use for sustainable agricultural development. Formulating policies that advocate soil conservation, especially in uplands, to encourage the construction of structures such as ridges to reduce runoff speed and silver leaf whitefly spread Researchers: Researching on new and effective pest control methods such as lowering the number of insects to be tolerated before economic yield losses (economic intervention thresholds) are attained Research on simple, cheap, and locally available materials to construct screen houses to allow small resource-poor farmers to practice protected agriculture to minimize silver leaf whitefly attacks on their crops. Isolation and characterization of new predators and parasitoids and find the proper combination for effective pest control. Means of environmental restoration to harbor predators and parasitoids that can kill silver leaf whiteflies. Researching on means of increasing entomopathogenic fungi' virulence, stability, and shelf life Research on cheap and safe irrigation methods for small-scale farmers to reduce the spread of silver leaf whitefly through conventional irrigation methods. Establish soil specific tomato plant mineral requirements for improved African tomato production. Growers Prepare their fields to direct excess water to the water bodies and dig dams to receive and store excess water to avoid carrying silver leaf whiteflies from one area to another. Add organic matter to their tomato fields to improve the soil water holding capacity. Applying soil specific tomato plant mineral fertilizers for improved African tomato production. To research the best combination of the IPM methods to come up with a combination that is effective and efficient in reducing insect population to a manageable level. Growers: Adopt pest control methods developed and approved by researchers to be the best n reducing the pest population.
Production cost	Increased pesticide application rates and frequency (Satar *et al.* 2018) Increased viral diseases (Ochilo *et al.* 2019)	Policymakers: Addressing proper pesticides usage for safer food production and environmental protection Researchers: More research on pesticides with different modes of action and alternatives to pesticides pest control methods Growers: Seeking education and knowledge on pests and their proper control as they lack such knowledge and application of pesticides with different modes of action to break down pest resistance to pesticides (Matowo *et al.* 2020)

there are limited number of known predators and parasitoids for controlling silver leaf whitefly pests.

Use of entomopathogens, particularly entomopathogenic fungi (EPF)

Microorganisms such as bacteria, fungus, and viruses can kill arthropods (Gonzalez *et al.* 2016). Out of all insect-killing entomopathogens, EPF are the most effective against sap-sucking insect pests such as Silver leaf whiteflies worldwide (BuGtI *et al.* 2018), as the fungi directly rupture the host cuticle and enter the silver leaf whitefly haemocoel in the process of sap-sucking unlike bacteria and viruses that need to be ingested by the host (Lacey *et al.* 2015; Dong *et* *al.* 2016). Entomopathogens can exhibit a multi-site action, which prevents silver leaf whitefly from resistance development and if rationally used, they aid in managing resistance (Ruiu 2018).

EPF are pathogenic species to insects such as silver leaf whitefly (Maina *et al.* 2018), taking the lead of biopesticides in the world market in controlling silver leaf whitefly, where about 100 mycoinsecticides are commercially available (Jaronski and Mascarin 2017).

Most EPF are from from the phylum entomophthoromycota and Ascomycota in the order Hypocreales, although they are less aggressive when compared with those from the order entomophtorales (Humber 2012). Those from the order entomophtorales can cause dramatic epizootics that rapidly reduce the silver leaf whitefly population. However, their mass production in the laboratory, storage, and formulation is complex, limiting their use as a biological control (Pell *et al.* 2010).

Commonly commercial and mainly used EPF are *Metarhiziun anisopliae, Lecanicillium or Verticillium, Beauveria bassiana*, *Isaria fumosorosea and Ashersonia* spp. *that* cause natural mortality to silver leaf whiteflies at all life stages (Dong *et al.* 2016; Gao *et al.* 2017; Hatting *et al.* 2019). Nevertheless, EPF have a limited shelf life, less stable and slow action, contributing to their slow development as mycoinsecticides (Dong *et al.* 2016). Also, some EPF are less aggressive example Hypocreales (Humber 2012), while mass production in the laboratory, storage and formulation of some EPF like entomophtorales is complex, limiting their use as a biological control (Pell *et al.* 2010). Also, pathogenic insect fungi work better in a controlled environment such as greenhouses, which are not affordable by African farmers who work under open fields, limiting the application of EPF in the African farming context.

Cultural method

The cultural silver leaf whitefly control method is an approach that involves careful management of environmental factors (Spatial and temporal) and production practices to limit silver leaf whitefly damage (Perring *et al.* 2018). Cultural methods, especially those involving several plant species and silver leaf whitefly, may be complex to implement. Still, they are more common in African small-scale diversified farming than in large-scale monoculture production (Walgenbach 2018). Some standard silver leaf whitefly cultural control methods are reviewed hereunder.

