UNIVERSITY OF GHANA
COLLEGE OF BASIC AND APPLIED SCIENCES

DIVERSITY OF THRIPS (THYSANOPTERA: THRIPIDAE) ON EXPORT VEGETABLES, THEIR SUSTAINABLE MANAGEMENT AND PHYTOSANITARY IMPLICATIONS

BY
NKAFU THERESE NGOSONG
10553296

TTHIS THESIS IS SUBMITTED TO THE UNIVERSITY OF GHANA, LEGON IN PARTIAL FULFILLMENT OF THE REQUIREMENT FOR THE AWARD OF PHD IN ENTOMOLOGY DEGREE.

AFRICAN REGIONAL POSTGRADUATE PROGRAMME IN INSECT SCIENCE (ARPPIS), UNIVERSITY OF GHANA, LEGON GHANA.

Joint Interschool International Programme for the Training of Entomologists in West Africa. Collaborating Departments: Animal Biology and Conservation Science (School of Biological Sciences) and Crop Science (School of Agriculture), College of Basic and Applied Sciences, University of Ghana, Legon.

JANUARY 2023

DECLARATION

This thesis is my original research carried out under supervision, which has not been presented at another university. Other works that served as sources of information have been properly acknowledged.

Candidate…………………………………………………… Date 27/06/2024…………………………………………

Nkafu Therese Ngosong

Principal Supervisor………………………………… Date 27/06/2024…………………………………………

Prof. Ken Okwae Fening

Co-supervisor………………………………… Date 27-06-2024…………………………………………

Prof. Kwame Afreh-Nuamah

DEDICATION

This thesis is dedicated to my husband, Ajonglefac Martin Fonyi, my two gorgeous daughters Njinju Thermat Ajonglefac and Nkafu Donatella Ajonglefac and my parents Ntimeh Charles Nkafu and Akohngwa Helen Nkafu for coping with all the display for four years.

ACKNOWLEGDEMENTS

First and foremost, I would like to express my heartfelt gratitude to the Almighty God for the good things He has done and will surely do in the future. I would like to thank my supervisors, Prof. Ken Okwae Fening and Prof. Kwame Afreh-Nuamah, for their guidance and constructive criticisms throughout the entire field work and thesis writing-up. It is because of their encouragement, patience, and invaluable contribution that I was able to complete this work. I humbly appreciate the effort of Prof. Ken Okwae Fening, who helped me secure part of the funds I desperately needed for this project. I am grateful to all ARPPIS lecturers, teaching staff, and administrative personnel for their practical and theoretical assistance. Former ARPPIS Coordinator, Dr. Maxwell Kelvin Billah and ARPPIS Coordinator, Prof. Ken Okwae Fening are thanked for their administrative assistance. I am super excited with the Ghanaian vegetable export companies and their staff for giving access to their farms for data collection. Specifically, I thank Mr Benjamin Agbesi, the Chief Executive Officer of AB Farms for providing land, irrigation, and other farm inputs for this project. I am grateful to the management of the teaching and research farm of the University of Ghana, especially the farm manager, Mr. Prosper for allocating a plot for this project. I am indebted to Mr. Ajonglefac Martin Fonyi for being of help anytime I needed one. His assistance together with Mr. Ndome Aladu during data collection is highly acknowledged. I acknowledge with thanks and appreciation the financial support from CABI and the assistance of PPRSD staff such as Mr. Prudence Attipoe, (for providing the preliminary information on vegetable exporters and their contacts), Mr Copperfield Banini and Mrs. Hannah Serwaa Nuamah (for their assistance during thrips identification). I appreciate the effort of Mr. Davis in thrips identification. I thank the Department of Animal Biology and Conservation Science for allowing me to use their microscopes for high quality thrips imaging and biotechnology laboratory for enabling access to their incubators. I am elated to the contributions of Dr. Gesmalla Abdelmutalab A. Azrag at the International Centre of Insect Physiology and Ecology (ICIPE), Kenya for his technical support and guidance during data analysis with the Insect Lifecycle Modelling Software. Dr. Tonnang Henri is very much appreciated for linking me with Dr. Gesmalla for analysis. The endless contributions of Mr. Peter Nzei, Ms. Forchibe Ethelyn, Mr. Adom Medetissi are sincerely appreciated.

I would like to express my gratitude and appreciation to my parents for their unending prayers and encouragement throughout my studies. To my uncles and their wives, Mr. and Mrs. Akemnda Eric Achankeng, Mr. and Mrs. Ntimeh Micheal, Mr. and Mrs. Atemnkeng George and Mr. and Mrs. Nchongany Paul, I say may the good Lord bless you all for your love and discipline you instilled in me. In particular, I would like to express my gratitude to Ms. Ntimeh Beatrice and Mr. and Mrs. Mogambo for their advice and financial support. Mr. and Mrs. Asongalem Aminateh’s assistance in a variety of ways is especially acknowledged. I am sincerely grateful to the Fonyi’s family especially Mrs. Rosa Awungia Fonyi and Mrs. Juliana Njinju for their support during this period. Special thanks go to people who contributed in one way or the other in ensuring my mental stability, including but not limited to Roger Sigismund Anderson, Deric V. Tanka, Eric W. Nyuydze and Dr. Ndong Ignatius. Finally, my sincere appreciation goes to the German Academic Exchange Service (DAAD) for providing funds for my PhD studies and to the University of Ghana, Legon, for offering an opportunity for me to carry out my studies.

ABSTRACT

The horticulture industry contributes significantly to Ghana's GDP through the cultivation and export of several exotic vegetables such as eggplant, chilli pepper, and tinder. These vegetables, mostly cultivated in the Southern part of the country are hosts to several insect pests such as thrips. Whilst some thrips species are biologically significant, others threaten the potential of Ghana to remain competitive in the export market through their ability to feed, transmit tospoviruses and physically contaminate exported consignments which often has phytosanitary implications. Efforts at controlling thrips populations with the current pest management approach of synthetic pesticides have proved futile due to their thigmotactic behaviour, lifecycle attributes and their minute size. It is critical in any pest management programme to correctly identify the species in question and combine knowledge of the biology and thermal requirements to improve on planning, timing and precision of pest management interventions. This thesis sought to understand the diversity and biology of thrips and look at pest management approaches that could guarantee the export requirements of thrips-free produce. Surveys were conducted in the Greater Accra, Eastern and Central regions on selected export vegetables from September 2019 to January 2021, to identify the thrips on export vegetables, their abundance and diversity between regions and crops. In each region, four vegetable export growing farms/localities were selected and thrips were collected from six export vegetables/location. In each crop, 40 plants were randomly selected in an X-pattern and thrips were collected into 60% alcohol for identification. A total of eight thrips species were identified including the South-East Asian thrips, *Thrips parvispinus* (Karny), the cotton thrips, *Frankliniella schultzei* (Trybom), the onion thrips, *Thrips tabaci* (Lindeman), the vespiform thrips, *Franklinothrips vespiformis* amongst others. *Luffa acutangular* supported a higher abundance of thrips, but diversity was greatest on *Solanum melongena* and *Capsicum frutescens.* Across the regions, the Central region had the greatest diversity of thrips with the invasive species, *T. parvispinus*, as the most dominant. This objective highlights the need for targeted control measures that are effective against the thrips species present to be developed, to enhance the quality and export potential of vegetables. As it is essential to keep tract of the population of the identified thrips species to understand the population dynamics and implement timely control measures, the species composition and population dynamics of thrips was monitored using blue, yellow, and white sticky traps on commercial eggplant and chilli farms in Tuba in two cropping seasons of 2020/2021. Each field was divided into 8 blocks and in each replicate, all trap colours representing three treatments were randomly tied on stakes at the centre for the respective crop. Data loggers were installed to record hourly climatic variables. Three thrips species (*T. parvispinus*, *F. schultzei* and *T. tabaci*) were identified from each of the commercial farms and the different species showed varied attractiveness to colour traps for both seasons, with white proving more attractive to *T. parvispinus*. The dynamics of the species varied significantly with the season and climatic factors (temperature and relative humidity) but not with the crop. Optimum temperatures and relative humidity of 28 ºC – 31 ºC and 60%-78 %, respectively showed a positive linear relationship between the trapped insects with temperature and RH whilst extreme environmental factors (35 ºC) negatively affected their abundance. Incorporating white sticky traps into the country-wide monitoring plan can improve the effectiveness of pest management interventions. To understand how the most important environmental factor, temperature, influence the biology of the invasive species, *T. parvispinus*, its growth and development was studied under six constant temperatures to develop a temperature-dependent phenology model for predicting future climatic trend. Mathematical functions were fitted to describe the relationship between temperature and demographic attributes of *T. parvispinus* using the "model builder" and "validation and simulation" components of the insect life cycle modelling software. The fitted mathematical functions were compiled to develop the overall phenology model which was used to simulate the life table parameters. Temperature influenced the biology of *T. parvispinus*, which had six life stages including the egg, two larval instars, propupa, pupa and adult stages. The development time decreased with increasing temperatures such that the longest egg-to-adult development time of 37.72 days occurred at 15 ºC, whilst the shortest of 8.84 days occurred at 35 ºC. Development rate was fastest at higher temperatures. The model predicted 25 ºC to 30 ºC as favourable temperatures for the reproduction of *T. parvispinus*, with maximum eggs of 54.83 at 30 ºC. The growth parameters such as the gross reproductive rate was maximum at 35 ºC with 45 offspring per generation, compared to 33.42 and 9.80 at 25 ºC and 15 ºC, respectively. This result provides for the first-time baseline optimal thermal requirements, useful in planning and timing pest management interventions for this pest in the context of climate change. To determine the efficacy of novel insecticides in suppressing thrips population, the variability in the population dynamics of thrips to pest management options and the economic feasibility of using pest management modules in thrips control, two field experiments were conducted in the Deciduous Forest and Coastal Savannah agroecological zones in the major and minor rainy seasons of 2020/2021. In the first experiment, eggplant seedlings transplanted on 5.4 x 5.4 m field plots were sprayed with novel insecticides Agroblaster®, Agroclean®, Viper, Akape® and Alphacep® after the thrips population reached a threshold of 1.5 thrips/leaf. Data on thrips numbers, damage, natural enemies, and other pests were collected one day before application (1DBS), and at 3, 5 and 9 days after each application (3DAS, 5DAS and 9DAS, respectively). The efficacy of treatments, within-plant distribution and yield data were assessed. The thrips population, damage and yield were lower on treated plots than the control plots and also in the Coastal Savannah than the Deciduous Forest zone for all seasons. Different treatments had different efficacies depending on the mode of action, location and season. Alphacep® was the best treatment at 3DAS and Agroclean® and Agroblaster® were best at 9DAS. Alphacep® reduced spiders' abundance and showed slight to strong phytotoxicity, whilst other insecticides did not affect natural enemies and plants. Yield was highest in the Coastal Savannah zone. The result of the second experiment with four treatments (chemical intensive, less-risk, integrated control (IPM) and control) showed that the population dynamics of thrips varied across treatments and sampling time. The IPM treatment had the lowest abundance of thrips and other pests, the highest yield and cost-benefit ratio. This information can be used to select appropriate location-specific insecticides/options for use in vegetable production, increase yield and lower production cost. In conclusion, this thesis provides the first time a comprehensive study of thrips across different vegetable agroecosystems in Ghana, contributing to a better understanding of thrips biodiversity and highlighting the need for integrated pest management strategies tailored to each crop and region to effectively mitigate thrips infestations to meet sanitary and phytosanitary standards while preserving local biodiversity. Enhanced monitoring programs and capacity building efforts in thrips identification are recommended to support sustainable agricultural practices and safeguard Ghana's vegetable exports against thrips-related challenges.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF PLATES

LIST OF ABBREVIATIONS

US$	United States Dollar
ANOVA	Analysis of Variance
ARPPIS	African Regional Postgraduate Programme in Insect Science
IPM	Integrated Pest Management
Ha	Hectare
1DBS	One Day Before Spray
DAS	Days After Spray
SE	Standard Error
Trt	Treatment
Phyt	Phytotoxicity
ISSN	International Standard Serial Number
DAAD	German Academic Exchange Service
MoFA	Ministry of Food and Agriculture
CABI	Centre for Agriculture and Biosciences International
PPRSD	Plant Protection and Regulatory Services Directorate
GAVEX	Ghana Association of Vegetable Exporters
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH
USAID	United States Agency for International Development

LISTS OF APPENDICES

CHAPTER 1

1.0 GENERAL INTRODUCTION

1.1 Background

Ghana exports about 20,000 tonnes of vegetables comprising eggplant, chillies, guar beans, okra, tinda, marrows, gourds and yard-long beans annually to the EU and Switzerland (Gyau and Spiller, 2007; GEPC, 2010; GNBCC, 2023). The export of vegetables to foreign countries serves as a source of foreign exchange for Ghana and promotes food sovereignty and food security. The involvement of out-growers and exporters in the vegetable export value chain offers sustainable employment and a source of livelihood (Dinham, 2003; Afari-Sefa *et al*., 2015), in addition to the health, nutritional and medicinal benefits to both the local and international society. The vegetable market has grown increasingly competitive as a result of the entry of several developed and emerging countries into the industry (Gyau and Spiller, 2007). Furthermore, with the drive for a healthy diet, there is an increasing demand for vegetables both locally and internationally (GhanaVeg Sector Reports, 2016).