Crop management

Crop management involves good agricultural practices, including fertilizers and irrigation methods. The fertilizer and irrigation methods can play a role in controlling silver leaf whiteflies if used judiciously. Nitrogenous fertilizers are applied to supply nitrogen, an essential plant nutrient that promotes growth and determines the ultimate yield and quality of vegetables through the synthesis and accumulation of free amino acids, proteins, and sugars (Ddamulira *et al.* 2019). Tomato farmers in Africa commonly use nitrogenous fertilizers due to their importance (Ortas 2013). However, nitrogen accumulation in plants directly attracts more Silver leaf whitefly to feed and promote their growth (Walgenbach 2018), oviposition with less feeding (Park *et al.* 2009), and affect silver leaf whitefly's optimal growth in case it is limited. Further, Nitrogen fertilizers increase Silver leaf whiteflies' feeding preference, food consumption, growth, survival, reproduction and population density, thereby increasing the susceptibility of crop plants to sucking pests (Hosseini-Gharalari *et al.* 2015; Bala *et al.* 2018).

On the other hand, the method of irrigation used has a relationship with silver leaf whitefly infestation and the virus occurrence, where drip irrigation is associated with lower silver leaf whitefly densities and virus incidence (Abd-Rabou and Simmons 2012) as the irrigation feeds water at the plant root zone and reduces the possibility of splashing silver leaf whiteflies and the virus to the nearby host. In Africa, about 80 per cent of farmers are small scale who carry out rain-fed agriculture where runoff can push silver leaf whiteflies and spread them widely to nearby farms (Lowder *et al.* 2016).

Fallowing and host-free period

Fallowing and host-free periods are periods created between successive cropping seasons by removing alternative hosts to deprive silver leaf whitefly and the virus from a food source as they can survive all year round with the availability of host plants (Chandel *et al.* 2012). The practice can be altering planting dates to provide as much time as possible between successive crops to reduce silver leaf whitefly and virus density (Perring *et al.* 2018). Nevertheless, the practice can be difficult as silver leaf whitefly has many host plants, including weeds, as detected in over 460 samples of 50 different weed species from 15 plant families (Papayiannis *et al.* 2011). Therefore, in Africa, where the climate permits a wide range of host plants, silver leaf whitefly management requires efforts from all stakeholders.

A host-free period can be created by uprooting old hibernated and hidden host plants at a distance of 10 km^2 as done in Cyprus to deprive silver leaf whitefly of a food source (Walgenbach 2018). The host-free method is affordable to farmers due to its little cost, making it applicable in Africa. However, farmers lack knowledge of all silver leaf whitefly host plants.

The use of trap crops

Trap crops are alternative hosts to insect pests such as Silver leaf whiteflies that attract, intercept and retain the target pest and reduce their damage to the main crop (Deletre *et al.*

2016). These crops produce volatiles that influences the insect's selection and preference to a particular host plant based on their suitability as the substrate for egg-laying and development (Smith *et al.* 2014). This volatiles produced by the host plants attracts and influence the insect's host selection before the insect lands on the main crop (Luan *et al.* 2013). Examples of trap crops are squash when planted with tomatoes, eggplant planted with maize or eggplant planted with tomatoes (Choi *et al.* 2016). Also *Solanum viarum* growing with tomatoes acted as a trap crop for *Helicoverpa armigera*, prohibited larval growth and survival (Gyawali *et al.* 2021).

The method is of high potential in controlling invasive insects such as Silver leaf whiteflies in crops grown outside greenhouses, particularly in Africa, where farmers grow several crops simultaneously on the same field (Mercader *et al.* 2011). Therefore, there is a need for intercropping repellent plants (push) and attractive plants (pull) to influence pest population and distribution (Khan *et al.* 2008). In the African farming context, this silver leaf whitefly control method is less costly and suitable.

Reflectance mulches

Reflectance mulches are plastic metalized Ultra Violate materials that are used as mulches (Perring *et al.* 2018). These materials interfere with the radiation necessary for the insect's ecological behavior adaptation, by providing surface area for reflection of some light wavelength into the sky, affecting silver leaf whitefly landing behavior and deterring them from the crop (Doukas and Payne 2014; Ojiako *et al.* 2018). The materials can be used in making UV-blocking nets and silvery/white ground coverings that also control silver leaf whiteflies. Nevertheless, living mulches, including other plants, can surround the protected crops to mask them from silver leaf whitefly.