Despite the remarkable returns and promising prospects from this sector, Ghana's potential to continuously trade vegetables is threatened by a number of factors, the most serious of which are insect pests infestation (Mochiah *et al*., 2011; Abang *et al*., 2014; Adom *et al*., 2020; Fening *et al*., 2020; Ndlela *et al*., 2022), such as thrips. Thrips (Thysanoptera: Thripidae) consume various parts of the plants including leaves, flower buds, flowers and fruits resulting in whitish-translucent patches on the affected part, a process termed scaring (Hodges *et al*., 2009; Srinivasan, 2009; Reitz, 2009). The scaring by thrips affects photosynthesis and carbon allocation and causes leaf drop and flower abortion in the affected plant part resulting in a decrease in yield (Welter *et al*., 1990; Shipp *et al*., 1998; Bacci *et al*., 2008). Feeding and oviposition damage on fruits reduces their market value as they are downgraded due to poor appearance. In addition, the physical presence of quarantine thrips species on export consignments has phytosanitary consequences which disrupt the trade of these vegetables internationally (Abang e*t al*., 2014; GhanaVeg Sector Reports, 2016; Kumar *et al*., 2016; Okolle *et al*., 2016; Fening *et al*., 2020).

The vegetable export industry in Ghana witnessed a ban in October 2015 to 31st December 2017 for certain export crops (aubergines, eggplant, pepper and gourds) due to the presence of harmful organisms such as thrips, false codling moths, whiteflies and fruit flies on exported commodities, among which, thrips had the highest number of interceptions (GhanaVeg Sector Reports, 2016, 2017; Fening and Billah, 2019). This single act cost Ghana $10 billion in foreign exchange (Ghana Talks Business, 2017), for the affected vegetables including *Solanum* spp. (aubergine and eggplant), *Capsicum* sp. (pepper), and gourds (bitter, luffa and bottle gourds)(*Momordica*, *Luffa* and *Lagenaria*, respectively). The government of Ghana set up an export task force with financial and logistics support from the development partners (CABI, GIZ and USAID) and technical support from scientists (Entomologists from UG ARPPIS), together with Ghana's NPPO (PPRSD of MoFA) and the exporters (GAVEX) to combat these pests and to uplift the ban. This task force laid a comprehensive action plan and protocols to manage these pests which culminated in developing the roadmap for pest reduction to assist farmers/exporters to conform to market standards (GhanaVeg Sector Reports, 2017). This ban by the EU was uplifted on 01 January 2018 (Fening and Billah, 2019).

Despite the successes made, some challenges do exist whereby some farmers and exporters do not strictly follow the protocols for pest management, thus leading to a rise in local interceptions at the KIA (Kotoka International Airport). This led to Ghana's NPPO, PPRSD of MoFA imposing a local ban effective 1st June 2019 for 4 months to ensure exporters and their out-growers follow strictly the approved protocols for pest management (Sodjah and Aliyah, 2019).

1.2 Justification

Ghana is one of the African countries with the highest number of notifications of thrips in the EU and Switzerland (EUROPHYT, 2014, 2015, 2016, 2019, 2020) and among the export vegetables, eggplant (*Solanum melongena*) has had one of the highest number of thrips infestation (EUROPHYT, 2014-2018). Infestation by thrips can result in serious economic losses, be it quarantine species or not (Fening *et al*., 2022). Ghana has not recorded any of the quarantine thrips species, *Thrips palmi* Karny (Thysanoptera: Thripidae), *Scirtothrips dorsalis* Hood (Thysanoptera: Thripidae), *Scirtothrips citri* Moulton (Thysanoptera: Thripidae), *Scirtothrips aurantii* Faure (Thysanoptera: Thripidae) and *Frankliniella occidentalis* Pergande (Thysanoptera: Thripidae) (*T. palmi*, *S. citri* and *S. aurantii*: EPPO A1; *F. occidentalis* and *S. dorsalis*: EPPO A2) (CABI, 2019; EPPO, 2019), though previous interceptions have been attributed to *T. palmi* (EPPO, 2004). The certainty of these notification is sometimes doubtful as most interceptions on thrips are hardly identified to the species level (Timm *et al*., 2008; Bragard *et al*., 2019; Fening *et al*., 2022), partly due to their small sizes (Timm *et al*., 2008; Iftikhar *et al*., 2016a), which makes the study of this group of insects technically difficult. On the other hand, an invasive species, *Thrips parvispinus* Karny (Thysanoptera: Thripidae) with the potential to cause serious phytosanitary sanctions has recently been reported in ridged gourd farms in Ghana (Fening *et al*., 2022). Studying its biology under varying temperature conditions will help us to understand the biological parameters, reason for its invasiveness and inform decision-making on the timing of pest management interventions.

In Ghana, research on thrips have focused on management using insecticides (Tanzubil, 1991; Tamò *et al*., 2002 and Abudulai *et al*., 2006; Baah *et al*., 2015; Amouzou *et al*., 2022, Fening *et* *al*., 2022), host plant resistance (Salifu, 1982; Abudulai *et al*., 2006; Tanzubil *et al*., 2008) and the only diversity study conducted by Yong (2015) looked at thrips species composition in the Greater Accra and Eastern regions of Ghana. Adding to the fact that this study concentrated mainly on local vegetables, thrips identification was done morphologically which is usually, hindered by the limited expertise and skills of the identifier. Little is known about the diversity of thrips on vegetables grown for export which ought to be the primary step if Ghana hopes to remain competitive in the export market (Amouzou *et al*., 2022; Fening *et al*., 2022). It is, thus, important to correctly identify thrips species on Ghanaian export vegetables in a bid to document the species present to ensure appropriate management strategies are instituted subsequently (especially for priority quarantine species whose export requirements are stricter) and to keep our guards in event of the introduction of new species.

The new EU Plant Health Directive (Implementing Regulation (EU) 2019/2072) of 28 November 2019 sets more stricter new standards which must be met before countries are allowed to export. These rules apply both to quarantine and regulatory non-quarantine pests, and they differ depending on the pest or plant species. The Europe-Africa-Caribbean-Pacific Liaison Committee (COLEACP (2020) suggests forming committees or taskforces to bring all stakeholders, including producers, exporters, and National Plant Protection Organisations (NPPOs), together for productive dialogue to agree on the necessary action in order to comply with the new legislation. This may include conducting pest risk analysis for suspected *Thrips* spp. that pose greater threat to the African-Caribbean Pacific (ACP) countries, enhanced surveys, establishment of national monitoring, emergency preparedness, contingency and eradication plans, etc (KO Fening Pers. Comm.) or adopting improved farming methods to ensure export countries are pest-free or established pest-free farms cultivated with maximum supervision and protection (Amouzou *et al*., 2022; Fening *et al*., 2022).

The implementation of improved farming methods requires active research that re-evaluates the already existing interventions and proposes alternatives that shifts from the current broad-spectrum synthetic pesticide's regime with documented negative effects on the environment, public health, consumers, and international trade (Amoah *et al*., 2006; Bempah *et al*., 2011; Seal *et al*.,2013; Abass *et al*., 2016; GhanaVeg Sector Reports, 2017; Mohammed *et al*., 2019) to more friendly management options (Fening *et al*., 2022). Under this new approach, if pesticides must be used, then they should be applied only at pest population thresholds, and target-specific, low-risk insecticides must be selected to guarantee food and environmental safety. This necessitates further endless research on aspects of the bioecology and the impact of the currently approved pesticides as well as the evaluation of newer groups of pesticides that can be recommended for inclusion in the Environmental Protection Agency (EPA) list of approved pesticides. Therefore, the continuous export of vegetables in Ghana will only be possible if vegetables are produced in a way that the quality is guaranteed both for the consumers and to meet the strict phytosanitary requirements with the coming into force of the EU new Plant Health Regulations (Fening and Billah, 2017, 2019).

This work would constitute the first comparative study of Thysanoptera in different agroecosystems of export vegetables and would be a contribution to the knowledge of the entomofauna of Thysanoptera in Ghana. It also forms part of the larger effort to ensure that vegetables meet the export requirements of thrips-free produce for Ghana and the data could form the relevant baseline documentation in eventual justification for interception or if the country is subjected to audit by EU authorities.

1.3 Objectives

1.3.1 Main Objective

The main objective of this research is to identify the thrips' species on export vegetables and contribute to their sustainable management to enhance the export of vegetables such as eggplant to the European Union.

1.3.2 Specific objectives

The specific objectives of this study are to:

1. Determine the diversity and abundance of thrips on selected export vegetables in Southern Ghana.
2. Evaluate the performance of different colours of sticky traps in monitoring thrips population on eggplant and chillies.
3. Determine the developmental potential of the South-East Asian thrips, *Thrips parvispinus* (Thysanoptera: Thripidae) under different temperature regimes.
4. Evaluate the efficacy of pest management options on thrips and associated natural enemies on eggplant across two distinct agroecological zones in Ghana.

CHAPTER 2

2.0 LITERATURE REVIEW

2.1 Thrips, the order Thysanoptera

Thrips ("woodworm" in Greek) are very tiny insects normally considered to constitute a single insect order, the Thysanoptera. This accepted name refers to their fringed wings, although similar hairy fringes also occur on small species of caddisflies, beetles, wasps and moths (Lewis, 1968; Mound, 2018). Thrips differ from all other insects for the following reasons; adults and larvae have asymmetrical mouth cone with a single mandible with the right mandible being vestigial and reduced (Ananthakrishnan, 1970; Buckman *et al*., 2013); thrips lack a pair of tarsal claws found in most insects but they do have a bladder-like structure on their feet which led to their early classification as Physapoda (Buckman *et al*., 2013). Thrips vary in colour from black to dark brown, yellow to pale white, an attribute that allows them to adapt to different environments, thereby avoiding detection by predators. The antennae have six to ten segments and adults may be wingless or winged. However, winged forms are weak fliers but thrips have a large surface area-to-volume ratio (Mound, 2005), which enhances their long-distance movement through the wind.

2.2 Origin of thrips (Thysanoptera)

The first recorded mention of thrips dates from the 17th century, with a sketch by Philippo Bonanni (a Catholic priest) in 1691, which was later identified as the male of *Anthothrips statices* (Thysanoptera: Tubulifera) by Uzel (1895). In 1744, Baron Carl De Geer (Swedish entomologist) described two species in the genus *Physapus* and Linnaeus in 1746 in addition to the two re-named species accredited to De Geer, described a third species as *Thrips elytris albis nigrisque fasciis, corpore atro* and proposed Thrips ("thysanos" meaning fringe and "ptera" meaning wings in

Greek) as the group name for these insects. He also placed this genus at the end of the Hemiptera, but this was before 1758 when binomial nomenclature became widely accepted. In 1836 Alexander Henry Haliday (Irish entomologist) described 41 species in 11 genera including their morphology and biology and proposed the order name of Thysanoptera. Other small contributions to thrips anatomy, biology and systematics were published by several authors (Walker, 1852; Fitch, 1855). Notwithstanding their contributions, the first monograph dealing exclusively with this insect order was issued in 1895 by Heinrich Uzel (Czech entomologist). This 500-page book not only summarized comprehensively almost all previously published information on Thysanoptera but described 11 new genera, 63 species and 25 varieties, together with identification keys and illustrations (Uzel, 1895). This remarkable work forms the basis on which all subsequent research is conducted, as H. Uzel is considered the father of Thysanoptera studies (Uzel, 1895; Fedor *et al.*, 2010; ThripsWiki, 2019).

2.3 Phylogeny of Thrips

Thysanoptera is classified into two suborders; the Terebrantia and the Tubulifera (Lewis, 1968; Ananthakrishnan, 1970; Moritz *et al.*, 2004b; Mound, 2018), with considerable differences between them. Thrips belonging to Terebrantia possess a distinct saw-like ovipositor in the females which it uses to insert eggs into plant tissues (Childers and Achor, 1995; Moritz *et al.*, 2004b), forewings have a system of veins and sometimes cross-veins, a distinct wing chaetotaxy and 2 to 8 segmented maxillary palp and maxillary stylets confined to the mouth cone. According to Ananthakrishnan (1970), female species of Tubulifera suborder lack the ovipositor, but Palmer (1990) and Mound (2018) found an internal eversible chute-like ovipositor in these species, where the eggs are deposited superficially rather than inserted into tissues. Their tenth abdominal segment is tubular, and the genitalia emerges ventrally at the base of the tube, the forewings have no veins, cross-veins or setae, the fringes are nearly straight, never wavy, maxillary palp always two-segmented, and the maxillary stylets almost always retracted far back into the head. Sigmoid setae are also present on the abdominal tergites to keep the wing in place while at rest.

The Tubulifera is the largest of the suborders, with about 3500 species, but these are all members of one family, the Phlaeothripidae. On the other hand, the Terebrantia contains 2500 species distributed in eight families (Table 2.1) (Moritz *et al*., 2004a, b). Members of the Aeolothripidae and Melanthripidae have relatively broad wings that usually have dark-coloured bands. Species of the Melanthripidae are flower-feeding, but although the Aeolothripidae often lives in flowers, they feed not only on plant tissues but also on other thrips larvae inhabiting those flowers (Buckman *et al*., 2013). Heterothripidae are flower living species and Merothripidae and Uzelothripidae are minute, wingless fungus feeding species. Species of Aeolothripidae are mainly found in the temperate regions whereas, Merothripidae are mainly in the Neotropics (Mound and Teulon, 1995). The family Thripidae consists of about 2000 species and contains all the pest thrips species.

Table 2.1. Sub-orders of Thysanoptera and number of species.

Sub-order	*Family*	*Sub-family*	*Genera*	*Number of species*
Terebrantia	Melanthripidae		6	75
	Merothripidae		5	18
	Aeolothripidae		28	200
	Stenurothripidae		12	24
	Heterothripidae		7	75
	Fauriellidae		4	5
	Thripidae	Panchaetothripinae	40	140
		Sericothripinae	3	145
		Dendrothripinae	15	100
		Thripinae	240	1700
	Uzelothripidae		1	1
Tubulifera	Phlaeothripidae	Phlaeothripinae	375	2820
		Idolothripinae	80	715

(Moritz *et al*., 2004a; Mound, 2015; Mound and Teulon, 1995).

2.3.1 Family Thripidae

The families Phlaeothripidae and Thripidae contain about 93% of all thrips species (Mound, 1997). Over 2066 thrips species constitute the family Thripidae grouped in four subfamilies, including Panchaetothripinae, Sericothripinae, Dendrothripinae and Thripinae with 35/125, 3/140, 13/95 and 225/1700 genera/species respectively (Mirab-balou and Xue-xin, 2011; Buckman *et al*., 2013). It contains two hundred and ninety genera but for easy understanding, Mound *et al*. (1981) classified them into eight genera which are Scirtothrips, Frankliniella, Mycterothrips, Thrips, Anaphothrips, Taeniothrips, Megalurothrips and Trichromothrips.

2.4 General biology of thrips

There is much controversy on the type of metamorphosis undergone by thrips. Whilst some studies regard thrips as hemimetabolous (undergo incomplete or gradual metamorphosis producing offspring's called nymphs which resemble the adults), others consider them to be holometabolous (undergo complete metamorphosis producing offspring's called larvae). Nevertheless, Mound (2005) and Mound (2018) opined that, thrips are hemimetabolous insects, because the pupae have external wing buds similar to those on the nymphs of Hemiptera and other hemimetabolous insects, although the organs of the body are fully reorganized during the pupal stages, as in the holometabolous endopterygotes such as beetles, flies, and moths. Generally, the biology of all thrips is very simple and common among all species, however, deviation from these shared traits will be discussed in the respective paragraphs in section 2.4.1. The biology of several species have been reviewed and or studied including *Thrips tabaci* Lindeman (Thysanoptera: Thripidae) (Pourian *et al*., 2009; Gill *et al*., 2015), *F. occidentalis* (Moritz *et al*., 2004b; Reitz, 2009), *T. palmi* (Kawai, 1990; Capinera, 2000; Cannon *et al*., 2007; Yadav and Chang, 2012a, b), and *Megalurothrips sjostedti* Trybom (Thysanoptera: Thripidae) (Salifu, 1982).

2.4.1 Life cycle of Thrips

The length of one full reproductive cycle (Plate 1) of thrips varies between species, host type, host quality and temperature. Averagely, it takes between 24-28 days for thrips to complete development at 25 ºC (Kawai, 1990), but may be shorten to 11 and 12 days at 29 ºC for *Frankliniella tritici* Fitch (Thysanoptera: Thripidae) and *Frankliniella occidentalis*, respectively (Reitz, 2008, 2009), 14 days at 23 ºC for *F. occidentalis* (Moritz *et al*., 2004b) or prolong to 40.7 days at 20 ºC or 80.2 days at 15 ºC for *T. palmi* (Kawai, 1990). Thysanoptera have six or seven life stages: egg, first and second larval instars, two or three pupal stages for Terabrantia and Tubulifera, respectively, and an adult stage (Healey, 2016). Adult female thrips lay eggs in or on plant tissues and upon hatching, larvae begin to feed on the plants which later drop to the ground for pupation (Kawai, 1990). The propupal and pupal stages don't feed and are immobile or only moves sluggishly when disturbed (Reitz, 2009; Joseph *et al*., 2016). The cycle completes when the pupa moults to adult which mate or not to produce eggs for the cycle to start over again. Distinguishably, the pupal stages are immobile and inactive, possess two pairs of vestigial wings and have fewer antennal segments whereas, the macropterous adults have well-formed wings with six to nine antennal segments.

2.4.1.1 Eggs

Thrips lay very small eggs, which measure around 0.1 mm wide and 0.25 mm long for Terabrantia species and about 0.35-0.55 mm for Tubulifera species (Childers and Achor, 1995). When the eggs are first laid, they are whitish and gradually turn pale yellow as they mature. The eggs are kidney-shaped for Terebrantia species and are often placed singly in cut slit within the plant tissue and are, therefore, not visible (Childers and Achor, 1995; Leighl, 1995). However, Tubuliferan eggs, such as *Haplothrips* spp. (Thysanoptera: Phlaeothripidae), are cylindrical and are either laid individually or in clusters which remain exposed on surfaces of plants (Lewis, 1973), making them more susceptible to predation. Depending on the temperature, the egg stage takes 4 days to hatch to first instar larva, though Reitz (2008) found *F. occidentalis* and *F. tritici* to hatch within 3 days. Thrips prefer non-expanding mature leaves for egg laying as this avoid crushing of the eggs during leaf expansion (Terry, 1997). A single adult female of *Thrips parvispinus* (Karny) (Thysanoptera: Thripidae) can lay 15 eggs averagely per lifecycle, whereas, a *T. palmi adult* female can produce 64.2 eggs at 25 °C and 23.4 eggs at 16 °C, suggesting egg development and oviposition is temperature dependent (Yadav and Chang, 2014).

2.4.1.2 Larvae

All Thysanoptera have the first two instars called larvae, which are both active and free-living (Samler, 2012; Yong, 2015; Reitz, 2009). The first instar is very minute, whitish, moves faster and require a very short time depending on temperature to moult to the second larval instar. The second instar is a little bigger and varies in pale-yellow to orange depending on the species (Moritz *et al*., 2004b). The first and second instar larvae, though similar to adults, differ in having undeveloped genitalia, fewer antennal segments, a membranous cuticle with discrete patches of thickened chitin and wingless externally but possess internally developing wings (Triplehorn *et al*., 2005). The duration of each larval stage is temperature dependent and at 23 ºC it takes 3.07 days for *F. occidentalis* first instar to become second larval instars and 3.64 days for second instar to moult to the next stage (Moritz *et al*., 2004b).

2.4.1.3 Pro-pupae and pupae

At the end of the second instar, the larva undergoes pupation which may take place in the soil beneath, leaf litter or even on the plant depending on the species (Kawai, 1990; Moritz *et al*., 2004b). For some species, the second larval instar of some Terebrantia spin a cocoon (Timm *et* *al*., 2008). Both Terebrantia and Tubulifera have two and three pupal instars, respectively (Palmer, 1990; Moritz *et al*., 2004b; Yadav and Chang, 2012b). The first stage called the propupa is a less active and non-feeding stage with developing wing pads and short, horn-like antennae. The second stage called the pupa is also non-feeding, mostly non-mobile and has longer wing pads and antennae which are folded backward over the head in Terebrantia but lies along the sides of the head in Tubulifera (Palmer, 1990). The duration of pupal development depends on the temperature and thrips species. Both the pro-pupa and pupa of *F. occidentalis* complete development in 1.09 and 2.54 days, respectively at 23 ºC (Moritz *et al*., 2004b), and in 1.18 and 3.05 days, respectively for *T. palmi* at 25 ºC (Yadav and Chang, 2012b).

2.4.1.4 Adults

Adult thrips are winged, tiny (1 to 1.5 mm long) and slender. The wings are narrow, long and fringed with long hairs, and when at rest, they converge at the back over the body. They vary in colour from black, brown, pale, yellow to dark brown depending on the thrips species (Palmer, 1990). Most thrips have specific feeding sites (Palmer, 1990) and adult of most species feed on flowers of a wide range of host plants, even on hosts not suitable for reproduction (Chellemi *et al*., 1994). Adults also feed on young leaves when there's flower scarcity, though they are naturally suitable for larval feeding for some species (Funderburk *et al*., 2002a). The lifespan of adults is temperature-dependent, and females live longer than males (Yadav and Chang, 2012a). Reitz (2008) found a significantly higher adult longevity for *F. occidentalis* (39 days for females) than *F. tritici* (38 days for females).

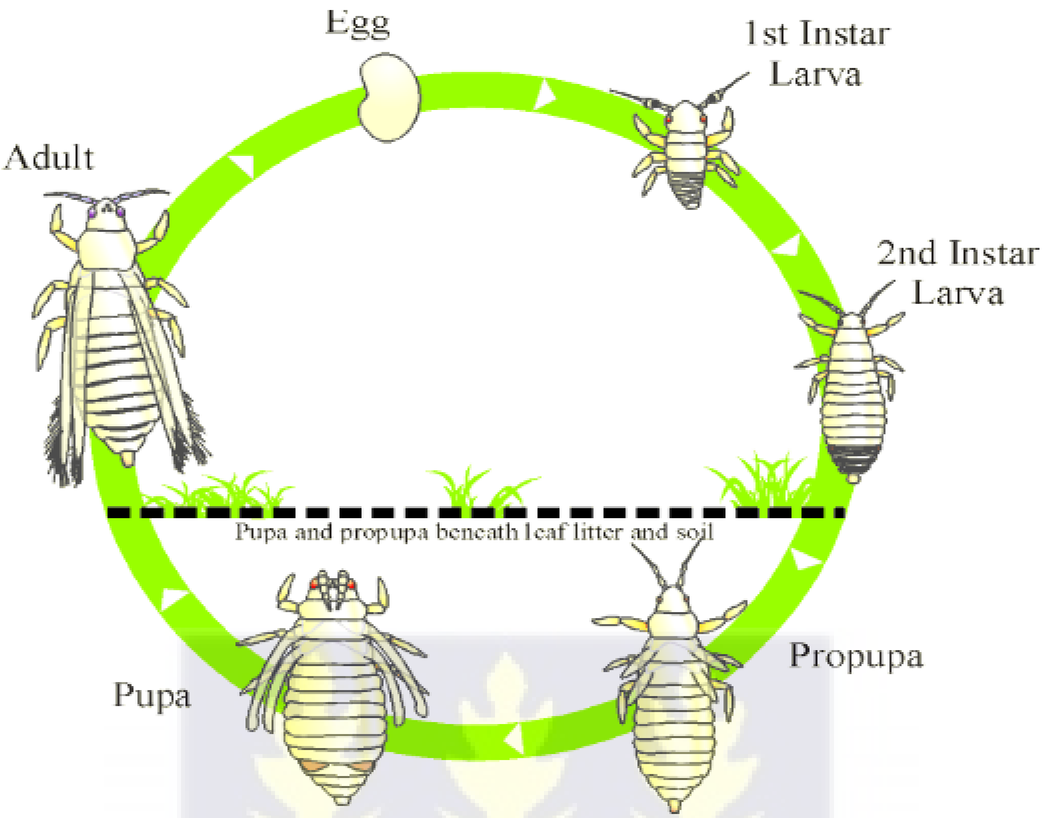


Plate 2.1. General lifecycle of Terabrantia thrips (source: https://cisr.ucr.edu/invasive-species/avocado-thrips).

2.4.2 Nutrition

Nutrient requirements for thrips include protein, vitamins, lipids, carbohydrates, inorganic salts, water and other nutrients (Yu *et al*., 2018). These nutrients are obtained as thrips feed on their respective hosts, plant tissues for phytophagous species, fungi for fungivorous species and prey for predators. Optimal amounts of these nutrients aid in thrips development and reproduction likewise very high or low nutrients amounts could have some implications on thrips development. However, their opportunistic behaviour allows them to feed on mixed diets to meet the nutritional requirements for many species such as *T. tabaci*, Western flower thrips and *A. intermedius* (Bagnall) (Thysanoptera: Aeolothripidae) (Lewis, 1973; Bournier *et al*., 1979; Mound and Teulon, 1995). For plant feeders, nutrition is extremely important because insects (prey) have a higher protein and nitrogen content than the plants on which they feed (Kirk, 1995). A study by Strong *et al*. (1984) disclosed that an increase in nitrogen content could improve assimilation and thrips growth parameters which in essence increased growth, survival and reproduction rates.

Total nitrogen content is a good indicator of the nutritional value of the thrips diet and the form or availability of nitrogen affects their development. Polyphagy in the greenhouse thrips, *Heliothrips haemorrhoidalis* Bouche (Thysanoptera: Thripidae), appears to be linked to the availability of soluble nitrogen (Mound, 2005).

Many studies on thrips have compared the effects of various diets on factors such as oviposition, mortality and growth rates, however, many studies on the nutritional content of insect food have mainly focused on water and nitrogen content (Slansky and Scriber, 1985; Malik *et al*., 2009). Leaf buds, insect prey, seeds and pollen have high nitrogen contents, whereas fleshy fruits and mature leaves have lower nitrogen which causes most thrips to feed primarily on nitrogen-rich foods. Leaf feeders particularly prefer leaf buds because, in addition to their high nitrogen content, they are softer and provide a more humid microclimate (Kirk, 1995). Nitrogen and water content reduces with leaf senescence which tends to reduce thrips' attraction to mature leaves (Slansky and Scriber, 1985; Kirk, 1995). However, thrips that feed on low nitrogen foods can complement their nutrients by consuming mixed diets through predation or cannibalism, especially during high nitrogen requirements such as egg development and maturation (McNeil and Southwood, 1978; Hulshof *et al*., 2003). The growth and development of some thrips have been shown to increase with the addition of small insect prey such as mites, or pollen to the plant tissue diet (Bournier *et al*., 1979; Hulshof *et al*., 2003).