The effectiveness of reflectance mulches depends much on the mulch colour, whereby materials painted with aluminium and aluminium foil, grey and silver are the most effective in controlling Silver leaf whiteflies (Patel *et al.* 2021). These mulches work best during the early crop growth stages, especially in the first 5 weeks after planting, when the virus carried by Silver leaf whiteflies is likely to invade the plant. With time the quality of the mulches decreases due to decreasing of the UV reflectance ability as the mulch gets contaminated with the soil and shaded as the target plant grow and subsequently needs to be changed over time (Smith *et al.* 2000). Unfortunately, this silver leaf whitefly control technology is not reported in Africa, although it is very suitable. Accordingly, African nations can transfer such technology to Africa to help deal with silver leaf whiteflies.

The use of sticky insect traps

Insect traps are used to monitor the silver leaf whitefly population changes in the greenhouse and conventional cultivation to help determine the insect's entrance site, infestation spots, insect presence and quantity, distribution pattern and species density (Hosseini-Gharalari *et al.* 2015). The traps provide farmers with important information that guides their decisions on when to get the maximum benefits and reduce pesticides usage. The traps may have an adhesive inner layer or adhesive layer mixed with food bait to attract and kill insect pests such as silver leaf whitefly. Furthermore, the traps are of various colours depending on the target insect, although most insects are attracted to yellow, making yellow sticky traps dominant (Pedigo and Rice 2014). However, a combination of colours and food baits containing food material as an attractant and an insecticide might increase the trap's effectiveness against silver leaf whitefly.

Intercropping and companion farming

Intercropping is a practice where multiple crops are planted simultaneously on the same field (Lulie 2017). Intercropping makes efficient labour usage, increases income and diet diversity, stabilizes production, maximizes return under low technology levels, and, most importantly, reduces diseases and pests such as silver leaf whitefly. Furthermore, intercropping allow insect pest such as silver leaf whitefly to feed for a shorter period than when only one host is available as they move from one host plant to the next (Mutisya *et al.* 2016). In the African farming context, many crops that can be intercropped as means to control silver leaf whitefly are available. Some of them are intercropping tomatoes with tubers, cereals and other vegetables (Umeh *et al.* 2002), intercropping tomatoes with onion. Tomatoes grown in combination with basil had the lowest silver leaf whitefly infestation (Son *et al.* 2018). Intercropping tomato and coriander increase the diversity of predatory arthropods and, in turn, reduces the population of tomato leaf miner (Medeiros *et al.* 2009). Also, intercropping maize and leguminous crops showed a significant reduction of Fall Armyworm (FAW) and maize stem borer at the early stages of the crop growth to tasseling in Uganda (Hailu *et al.* 2018). Thus, intercropping allow African farmers to control silver leaf whitefly as most African farmers are familiar with the method.

Using greenhouses and screen houses

Greenhouses and screen houses are constructed by nets and plastic films to provide physical barriers that restrict silver leaf whitefly from accessing the crops and protect the crop from extreme weather conditions leading to improved crop yield (Mutisya *et al.* 2016; Sotelo-Cardona *et al.* 2021). For example, the use of insect nets in the production of cabbage seedlings modified the nursery microclimate, reduced insect pests, and improved cabbage production in Kenya (Muleke *et al.* 2013) while in Tanzania insect nets reduced insect pests such as silver leaf whitefly in tomatoes and increased yields (Nordey *et al.* 2020). Additionally, the insect nets can be treated with insecticides to prohibit insects pests. An example was using nets treated with alpha-cypermethrin that successfully reduced the population of silver leaf whitefly and black bean aphids in French beans (Martin *et al.* 2013; Gogo *et al.* 2014). The mesh sizes of 230 × 900 µm or less is required to exclude silver leaf whitefly while keeping the structure ventilated (Bethke and Paine 1991). The use of nets with a mesh size smaller than the mentioned will challenge the ventilation needed to manage relative humidity and temperature in the system (Stansly and Naranjo 2010). Also, electrically charged screens effectively control Silver leaf whiteflies, although their application in the African farming context may be complex as the method is expensive (Nonomura *et al.* 2014; Takikawa *et al.* 2016).

The use of resistant plant materials

Resistant plant materials are materials that can produce several secondary chemicals that are either anti-nutritional or toxic, which enable them to survive insect pests such as Silver leaf whitefly (Ndakidemi and Dakora 2003; Vosman *et al.* 2018). Such plants have defense mechanisms that interfere with the insect (silver leaf whitefly) behavioral and or physiological activities (Vosman *et al.* 2018) and directly cause toxicity to the insect or immobilize them on the leaf due to their sticky nature (Rakha *et al.* 2017). The plant defense can be specific to one insect species or attack multiple insect pests to give plant-wide protection. The type and presence of glandular trichomes determine the pant defense. Glandular trichomes are hair-like structures that produce and store plant compounds (metabolites) responsible for plant resistance against enemies such as Silver leaf whiteflies and they are types I, IV, VI and VII (Bleeker *et al.* 2012; Perring *et al.* 2018).