A rod-shaped bacteria lives in symbiotic association in thrips gut which serves as a source of amino acids for thrips (McNeill and Southwood, 1978).

2.4.3 Natural enemies

Several groups of organisms are known to attack thrips, but except for some thrips species, the records are generally scattered in the literature and, the review publications concerning thrips' natural enemies are limited (Callan 1943; Sanjta and Chauhan, 2015).

2.4.3.1 Predators of thrips

Predators are organisms that feed on other organisms, called prey to suppress their populations below damaging levels. Documented predators of thrips are from the families; Anthocoridae (minute pirate bugs), Lygaeidae (big-eyed bugs), Nabidae (damsel bugs), Chrysopidae (lacewings), Aeolothripidae (predatory thrips), Syrphidae (hoverflies), Coccinellidae (ladybugs), Phlaeothripae (*Haplothrips victoriensis* Bagnall), Phytoseiidae (predatory mites), and Miridae (*Campylomma* sp.) (Callan, 1943; Ananthakrishnan, 1970; Hirose *et al*., 1993; Funderburk *et al*., 2011).

The minute pirate bugs (Family Anthocoridae) are the most important predators of thrips (Funderburk *et al*., 2000; Tyler-julian, 2013). A ratio of one predatory bug to 180 thrips is adequate to suppress thrips populations under field conditions, whilst a predator-prey ratio of 1:40 is adequate to control thrips effectively (Funderburk *et al*., 2011). Funderburk *et al*. (2000) showed that the predatory bugs, *Orius* spp. were able to offer effective control of *Frankliniella* species in field peppers, in the absence of insecticides. The anthocorid, *Orius insidiosus* (Plate 2) has a widespread distribution, with records in South America, Central America, North America and the Caribbean (Funderburk *et al*., 2000; Funderburk *et al*., 2011), West Indies (Herring, 1966) and the Pacific Islands (Capinera, 2020). Yasunaga (1997) documented five indigenous Orius species (*O.*

strigicollis (Poppius), *O. minutus* (Linnaeus), *O. tantillus* (Motschlsky) and *O. nagaii Yasunaga*) in Japan where *O. sauteri* successfully suppressed *T. palmi* under field and greenhouse conditions. Hirose *et al*. (1993) surveyed thrips natural enemies in Thailand and reported *Amblyseius* sp. (Phytoseiidae) as a natural predator of *T. palmi* second instar larvae instar.

In West Africa, the predatory mite, *Iphyseius* (Phytoseiidae) (preys on the eggs of *M. sjostedti*), all the life stages of minute pirate bug (Anthocoridae), ladybird beetles, *Cheilomenes* (Coccinellidae), some species of big-eyed bugs, *Geocoris* (Geocoridae) and larvae of rove beetles, *Paederus* (Staphylinidae) are known to attack *Megalurothrips* nymphs (Tamò *et al*., 1993). In South Africa, the predatory mite, *Euseius addoensis addoensis* (McMurtry) (Acari: Phytoseiidae) successfully reduced *Scirtothrips aurantii* population and damage in citrus orchards (Grout and Richards, 1992).

Other predators of thrips include spiders from the families Salticidae, Thomisidae, Oxyopidae, Theridiidae, Uloboridae, and Aranidae (Zhang and Young, 1998; Sanjta and Chauhan, 2015), pseudoscorpions and ants (Ananthakrishnan, 1970).

The use of indigenous natural enemies as biocontrol agents is beneficial because they are already adapted to environmental conditions and non-target environmental effects of the introduction of alien species are avoided. However, some biocontrol agents such as *Orius* species exhibit reproductive diapause which limits their use in biological control (Yano, 2004).

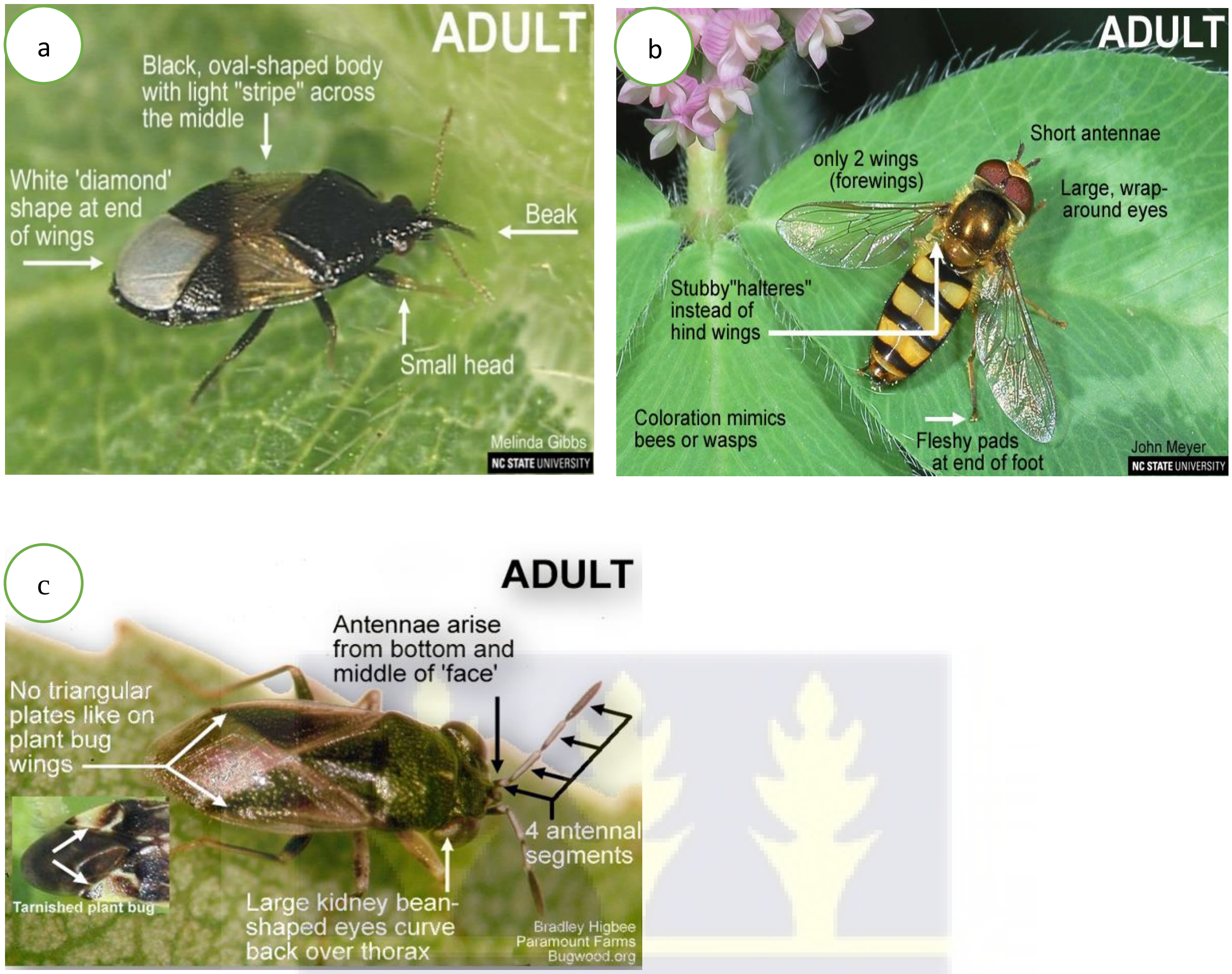


Plate 2.2. Natural enemies of thrips with identification features (a) minute pirate bug, (b) hoverfly, (c) big-eyed bug (Melinda Gibbs and John Meyer, NC State University; Bradley Higbee, Paramount Farms, Bugwood.org).

2.4.3.2 Parasites/Parasitoids of thrips

A parasite is an organism that lives on or in another organism, called host, and derives nutrients from it at the expense of its host. Parasitoids for controlling thrips have been reported from the superfamily Chalcidoidea, in the families Eulophidae (Hymenoptera) and Trichogrammatidae (Hymenoptera) and the nematode parasite belonging to the genus Thripinema (Nematoda: Tylenchida: Allantonematidae) (Ananthakrishnan, 1970; Hirose *et al*., 1993; Zhang and Young, 1998; Yu *et al.*, 2018). Some known parasitoids of Thysanoptera worldwide are shown in table

2.2. Whilst some authors have achieved success in parasitoids-thrips control, others have not, especially with indigenous parasitoids.

The eulophid larva parasitoid, *Goetheana parvipennis* Gahan (Hymenoptera: Eulophidae) from Ghana was introduced and established in the West Indies for the control of *T. tabaci* and *Selenothrips rubrocinctus* Giard (Thysanoptera: Thripidae) (Muniappan *et al*., 2012), but failed to provide economic control of the cocoa thrips (Wolcott 1951; Bennett *et al*., 1993). *Ceranisus menes* Walker (Hymenoptera: Eulophidae) is an important and the most effective parasitoid of the onion thrips in Japan (Hirose *et al*., 1993). Diop (1999) compared the biology of the Asian strain of *C. menes* (one strain from Malaysia and two from India) to that of the African decent (local strain from Benin) on their host (*M. sjostedti*). He found the local strain to be the most effective in the host selection phase for parasitisation but both Indian and Benin strains had poor survival rates. He further concluded that none of the 4 strains of *C. menes* from Asia and Africa was able to successfully parasitize their host due to behavioural and/or physiological incompatibility with the host. This is the reason Tamò *et al*. (2002) probably stated that the African strain of this endoparasitoid is ineffective in suppressing the thrips population, though the potential of a close relative, *C. femoratus* discovered in Cameroon recently with high parasitisation efficiency is overwhelming.

A study by Mason and Heinz (2002) found that *F. occidentalis* infested by *Thripinema nicklewoodi* effectively suppressed its populations and reduced the transmission of tomato spotted wilt virus by 50%. Thripinema nematode species are free-living obligate parasites which attack thrips in the moist microclimate within flowers and leaf galls. The infective female enters the host hemocoel and oviposits within 4-5 days which hatch into juveniles between 6-8 days. The juveniles feed on hemocoel and do not kill their thrips host unlike in other nematode groups such Heterorhabditidae, however, infected larvae and adults become sterile reducing the feeding and virus transmission rate (Sims *et al*., 2009; Sprague and Funderburk, 2017).

Table 2.2. Some parasites/parasitoids of Thysanoptera.

Parasites/Parasitoids	*Thysanoptera host*
Insecta (Hymenoptera) *Thripoctenus brui* Vuillet	*Kakothrips robustus* (Uzcl), *Thrips tabaci* Lindmann, *Taeniothrips alliorum* Priesner
Ceranisus menes Walker*	Several thrips' species
Ceranisus femoratus Gahan*	*Megalurothrips sjostedti*, *Megalurothrips usitatus*
Thripoctenus russelli Crawford	*Hercothrips fasciatus* Pergandc, *Frankliniella tritici* (Fitch), *Thrips tabaci* Lindmann, *Taeniothrips simplex* Morison, *Taeniothrips picipes* (Zett) *Taeniothrips atratus* (Haliday)
Thripoctenus maculatus Wtrst.	*Thrips* sp. on vines
Thripoctenus nublipennis Williams	*Cryptothrips rectangularis* Hood, *Megalothrips spinosus* Hood
Dasyscapus parvipennis Gahan	*Thrips tabaci* Lindmann, *Heliothrips rubrocinctus* (Giard)
Thripoctenus vinctus Gahan	*Taeniothrips longistyills* Karny
Thripoctenus kutteri Ferriere	Kakothrips robustus (Uzel)
Thripoctenus sp.	*Retithrips aegypliacus* Marchal
Tetrastichus gentilei Del G.	*Liothrips oleae* (Costa)
Megrapragma spp.*	*Megalurothrips sjostedti*
Oligosita sp*	*Megalurothrips sjostedti*
Tetrastichus thripophonus Waterston	*Liothrips urichi* Karny
Pezomachus thripites Taylor	*Thrips* sp. on wheat
Megaphragma mymaripennis Timb	*Heliothrips haemorrhoidalis* Bouche
Goetheana parvipennis Gah. *	*Thrips tabaci*
Secernentea (Tylenchida) *Thripinema fuscum* Tipping and Nguyen	*Frankliniella fusca* (Hinds)
T. nicklewoodi Tylenchida *Thripinema khrustalevi* (Chizoy and others)	*Frankliniella occidentalis* *Frankliniella australis* (Morgan)

(Ananthakrishnan, 1970; Funderburk *et al*., 2002b; Mason and Heinz, 2002; Tamò *et al*., 2002, 2003; Sprague and Funderburk, 2017). Parasites/parasitoids with * are found in Africa. The genus *Thripoctenus* was described by Crawford in 1911 and later synonymized under *Ceranisus* by Graham in 1959.

2.4.3.3 Pathogens/Entomopathogens

A pathogen is an organism that causes disease. Generally, very few pathogens of thrips have been documented due to the specificity of these disease-causing organisms. Entomopathogens are pathogens that cause disease and kill insects. Known thrips pathogens include the entomogenous fungi (*Verticillium lecanii* (Zimm) Viégas, which is parasitic on recently emerged adults (Zhang and Young, 1998; Sanjta and Chauhan, 2015), *Metarhizium anisopliae* (Metchnikoff) Sorokin (Clavicipitaceae) and *Beauveria bassiana* (Bals. -Criv.) Vuill. (Cordycipitaceae) and the *Heterorhabditis bacteriophora* nematode species.

Ngakou *et al*. (2008) documented the use of *M. anisopliae* in combination with arbuscular mycorrhiza fungi and rhizobia and their combinations for effective control of *M. sjostedti* under field conditions in Cameroon.

2.4.4 Host association

Thrips inhabit plants of all categories including Angiosperms, Pteridophytes, Bryophytes and Gymnosperms (Ananthakrishnan, 1970; Mound, 2005). However, ecologically they prefer host plants from the families Gramineae, Compositae, Cyperaceae and Leguminoseae, which provide favourable microclimatic tolerance and suitable places of concealment (Ananthakrishnan, 1970). Some other species feed on fungal spores or hyphal fluid under the bark of plants, in leaf-litter or at the base of grasses (Timm *et al*., 2008). A majority of thrips are polyphagous and are able to maintain a small, lasting population on left over weeds after a cropping season or even on cover crops, whilst some are even cannibalistic such as *F. occidentalis* (Kirk, 1995) and *A. intermedius* (Bournier *et al*., 1979). Thrips species have varied host plant preferences. For example, the melon thrips population growth on eggplant is extremely high, yet on sweet pepper, their density is exceedingly low, and larvae fed on strawberry and tomato cannot pupate (Kawai, 1986, 1990).

In Africa Palmer (1990) listed several crops susceptible to thrips infestation including bananas, tea, onions, cocoa, coffee, citrus, maize, grapes, sugar, pyrethrum, cotton, cereal crops like maize, and leguminous crops such as cowpeas and alfalfa. Added to this list are more host plants on which thrips have been intercepted in the EU from different African countries (Table 2.4).

Unfortunately, thrips' feeding habits cannot be identified by examining their feeding stylets. The various thrips hosts documented in literature are usually based on observations from field collected specimens (Mound and Teulon, 1995). As a result, they are mostly "finding places," and true host plant breeding records can only be established by conducting bioecology studies in the laboratory or by repetitive collection and recognition of thrips larvae, which is frequently impossible due to the cost involved and a lack of morphological keys for thrips larvae. Consequently, most Thysanoptera species' primary host plants are still questionable or unknown (Mound and Teulon, 1995; Vierbergen *et al*., 2010; Stuart *et al*., 2011; Bravo-Pérez *et al*., 2018).

2.5 Behaviour of thrips

2.5.1 Feeding

Many species of thrips are phytophagous, feeding on various plant parts such as flowers, flower buds, leaves, fruit, nectar, and pollen. A few genera are fungivorous feeding on spores and hyphae on stems, under the bark of trees or on dead hanging leaves or are predatory feeding on other species of thrips, whiteflies, scale insects, and mites (Mound and Teulon, 1995; Kirk, 1995). The feeding behaviour of all Thysanoptera is similar. Thrips have two well-developed maxillary stylets which join to form a sucking tube. The labrum and labium join to form a mouth cone that protects the sucking tube and other feeding structures including an elongate hypopharynx, cibarial and salivary pumps, and the left mandibular stylet (Heming, 1978). According to previous research, thrips have a rasping-sucking mouthpart which made their ability to feed on other foods such as pollen unknown (Kirk, 1995; Mound, 2005), but current evidence suggests they are piercing-sucking feeders which allows them to feed on a wide host range, including pollen (Lewis, 1968; Tan *et al*., 2016).

Once thrips find a suitable substrate for feeding, they use the antennae and legs to walk in circles or form a "figure eight" on the host (Mound, 2005). As soon as a suitable spot is identified on the host, they puncture the cell wall which exudes a small liquid which is tested for the required nutrients with the palps. If the tissues and nutrients are sufficient, thrips begin feeding by pressing their mouth cone against the plant surface, which is kept in place by the labral pad. The mandible is then used to pierce through the substrate before being quickly replaced by the maxillae, which locate the plant tissue and suck out the cell contents (Childers and Achor, 1995; Kirk, 1995).

For pollen feeders, the grains are pierced and kept in place with the forelegs and/or palps. Continuous feeding is then ensured by repeated protraction and retraction of the mandibular stylet by shortening the mouth cone. Hunter and Ullman (1989) found the maximum mandible extension of *F. schultzei* and *F. occidentalis* to be 50 µm, whilst that of the two larvae and adult female of *S. citri* was reported by Wiesenbom and Morse (1988) to be 20.8 µm, 10 µm, and 14.8 µm, respectively. The feeding time of *Thrips* on each pollen grain takes about 2-20 seconds, but this depends on the air temperature, the grain size and thrips species (Grinfel'd, 1959).

Thrips larvae and adults rid the excess waste and water from the body through the anus. In some species, however, the liquid excreted is held as a droplet between the anal hairs and when it attains a reasonable size, it is deposited on the leaf surface (Lewis, 1968; NT Ngosong, personal observation).

The food range of thrips is constrained by where it lives or by few behavioural or morphological characteristics. For instance, Aeolothripids are larger and tend to run faster than other thrips, an adaptation which can increase predation (Kirk, 1995). Since thrips pierce through the outer tissue to suck the cell contents, preference for young plants which have not yet developed defence mechanisms such as wax layer and/or tough outer tissue wall is paramount. Many species of thrips can coexist in a single ecological niche, it is, therefore, important to be able to distinguish between harmful and non-harmful species.

2.5.2 Mating

Mating takes place when the male holds the female around the pterothorax, maintains a superior position, and then twists the abdomen below for copulation. The mating couples can further be held in position by specific abdominal setae and appendages. A single male may successfully mate with many females. The spermatheca in females often store sperm after mating, however, in some overwintering species, the females retain the spermatozoa in the spermatheca for later fertilization. (Lewis, 1968).

2.5.3 Reproduction

Thrips undergo both sexual and asexual reproduction, though sexual reproduction is more common (Lewis, 1968; Samler, 2012). In some species, unmated females produce only female offspring and males are almost unknown, a phenomenon called thelytoky parthenogenesis and has been demonstrated in the grass thrips, *Anaphothrips obscurus* (= striatus) (Palmer, 1990). In some other populations such as *Haplothrips verbasci* Osborn (Thysanoptera: Phlaeothripidae) virgin females produce eggs which results in all males, called arrhenotoky parthenogenesis (Palmer, 1990). There are a few species that can practice both forms of reproduction. For instance, *T. tabaci* can reproduce asexually (parthenogenetically) and sexually, though thelytoky is the commonest mode of reproduction (Gill *et al*., 2015) and both arrhenotokous and thelytokous populations differ genetically (Kobayashi and Hasegawa, 2012). With *F. occidentalis*, even though, unfertilized eggs can produce females (albeit in small numbers), the normal trend is that the non-fertilized eggs develop into males, whilst the fertilized eggs develop into females (Moritz *et al*., 2004b). Majority of thrips are oviparous but a few of the largest species are viviparous or ovoviviparous such as in Megathripinae (Palmer, 1990). Thrips have very high fecundity and rapid reproductive rates which contribute to their potential as crop pests.

2.5.4 Dispersal behaviour

After most Thysanoptera moult to adults, they move over short distances to find suitable hosts (Ananthakrishnan, 1970; Aliakbarpour and Rawi, 2011) for foraging to complete their lifecycle. Thrips dispersal is either dispersive or non-dispersive.

2.5.4.1 Non-dispersive behaviour

Upon emergence and with the availability of sufficient suitable hosts, thrips larvae and adults begin feeding and their movement is restricted to these areas (Ananthakrishnan, 1970; Mound and Teulon, 1995) and associated with normal activities of feeding, mating, and ovipositing. Studies by Aliakbarpour and Rawi (2011) showed the number of adult thrips were highest at their reproduction site as opposed to the population collected 5 and 10 m away from a mango orchard. This however changes with the shortage of food or the appearance of extreme environmental conditions such as very low or high temperatures, humidity, and rainfall.

2.5.4.2 Dispersive behaviour

This is a type of behaviour typical of individuals trying to identify areas of suitable hosts or have left such areas when host abundance decreases (Ananthakrishnan, 1970; Badii, 2014). Dispersive behaviour of thrips is either natural or artificial (Hector, 2006). In natural dispersal, thrips search for needed resources by self-directed flight (active) or they get drifted by wind currents (passive). To prepare for flight, winged thrips bend their abdomen and use the wind holding setae on abdominal tergites V to VIII to comb the cilia of the wings to increase the surface area of the wings (Ellington, 1980). This facilitates take-off which seems to occur nearly vertically as in a helicopter. Certain instances may trigger adults to embark on dispersive movements. The first occurs when the food initially being used by the population for oviposition becomes limited or deteriorate causing wingless colonies to produce winged forms which could fly to favourable environments (Lewis, 1968). The second is linked to the occurrence of extreme environmental conditions and the last results from the movements of young adults which often show a strong ability to disperse during the period between their emergence from the pupae and the onset of sexual activity. On the other hand, artificial dispersal is human-aided and is facilitated by increased trade of agricultural products. Thrips are carried on several fruits and vegetables, cut and potted flowers that are imported and exported across borders. Their small sizes and the cryptic oviposition behaviour of adult females make detection at entry and exit points practically impossible (Mehle and Trdan, 2012). However, when dispersing individuals locate areas with satisfying physiological requirements, movement becomes non-dispersive.

2.5.5 Opportunistic behaviour

Opportunist is used in ecology to denote certain life history strategies of organisms and opportunistic species are organisms which exploit spasmodically or temporary occurring environments (Mound and Teulon, 1995; Funderburk, 2002). A greater percentage of thrips species are opportunists feeding on several crops and/or eggs, larvae and adults of other minute insects such as mites, coccids and other thrips (Ananthakrishnan, 1970; Funderburk, 2002). The predatory thrips, *Aeolothrips intermedius* will also feed on pollen grains of several plant species if their preferred natural prey source (*T. tabaci*) is limited (Conti, 2009). The onion thrips, Western flower thrips, tomato thrips and *T. imaginis* feed predominantly on crops and transmit tospoviruses but have also been documented preying on leaf-feeding mites (Mound, 2005; Mound and Teulon, 1995). Adults of the opportunistic and polyphagous flower-feeding thrips, *Thrips obscuratus* have been reported by Teulon and Penman (1990) on 225 plant species, with larvae found only in flowers of 51 species, aside two records on stone fruits and adults found mostly on flowers, but also on fruits and leaves of various plants. The most serious opportunistic thrips pests are those which can combine flower and leaf feeding such as *T. palmi*, *F. occidentalis*, and *F. schultzei*. According to Mound and Teulon (1995), *F. schultzei* was frequently collected on *Gossypium* leaves, but also on flowers of *Ipomoea* in Sudan. This opportunistic behaviour of thrips allows them to easily adapt to newer environments, colonize new areas and create large populations which, enhance their ability to become economically important agricultural pests.

2.6 Ecology

The biological diversity of thrips is highest in the tropics, nonetheless research effort has been concentrated in the temperate zone (Mound, 2018). Thysanoptera is extremely sensitive to environmental changes and requires specific climates or microclimates for optimal growth and development. They do have certain life history strategies such as opportunism, polyphagy and ability to reproduce in concealed environments (Reitz, 2009), that ensures continuity of their populations.

2.6.1 Population dynamics and diurnal rhythms

Thrips populations fluctuate throughout the year based on alteration of environmental factors. Studies on the population dynamics of the banana flower thrips, *Thrips hawaiiensis* Morgan using yellow sticky traps revealed that *T. hawaiiensis* occurred throughout the year with monthly fluctuation which recorded the highest population in October and November 2015 during the bud burst and young fruit emergence (Yu *et al*., 2018). Deligeorgidis *et al*. (2005) studied the distribution and seasonal variation of *T. tabaci* and *F. occidentalis* on cucumber and tomato from April to August. They observed variation in the populations of both species with peaked population density in the month of May. Both species were observed on leaves rather than flower. However, Kawai (1988) reported that more than 99% of *T. palmi* infested eggplant were found on leaves with less than 1% on flowers and fruits, whereas on sweet pepper, adults were more abundant on flowers than leaves. A study on the seasonal distribution of thrips revealed the presence of the tobacco thrips, *T. parvispinus,* 15 days after planting (DAP) which peaked at 50 thrips per sample at 22 DAP and had decreased to ≤ 5 thrips per sample by 45 DAP. Additionally, the initial incidence of *F. occidentalis* occurred at 27 DAP with higher population in flowers than leaves which peaked at 27 thrips per sample at 81 DAP and declined to 12 thrips at 117 DAP per sample (Reed and Sukamto, 1995). A correlation of microclimatic data, such as light, humidity, windspeed, and localized temperature with different thrips species indicates different species occupy different positions on plants and their population changes at different times of the day (Ananthakrishnan, 1970). Their peak flight activities occur between 8:00-10:00 am and between 2:00-4:00 pm in the greenhouse (Riis, 2021), necessitating differences in their populations at different times of the day.