Therefore the abundance of the metabolites produced by a certain tomato species depends on the type of glandular gland present and they correlate with its resistance against a particular insect pest (Firdaus *et al.* 2012). In most cases, metabolites responsible for tomato resistance are produced by wild tomato relatives such as *Solanum galapagense, S. pimpinellifolium, S. habrochaites* and *Solanum hirsutum* (Lima *et al.* 2016; Ben-Mahmoud *et al.* 2018). As such continuous screening of the existing tomato varieties and their related species for reduced pests (silver leaf whitefly), survival and fitness are essential (Curry and Pimentel 1971); thus, the involvement of crop production stakeholders in the continent is necessary. The use of pest-resistant tomato cultivars is an advantageous method in all farming conditions in Africa.

Chemical control method

The chemical pest control method uses synthetic pesticides to control pests. The method is considered to be highly effective, convenient and kills a mass of Silver leaf whiteflies within a short period after application (Jiu *et al.* 2017; Naveen *et al.* 2017). Due to these qualities, the chemical pest control method is chosen as the first method of silver leaf whitefly control and it is used by most tomato farmers in tomato growing areas in the world (Laizer *et al.* 2019; Melo *et al.* 2019; Tambe *et al.* 2019; Dube *et al.* 2020). As a result, there is an increase in the use of synthetic pesticides, where from 1990 to 2010 about 342,000 tons of pesticides were used with 25% used in the developing countries and mostly applied in vegetables (Bon *et al.* 2014).

However, a lack of knowledge on pesticides selection and use by farmers leads to increased use of pesticides with a single mode of action to fight silver leaf whiteflies (Laizer *et al.* 2019). As a result, Silver leaf whiteflies developed pesticides resistance, making this control method ineffective (Legg *et al.* 2014). Thus, tomato farmers increased pesticide spraying frequency to control silver leaf whitefly, which accelerated the resistance of silver leaf whitefly to pesticides (Satar *et al.* 2018). As a result, tomato growers shifted to more toxic and banned pesticides, including organochlorines, such as Dichlorodiphenyltrichloroethane (DDT) for silver leaf whitefly control (Dari *et al.* 2016). Due to its long persistence in the environment and residue in crop products, DDT was banned and replaced by pyrethroids in the late 1970 and 1980 (Naveen *et al.* 2017). Farmers also mixed pesticides which increased their synergies in controlling Silver leaf whiteflies. For instance, pyrethroids and a moderate amount of compounds from organophosphates and carbamates were mixed (Castle *et al.* 2014). However, the mixture lost its efficiency due to improper and uncontrolled use, and at the same time, the silver leaf whitefly showed reduced susceptibility to this mixture. Subsequently, newer insecticides entered the market for controlling Silver leaf whiteflies. Among them were the Insect Growth Regulators (IGR), pyriproxyfen, buprofezin and neonicotinoids (Horowitz *et al.* 2018). The use of these newer insecticides increased the threat to the environment, especially the non-target organisms and the consumers' health (Antwi and Reddy 2015; Baffour-Awuah *et al.* 2016).

Recommendation for a way forward about silver leaf whitefly in Africa

From the reviewed materials on the mechanisms for survival of silver leaf whitefly, the study recommends the provision of quality and up-to-date extension services to the tomato producers to equip them with the required knowledge for improved tomato production in Africa. Also, there is a need for joint action of all stakeholders involved in the tomato production value chain in addressing the problems due to silver leaf whitefly as summarized in Table 2, where each stakeholder has a role to play and in totality farmer’s production problems are settled. In terms of silver leaf whitefly control measure used and their suitability in the African context, tomato producers should select the control method that is applicable and affordable to the particular farming context to trap the merits of the method selected as summarized in Table 1.

Conclusion

Silver leaf whitefly threatens tomatoes and other crops of economic importance worldwide, causing substantial financial losses regardless of the available control options. Crop producers employed various silver leaf whitefly management options to keep the population of this pest at a manageable level. The most common silver leaf whitefly control options are chemical pesticides and cultural methods, minimal resistant plant cultivars and biological silver leaf whitefly control. Most cultural silver leaf whitefly control methods such as trap crops, intercropping and companion farming seem highly applicable in Africa. In contrast, some other techniques such as screens and greenhouses, reflectance mulches and resistant plant materials have low applicability among African small scale farmers because they are not affordable by these small and resource-poor farmers. Despite the efforts made to control silver leaf whitefly, the pest is still a big problem in tomato production in Africa. Therefore, there is a need to research more effective ways used elsewhere to control this pest.

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Author Contributions

SEM planned the study and write the 1st original draft, and PAN and ERM reviewed and edit the final draft of the manuscript. All authors contributed to finalizing this manuscript.

Conflicts Interests

The authors have declared that no competing interest exists.

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