2.6.2 Determinants of thrips abundance

Several factors regulate thrips population dynamics (Funderburk, 2002). An attempt at important factors regulating thrips abundance is provided below.

2.6.2.1 Effect of rainfall

Thrips thrive and reproduce normally in optimal rainfall conditions. When rains, however, become more intense, thrips population are easily washed off from host plants to the soil where they die by drowning. For example, heavy rains have been shown to wash down the onion thrips, *T. tabaci* from onion plants (North and Shelton, 1986; Ibrahim and Adesiyun, 2010), and excess soil moisture predisposes the non-feeding stages to attack by pathogens (Zhang and Young, 1998). When rainfall becomes limiting such as in dry conditions, host plant nutritional quality is impacted and their attractiveness to thrips may increase (Lewis, 1973), increasing their populations in such conditions. Secondly, when there is water stress, volatile compounds emitted by host plants rises which increases the pest's ability to locate their host plants, thereby enhancing their population growth (Takabayashi *et al*., 1994; Paré and Tumlinson, 1999). Zhang and Young (1998) reported the highest population of *T. palmi* in the dry season and attributed their lower numbers in the wet season to high mortality of prepupal and pupal stages in saturated soil. Fennah (1965) have demonstrated that in the dry season when cocoa trees are water stressed, the redbanded thrips, *Selenothrips rubrocintus*, feed on leaves around the margins of fungal lesions to increase their population drastically. Similarly, Waiganjo *et al*. (2008) found the dry weather (30.3 mm rainfall) with moderately high temperatures (15.6-28.2^{o}C) to increase the seasonal thrips abundance, whilst the wet season (391 mm rainfall) with moderately high relative humidity negatively correlated with thrips numbers. Fening *et al*. (2022) indicated that the highest population of *T. parvispinus* were collected in traps during the dry season.

2.6.2.2 Effect of temperature

Temperature is the most important factor affecting thrips development (Schauff, 2001). Within the optimal temperature range, increasing temperature will hasten thrips development to produce more generations per year (Kawai, 1990). This optimal range varies per thrips species but is between 22-28 °C for most species (Schauff, 2001; Yadav and Chang, 2014). However, temperature extremes can immobilize, kill, or cause aestivation in some species. Cold temperatures will render thrips immobile temporarily but will not immediately kill them unless such conditions occur over a long period. During very cold seasons, some species of thrips survive on winter weed hosts and can feed and reproduce on days when temperature is moderately warm, which increases their population in the process. Thrips development will not occur beyond the lower or upper developmental temperature thresholds. The lower and upper temperature threshold for *T. palmi* was estimated to be 11.6 ºC and 35 ºC, respectively (Kawai, 1986, 1990), and at 40, 48 and 55 ºC, *T. palmi* takes 1380, 30 and 7 minutes to be killed (Kawai, 1990). Yadav and Chang (2014) found a decline in the melon thrips' egg-to-adult developmental period from 35.7 to 9.6 days when the temperature increased from 16 to 31°C. He further reported that adult females lived longer at low temperature (56.7 days at 16 °C) and shorter at high temperature (18.7 days at 31 °C) and the longevity of adult males similarly was shortest at 31° C (15.5 days) and longest at 16 °C (50.7 days). Waiganjo *et al*., (2008) recorded an increase in *T. tabaci* seasonal abundance with moderately high temperatures of 15.6-28.2ºC under field conditions in Kenya. The relationship between temperature and insect development have been expressed generally by degree day models which depend on the accumulation of heat units above a specific threshold temperature. Degree day uses linear models which fail to predict insect development correctly at temperature extremes, necessitating the need for incorporating non-linear models in understanding insect responses to temperature (Stinner *et al*., 1974).

2.6.2.3 Effect of wind

Winged thrips are weak fliers, and their small sizes make them very susceptible to wind. Even unwinged thrips do take advantage of wind transport since all thrips have a large surface-area-to-volume ratio (Mound, 2005). Waiganjo *et al*. (2008) reported that wind speed was positively correlated with thrips captured both from plant samples and sticky traps. However, when prevailing winds become dry, the thrips population reduces as they easily die by desiccation in dry winds. For instance, a sudden decrease in *T. tabaci* population was attributed to the incidence of dry winds (Priesner, 1960).

2.6.2.4 Effect of light

Attempts to evaluate the visual attractiveness of thrips indicate they show specificity to different colours; white and yellow for *T. tabaci* (Rueda and Shelton 1995), and blue for *F. occidentalis* (Chen *et al*., 2004). *Thrips palmi* has been shown to avoid cucumbers or traps illuminated with red light, as opposed to those with white light (Murata *et al*., 2018, 2021).

2.6.2.5 Effect of elevation and height

The composition and structure of thrips may change with elevation; such that the thrips species present on a particular crop at a one location might be different from those present on the same crop in another location (Hameed *et al*., 2023). A suction trap was used by Lewis (1959) to estimate the true density of thrips species in the air by sampling a constant air volume. He concluded that thrips density decreased with height with the decreased rapidity varying between species and though they preferred flying at a height of 1 m, thrips were equally collected as high as 14.6 m. Thrips abundance associated with *Leucaena glauca* were greatest at low elevations (200-450 m) in June and at high elevations (500-640 m) in July (Yudin *et al*., 1986).

2.7 Rearing of thrips

For studying the life history, host plant resistance, behaviour, virus transmission or conducting insecticide screening assays, several thrips have been reared in the laboratory to provide sufficient numbers for such studies. Several methods do exist for rearing thrips in which several food sources can be used (Murai and Loomans, 2001). In one method, thrips are reared on whole plants or host plant parts in the laboratory (Callan, 1947) especially for phytophagous species which normally inhabit plant tissues. Different thrips species successfully reared with this method include, *F. occidentalis* on leaves and florets of chrysanthemum (C*hrysanthemum morrifolium*) (Katayama, 1997), *T. palmi* on leaves of eggplant (*Solanum melongena* L.) (Yadav and Chang, 2012a), *T. tabaci* and *T. palmi* on seeds of germinated broad bean (*Vicia faba* L.) (Murai and Loomans, 2001), *S. rubrocinctus* and several other thrips reared on several leaves in petri dishes and watch glasses (Callan, 1947), amongst others. In another method, artificial diet is used to supplement thrips nutritional needs for mass rearing intended for biological control purposes (Murai, 2000). For example, *T. palmi* reared on pollen and honey solution with the highest mean fecundity of 263 eggs/female at 23 ºC (Murai, 2000), *T. palmi* and other species of thrips reared on dry leaf and fruit powder (Koyama and Matsui, 1992; Trichilo and Leigh, 1988), or several other species reared on mixed diets [artificial and leaf tissue/predator diets e.g. cotton leaf plus pollen and prey (mites) eggs] (Trichilo and Leigh, 1988).

Pollen contains more nutrients and when thrips are reared on pollens, their egg production capacity as well as larva development is enhanced (Trichilo and Leigh, 1988; Tsai *et al*., 1996). Pollen from tea (*Camellia sinensis* (L.) O. Kuntze), pine (*Pinus thunbergii* Parl.), maize (*Zea mays* L.), cotton (*Gossypium barbadense* L.), ice plant (*Mesembryanthemum* spp.) and dried bee can be collected and stored for more than 2 years at −20 ºC for thrips rearing (Trichilo and Leigh, 1988; Murai and

Loomans, 2001). However, they can easily mould with excess moisture and an oviposition cage with gauze at the bottom can prevent high moisture contamination (Murai and Loomans, 2001). In general, when rearing thrips, it is critical to consider the temperature, light regime, relative humidity, and sanitation of the rearing cages/containers very seriously.

2.8 Identification of thrips

Identification of thrips species is extremely difficult because most thrips are very minute, averagely 1-1.5 mm in length and the distinguishing characters are inconspicuous. More so, greater number of thrips species can inhabit a single crop at a given time making identification cumbersome. Thrips can be identified morphologically or molecularly.

In morphological identification, certain diagnostic features are used in separating families, genera or even species of Thysanoptera. Some of which include colour, antennal segment, head shape, arrangement of the ocellar, prothoracic, wing and metanotum setae, presence, or absence of abdominal comb on tergite VIII, ovipositor shape among others (Plate 2.3). Generally speaking, morphological identification of thrips is possible and have been provided by Palmer (1990) and Mound (2010) for tropical Africa, Moritz *et al*. (2013) for East Africa, Hoddle *et al*. (2012) for California, and by Moritz *et al*. (2004a) for thrips of the world. However, identifying thrips morphologically have seen some setbacks, hence, molecular identification is currently being recommended to compliment the former.

Molecular identification uses chemical markers including RNA, DNA, and proteins to determine the genetic characteristics of the organisms. Molecular identification of thrips is provided by several authors (Moritz *et al*., 2000; Timm *et al*., 2008; Mehle and Trdan, 2012; Tyagi *et al*., 2015; Przybylska *et al*., 2018; Fening *et al*., 2022). Molecular identification can be used for all thrips stages or even on damaged specimens. However, molecular tests have limited specificity because they are developed for specific objectives and have been tested against a limited number of thrips species.

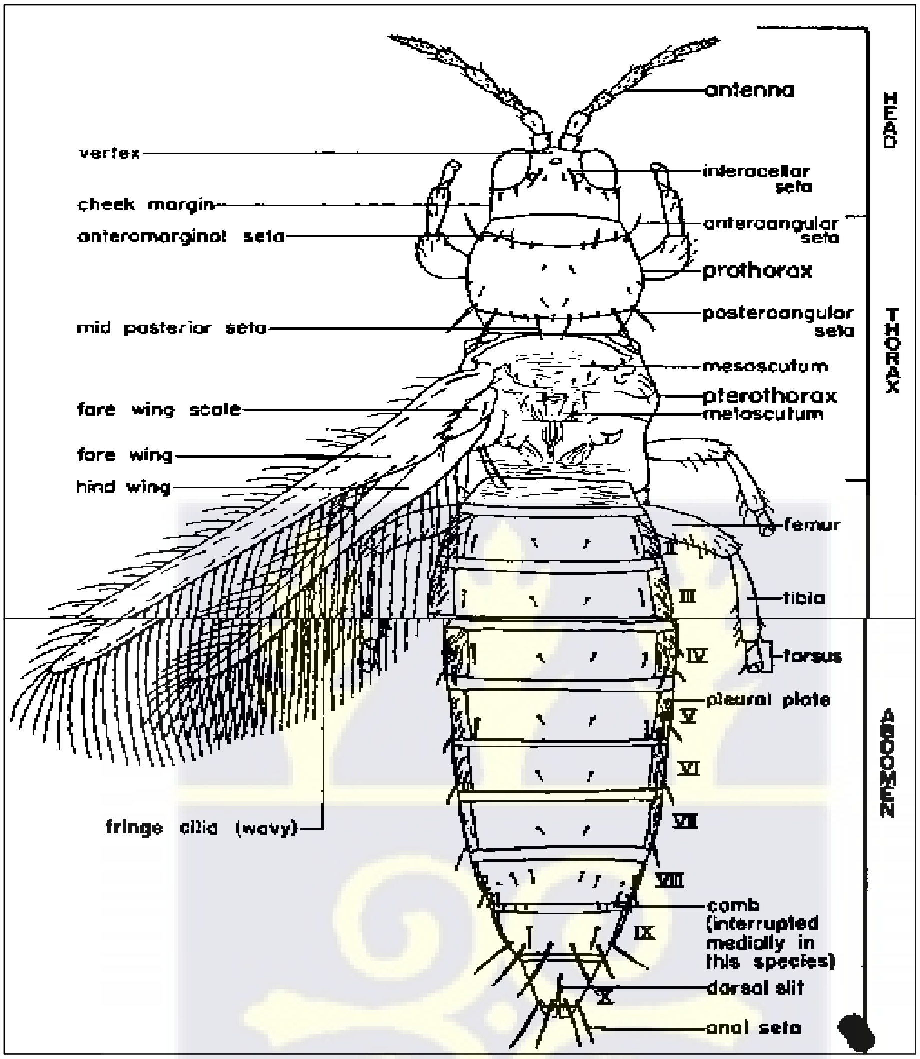


Plate 2.3. A typical Terabrantia thrips showing characteristic features for identification.

2.9 Economic importance of thrips

The challenge in thrips pest management is often linked to misidentification of the many species of thrips that can inhabit a particular crop at a given time. Given that approximately 50% of all described species are fungal feeders (Morse and Hoddle, 2006) but can co-exist with phytophagous species, the need to separate pest's species from non-pest's species becomes paramount, as this will improve understanding of their ecological roles.

2.9.1 Beneficial thrips

Not all species of thrips are damaging to crops. Some are considered beneficial to mankind for their role in pollination or in biological control for the suppression of other pests including other thrips of economic importance. This explains why correct identification of thrips species is critical as this informs decision making and ensures appropriate management options are sorted (i.e if control is warranted). Thrips of beneficial importance are from the Thysanopteran families Thripidae, Aeolothripidae and Phlaeothripidae. The predatory thrips, *Scolothrips indicus* (Thysanoptera: Thripidae) has been recorded feeding on mites where one larva consumed 6 adults, 7 nymphs and 55 eggs of spider mite (*Paratetrarhynchus pilosus*) in 3 days (Ananthakrishnan, 1970). *Franklinothripes vespiformis* (Thysanoptera: Aeolothripidae) is a predator of *T. palmi* egg and larvae on eggplant in Japan and Thailand (Hirose *et al*., 1993; Yano, 2004). Adults of the tubular black thrips, *Haplothrips victoriensis* Bagnall (Thysanoptera: Phlaeothripidae) have been shown to feed on two larvae of *T. palmi* per day in Northern Australia (Zhang and Young, 1998). It has an even wider prey range such as diamond back moth, two spotted mite, *Tyropagus* mite, *F. occidentalis*, spotted alfalfa aphid, and greenhouse whitefly in Southern Australia (Luong, 2008). *Aeolothrips intermedius* (Thysanoptera: Aeolothripidae) shows a predatory behaviour on *T. tabaci* and *F. occidentalis* and completes 3-4 generations a year in Italy. It was also the most dominant thrips species collected in a survey in Tuscany (Conti, 2009). In South Africa, some species of predatory thrips (*Aeolothrips* and *Scolothrips* spp.) were identified on blue sticky traps set on plum orchards (Allsopp, 2010), however, not much empirical data exists on bioecological studies on species of predatory thrips in Africa.

Predatory thrips have gained importance for their ability to be opportunists preying out of their host-prey range in contrast to most microbial which have a restricted host range (Samler, 2012; Mound and Teulon, 1995). Several flowers inhabiting thrips pollinate host plants by carrying pollen grains from the flower of one host to another (Lewis, 1973; Velayudhan and Annadurai, 1986). Carlson (1964) found low populations of *F. occidentalis* to improve pollination and seed set as opposed to caged plants that excluded thrips**.** Eliyahu *et al*. (2015) investigated the role of thrips as pollinators of the shrub, *Arctostaphylos pungens* (Ericaceae) and observed that flowers exposed to thrips produced significantly more fruits than those on which thrips were excluded**.** Fungus-feeding thrips play an important role in nutrient recycling and contribute to the maintenance of natural and forest ecosystems (Mound, 2005).

2.9.2 Pest species of thrips

A species of thrips is considered as a pest if its damage on the crop sufficiently reduces the quality or yield by an amount unredeemable by the farmer (Dent, 2000). In general, only 1% or a few 100 or 98 species of all described thrips species are serious pests attacking commercial crops (Lewis, 1973; Mound, 1997; Morse and Hoddle, 2006) though many other species have the potential to become pests (Mound and Teulon, 1995). This points to the fact that, their very minute size (0.5 mm to 14 mm) (Healey, 2016) makes them very susceptible to dehydration and will constantly need to obtain the necessary nutrients especially water through feeding, which increases their chances of sourcing and feeding on wide hosts and could easily attain pest status in the process. The majority (>90%) of thrips pests in the family Thripidae inhabit living plants (Minaei, 2014) and only a few species of Phlaeothripidae are pests which include *Gynaikothrips uzeli* Zimmerman, *Gynaikothrips ficorum* Marchal (Ficus pests) and *Haplothrips* spp., (grains pests in central Asia and Europe) (Moritz *et al*., 2004a; Stuart *et al*., 2011). Additionally, thrips such as

Limothrips cerealium, cause nuisance to humans by practising thigmotaxis where, they crawl into enclosed places including smoke detectors to activate fire alarms in homes, hospitals, and hotels (Mound, 2005).

2.9.2.1 Indigenous and exotic thrips pests

Thrips infesting crops in Africa are either indigenous or exotic (Monteiro *et al*., 1995; Grove *et al*., 2001; Banfo, 2009; Fening *et al*., 2022). Major thrips species attacking crops in Africa include; the cotton bud or blossom thrips (*Frankliniella schultzei*), onion thrips (*Thrips tabaci)*, Western flower thrips (*Frankliniella occidentalis*), African bean flower thrips (*Megalurothrips sjostedti*), black vine thrips (*Retithrips syriacus*), cocoa or red banded thrips (*Selenothrips rubrocintus)*, *Liothrips* spp, black tea thrips (*Heliothrips haemorrhoidales*), coffee thrips (*Diarthrothrips coffeae*), cereal thrips (*Haplothrips* spp), citrus thrips *(Scirtothrips aurantii*), banana thrips (*Hercinothrips bicinctus*), tomato thrips (*Ceratothripoides brunneus*), and tea thrips (*Scirtothrips kenyensis*) (Table 3) **(**Dennill and Erasmus, 1992; Grove *et al*., 2001; Banfo, 2009; Infonet-Biovision, 2022)**.** Marked differences may occur in pest status from place to place such that a species may be damaging to a particular plant but completely harmless to the same crop in another geographical area (Childers and Achor, 1995).

Even though Africa is known to be the origin of several thrips' species most importantly, the African bean flower thrips (*Megalurothrips sjostedti*), the continent has also become very vulnerable to several alien species, particularly with the intensification of international trade. *Thrips palmi* for example originated from the Island of Sumatra in 1925 but has expanded its distribution range through the Caribbean, Central and North America and Africa where it is present in Nigeria, Ivory Coast, Mauritius, Sudan and Reunion (Monteiro *et al*., 1995). This is similar to some other species such as *T. parvispinus* (Fening *et al*., 2022) and *F. occidentalis*.

The introduction and establishment of invasive species can cause serious ecological and economic implications with unpredictable consequences on native species (Badii, 2014). Alien species can disrupt mutualistic interactions, pest-natural-enemy synchrony, extinction of local species, loss of species diversity, and change the ecological role, potentially leading to local outbreaks with decreased pesticide effectiveness. A concerted effort is, therefore, needed from African governments, development partners and regulatory bodies to create awareness, provide technologies such as artificial intelligence and build capacities of African researchers and Quarantine staff to improve detection and prevention of invasive species at border checkpoints.

2.9.3 Damage caused by thrips

Thrips cause both direct and indirect injury to infested crops worldwide (Hodges *et al.*, 2009; Pappu *et al.*, 2009; Daimei *et al.*, 2017) with a substantial effect on crop yields (Boonham *et al.*, 2002) and the profit margins of farmers. Damage symptoms caused by thrips are similar for most species.

2.9.3.1 Direct damage by thrips

Thrips cause direct damage through their capacity to puncture several host plant parts and suck out plant cell sap. This cause slightly infested leaves to curl, discolour and become translucent on lower leaf surfaces (silvering), whilst heavily infested leaves become yellow or brown which dry out with time (Zhang and Young, 1998; Capinera, 2000; CABI/EPPO, 2001; Seal, 2004; Srinivasan, 2009; Muniappan *et al*., 2012; Yadav and Chang, 2013). This affects carbon allocation and photosynthetic capacity of the plant, and ultimately reduces yield (Rosenheim *et al.*, 1990; Shipp *et al.*, 1998; Bacci *et al.*, 2008; Subba and Ghosh, 2016). Direct damage is also caused by adult females during oviposition, where, created holes leave fruits scared, deformed and blemished which reduce the quality and market value (Layland *et al.*, 1994; Shipp *et al.*, 1998; Stuart *et al.*, 2011; Tan *et al*., 2016). Damaged fruits are downgraded due to poor appearance (Plate 2.4). Direct feeding activity of thrips further results in small black fecal spots which contaminate the leaves and fruits, thereby, lowering their aesthetic value. Mechanical injury caused by direct feeding renders damage plants susceptible for pathogen invasion. Larvae of some leaf feeding species, precisely Panchaetothripinae, excrete sticky droplets which attracts black sooty mould (Wilson, 1975). In most cases, it is difficult to control thrips damage on hosts because, damage caused by thrips is noticed before the physical presence of the minute pest is detected (Samler, 2012), meaning management decisions may be implemented after the damage has been inflicted.

Plate 2.4. Direct damage of thrips on host plants: (a) silvering damage on eggplant leaf, (b) scaring of eggplant fruit, (c) black varnish-like flecks of excrement on eggplant leaf, (d and e) shrinking and silvering of chilli flowers and (f) silvery damage on eggplant flower (Photos by Nkafu Therese Ngosong).

2.9.3.2 Indirect damage

Thrips cause indirect damage to horticultural products by their ability to transmit tospoviruses or act passively as carriers of bacterial and fungal spores (Childers and Achor, 1995). Tospovirus group of viruses is one of the most damaging groups of pathogens infesting both cultivated and uncultivated plants. There are 19 species of viruses in the tospovirus genus (Family: Bunyaviridae), all of which are spread exclusively by thrips (Tyler-julian, 2013). One of the tospovirus, tomato spotted wilt virus (TSWV) capable of infecting about 600 plant species is transmitted by up to nine thrips species including *Frankliniella intonsa* (Trybom), *F. cephalica*, *F. bispinosa*, *F. occidentalis*, *F. fusca*, *T. tabaci*, *F. schultzei*, *Thrips setosus* Moulton and *S. dorsalis* (Boonham *et al*., 2002; Morsello *et al*., 2008; Pappu *et al*., 2009). Damage by this virus results in flecks, rings or necrotic spots/lesions, streaks, leaf distortion and deformation, line patterns on leaves and fruit, dieback and leaf collapse, dropping of leaves or shedding of buds, stripes on petals and plant death caused by wilting (Broughton *et al*., 2004), which can cause 100% crop loss (Plate 2.5). More importantly, plants previously infected by the virus renders them more attracted for further thrips invasion, feeding and oviposition than unaffected plants (Maris *et al*., 2007).

Lakshmi *et al*. (1995), Daimei *et al*. (2017), and Ghosh *et al*. (2019) documented the ability of the melon thrips, *T. palmi*, to transmit the peanut bud necrosis virus whilst it's transmission potential for the capsicum chlorosis virus has been reported by Pappu *et al*. (2009).

Thrips spread tospoviruses in two ways, by primary infection and by secondary infection. In primary infection, a viruliferous adult with ability of transmitting a tospovirus locates a new field and feed on new plants, and subsequently transmitting the disease to uninfected plants. Secondary infection on the other hand occurs when the adults reproduce on the infected plants, as the larvae feed on the plants, they acquire the virus and upon becoming adults these infected thrips persistently transmit tospoviruses to uninfected plants within seconds of feeding on them (Nagata, 1999; Momol *et al*., 2004; Tyler-julian, 2013). Virus acquisition by the larvae occurs in the first or early second larval instars when the mid-gut, salivary glands and visceral muscles are closely connected (Moritz *et al*., 2004b). Once this connection is lost such as with the emergence of wing muscles which causes the supra-oesophageal ganglion to move towards the head, virus acquisition stops, and such larvae will be unable to acquire the virus. However, the virus is located in the lumen, the hemocoel, malpighian tubes, and in the salivary glands for viruliferous adults and though virus transmission occurs during feeding through salivary glands, transmission is also possible during oviposition and excrement (Moritz *et al*., 2004b; Daimei *et al*., 2017). Tospoviruses continue to pose a challenge in agriculture because thrips require a very short time to transmit viruses during feeding. Therefore, pesticides are ineffective in controlling primary infection as transmission is likely to have occurred before the pesticide effect is felt on the pest thrips (Momol *et al*., 2004). Unfortunately, most infections occur through primary spread which requires control methods that can repel the adults from feeding on plants. Targeting the larval stages can reduce secondary infection.

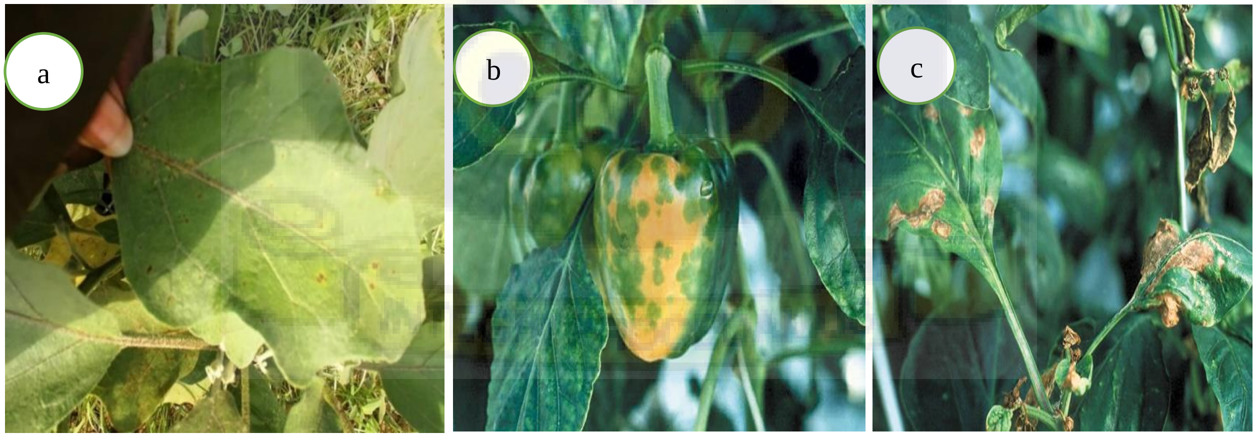


Plate 2.5. Indirect damage caused by tospoviruses; (a) necrotic lesions on eggplant leaves, (b and c) TSWV symptoms on pepper plant and fruit (Murphy *et al*., 2014; Nkafu Therese Ngosong).

Table 2.3. Damage symptoms of some thrips pests in Africa.

Pest thrips	Damage symptoms	Reference
Cowpea flower thrips (*Megalurothrips sjostedti*)	Feeding by the cowpea flower thrips causes floral parts to distort, discolour and fall off, resulting in decreased pollen production, flower, and yield losses. Three to five adults are required to cause economic damage on cowpea.	(Salifu, 1982; Tamò *et al*., 2002)
Black tea thrips or greenhouse thrips (GHT) (*Heliothrips haemorrhoidales*	It feeds mainly on leaves of hosts plants. Slightly Infested leaves become discoloured and distorted between lateral veins whilst severely damaged leaves turn yellow and drop from the plant. Damage sometimes occurs on the fruit where fruit scars > 2 cm can result in economic losses of > 50% in avocados. It has been reported as a severe pest of avocado fruit in South Africa.	(Dennill and Erasmus, 1992; Phillips *et al*., 1995)
Onion thrips (*Thrips tabaci*)	It feeds on developing flower buds and flower pedicels of onions. Damage results in small, silvery, shrunken areas which may coalesce to collapse the whole pedicel, leading to flower drop and reduction in seed yield. Feeding on onion bulbs results in scared bulbs which lowers the quality. It is a pest of many horticultural crops and present in several African countries including Ghana.	(Phillips *et al*., 1995; Bethke *et al*., 2014)

Western flower thrips (*Frankliniella occidentalis)*	Its feeding on several plant parts such as leaves, petals, open blooms, and fruits, results in discolouration and scarring of affected parts. Besides the feeding injury on host plants, this thrips vectors TSWV and other tospoviruses that affect herbaceous plants.	(Grove *et al*., 2001; Boonham *et al*., 2002; Reitz, 2009)
The melon thrips (*Thrips palmi*)	A key pest in tropical and sub-tropical regions including the Pacific, Southeast Asia, and the Caribbean Islands. It is regarded as the most dangerous pest with severe yield losses on watermelon in Nigeria. *T. palmi* also vector tospoviruses such as peanut bud necrosis virus, capsicum chlorosis virus, and watermelon bud necrosis virus.	(Kawai, 1990; Pappu *et al*., 2009; Burubai *et al*., 2011; Bethke *et al*., 2014; Daimei *et al*., 2017)

2.9.4 Economic impact of thrips

The economic impact of thrips pests includes yield and quality losses that arise because of thrips incidence and damage, the cost associated with additional research and certification programmes and the loss of export that arise from interceptions, restrictions or ban of thrips-infested consignments and/or countries. The net present value of the economic impact of *T. palmi* over 10 years is estimated between 16.9-19.6 million Euros in England (MacLeod *et al*., 2004). Yu *et al.* (2018) studied the effect of the banana thrips on the banana bud nutritional quality and reported the nutrient composition of banana infested flowers such as vitamin c, ash content, reducing sugar and proteins to be lower significantly in damaged than undamaged flowers which reduced the nutritional quality of the host plant, flower bud by-products and the banana fruit. Kendall and Capinera (1987) observed that, at densities of 10 *T. tabaci* per plant, a 7% and a 2-3% yield loss was obtained in the greenhouse and on-farm onion fields in Colorado, respectively. In other studies (Kendall and Capinera, 1987; Fournier *et al*., 1995; Waiganjo *et al*., 2008; Diaz-Montano *et al*., 2011), yield losses of more than 43% in thrips infested onion plantations have been reported. Welter *et al*. (1990) attested that mixed infestation of thrips (45.0 per cm^2), led to a 54.2% reduction on total cucumber fruit weight at harvest in Hawaii.

The economic impact of thrips is even more severe when they transmit tospoviruses, and virus-infected fruits are usually unmarketable (Nagata *et al*., 2002; Subba and Ghosh, 2016) or not harvested at all. *Thrips tabaci* is able to transmit the Iris yellow spot virus with yield loss of up to 100% (Diaz-Montano *et al*., 2011), whilst TSWV is transmitted by several thrips species can cause up to 100% crop loss in tomatoes, capsicum and lettuce (Broughton *et al*., 2004).

2.9.4.1 The phytosanitary implications of thrips pest for international trade

Thrips are very minute insect pests and difficult to identify. They have moderate ability to disperse by themselves but can be carried on plant and plant products or in shipping consignments during international trade (Mehle and Trdan, 2012). Some species are classified as A1 quarantine pests (pests recommended for regulation as a quarantine pest, and which are not present in an area) whilst others are A2 quarantine pests (pests recommended for regulation as quarantine pests, which are present in the area and being officially controlled) (OEPP/EPPO, 2018b), both of which are listed as priority pest by the EU. These thrips pests are, therefore, not allowed in new environments and their presence on consignments drive countries to impose trade barriers and other sanitary and phytosanitary sanctions (Fening and Billah, 2019, 2022).

Thrips palmi for instance, is an A1 quarantine pest in the European and Mediterranean Plant Protection Organization (EPPO) (OEPP/EPPO, 2018a, b) and an A2 quarantine pest in the Caribbean Plant Protection Commission (CPPC) (CABI/EPPO, 2001), and its introduction, establishment and spread is prohibited in all the Caribbean and EU member states. Generally, the presence of quarantine thrips pests on plants and plant products results in interceptions and severe phytosanitary sanctions in some cases which leads to loss in foreign exchange and some countries losing their competitiveness in the international market (Fening *et al*., 2022). Thrips interceptions have been a topic for debate because most of them are rarely identified to the species level and Bragard *et al*. (2019) indicated that interceptions on shipments containing *T. palmi* might not exactly be identified as *T. palmi* but as Thysanoptera, Thripidae or *Thrips* sp. Arguably, notifications reported as Thysanopera or Thripidae may just be any thrips species not of quarantine importance to warrant a severe phytosanitary sanction since export requirements for quarantine species are much more stricter. For instance, a recent study by Fening *et al*. (2022) has identified the tobacco thrips, *T. parvispinus* as the species of thrips commonly associated with ridged gourd (*Luffa acutangula*) production in Ghana, but EU has intercepted, *T. palmi* in several consignments of ridged gourds from Ghana to the EU. Whereas *T. palmi* is of quarantine importance, *T. parvispinus* is not (Fening *et al*., 2022).

Several interceptions on thrips have been recorded from commodities from African countries in the EU and Switzerland and Ghana seems to have experienced the greatest number of thrips interceptions for various commodities (especially *Solanum* and *Luffa*) exported to the EU (Table 2.4). This may have largely contributed to the ban on the trade of these vegetables from October 2015 to December 2017 (GhanaVeg Sector Reports, 2017; Fening and Billah, 2017).

Table 2.4. Interceptions of Thrips in commodities exported from Africa to EU and Switzerland, 2010-2021.

Number of interceptions						
Region	**Exported country**	**Host plant species**	**Thrips**	**2010-2015**	**2016-2021**	**Total number of interceptions/countries**
North Africa	Morocco	*Solanum melongena*	*Thrips palmi*	1	-	**3**
		Dianthus chinensis	*Thrips* sp.	-	2	
	Egypt	*Viola cornuta*	*Thrips*	-	1	**1**
East Africa	Kenya	*Momordica charantia*	*Thrips* sp.	4	-	**22**
		Solanum melongena	*Thrips* sp.	1	-	
		Momordica sp	Thripidae	1	-	
		Alstroemeria sp.	Thysanoptera	1	-	
		Ocimum basilicum	Thripidae	-	2	
		Rosa	Thrips	-	1	
		Rosa sp.	Thysanoptera	1	-	
		Limonium sp.	*Thrips* sp.	1	-	
		Alstroemeria sp.	Thripidae	1	-	
		Rosa sp.	*Thrips* sp.	1	-	
		Momordica charantia	Thripidae	1	-	
		Lisianthus sp.	Thripidae	1	-	
		Limonium sp.	Thripidae	2	-	
		Dianthus caryophyllus	Thysanoptera	-	1	
		Gypsophila paniculate	Thysanoptera	-	1	
		Solidago sp.	Thysanoptera	-	1	
		Chrysanthemum sp.	Thysanoptera	-	1	
	Mauritius	*Lisianthus* sp.	Thripidae	1	-	**23**
		Solanum melongena	Thysanoptera	4	-	
		Solanum macrocarpon	Thysanoptera	1	-	
		Momordica charantia	Thysanoptera	1	2	
		Solanum macrocarpon	*Thrips palmi*	-	1	
		Solanum melongena	*Thrips palmi*	3	1	
		Capsicum	*Thrips palmi*	-	1	
		Momordica sp.	Thripidae	3	-	
		Solanum melongena	Thripidae	3	1	

Table 2.4. (Continued)

Number of interceptions						
Region	**Exported country**	**Host plant species**	**Thrips**	**2010-2015**	**2016-2021**	**Total number of interceptions/countries**
		Solanum melongena	Thrips	-	1	
	Ethiopia	*Gypsophila* sp.	Thysanoptera	1	-	**2**
		Gypsophila	Thysanoptera	-	1	
	Tanzania	*Brachyscome* sp.	Thysanoptera	1	-	**9**
		Begonia sp.	Thysanoptera	1	-	
		Asteriscus sp.	Thysanoptera	1	-	
		Cestrum nocturnum	Thysanoptera	1	-	
		Fuchsia sp.	Thysanoptera	1	-	
		Felicia amelloides	Thysanoptera	1	-	
		Leucanthemum sp.	Thysanoptera	1		
		Sutera sp.	Thysanoptera	1	-	
		Pelargonium sp.	Thysanoptera	1	-	
	Uganda	*Sutera* sp.	Thripidae	-	1	**4**
		Solanum aethiopicum	*Thrips palmi*	-	2	
		Momordica charantia	Thripidae	1	-	
	Rwanda	*Momordica charantia*	*Thrips palmi*	-	1	**1**
Southern and Central Africa	Cameroon	*Capsicum annuum*	Thysanoptera	1	-	**3**
		Solanum aethiopicum	Thysanoptera	-	1	
		Solanum melongena	*Thrips palmi*	1	-	
	South Africa	*Gypsophila*	Thrips	-	1	**2**
		Cymbidium	Thrips	-	1	
	Ghana	*Luffa acutangula*	Thripidae	225	15	**491**
		Luffa sp.	Thripidae	6	-	
		Solanum melongena	Thripidae	181	6	
		Solanum melongena	*Thrips palmi*	17	-	
		Momordica charantia	*Thrips* sp.	1	-	
		Momordica charantia	Thripidae	1	5	
		Mangifera indica	*Thrips palmi*	1	-	
		Abelmoschus esculentus	Thripidae	2	1	
		Momordica sp.	Thripidae	11	-	
		Capsicum	Thripidae	-	1	
		Capsicum	Thysanoptera	-	1	
		Luffa acutangula	Thrips	-	2	
		Luffa acutangula	Thripidae	-	2	
		Solanum melongena	*Thrips* sp.	2	-	

Table 2.4. (Continued)

Number of interceptions						
Region	**Exported country**	**Host plant species**	**Thrips**	**2010-2015**	**2016-2021**	**Total number of interceptions/countries**
		Momordica charantia	*Thrips palmi*	1	-	
		Moringa oleifera	Thripidae	1	-	
		Luffa sp.	*Thrips palmi*	2	-	
		Momordica sp.	*Thrips* sp.	1	-	
		Luffa	Thripidae	-	3	
		Solanum	Thripidae	-	1	
		Solanum aethiopicum	Thrips	-	1	
		Solanum melongena var. *serpentinum*	Thripidae	-	1	
	Mali	*Mangifera indica*	Thripidae	2	-	**3**
		Mangifera sp.	Thripidae	1	-	
	Nigeria	*Telfairia occidentalis*	Thripidae	-	36	**52**
		Amaranthus viridis	Thripidae	-	2	
		Amaranthus	Thripidae	-	2	
		Amaranthus viridis	*Thrips palmi*	-	1	
		Celosia argentea	Thripidae	-	1	
		Corchorus	Thripidae	-	3	
		Rumex acetosa	Thripidae	-	1	
		Telfairia	Thripidae	-	1	
		Corchorus olitorius	Thripidae	-	1	
		Vernonia amygdalina	Thripidae	-	1	
		Solanum melongena	Thripidae	-	1	
		Celosia argentea	Thripidae	-	1	
		Telfairia occidentalis	Thripidae	-	1	
	Burkina Faso	*Solanum aethiopicum*	*Thrips palmi*	5	4	**11**
		Solanum aethiopicum	Thysanoptera	-	2	
	Togo	*Solanum aethiopicum*	Thysanoptera	-	2	**6**
		Solanum aethiopicum	Thrips	-	1	
		Solanum aethiopicum	*Thrips palmi*	2	1	
	Benin	*Solanum macrocarpon*	Thysanoptera	-	1	**1**
Total				**507**	**127**	**634**

- No report

Total number of interceptions per country is written in bold. Source: (EUROPHYT 2010-2021).

2.10 Management of thrips

Owing to the economic losses inflicted by thrips on vegetables, the need to reduce their populations below damaging levels or consider eradication for quarantine species is on the rise. Cultural, biological, chemical, and plant quarantine are among the methods recommended for thrips management (Afreh-Nuamah, 2003). However, the challenge in thrips management lies on their short lifecycles, broad host range, th igmotactic behaviour and high reproductive capacity (Monteiro *et al*., 1995). So, no one method is a fit-all solution especially for the extremely diverse Thysanoptera whose impact varies with weather condition, cropping season, crop type and aesthetic value of crops. In some cases, for instance, especially where a crop sustains a small injury, control is not needed as yield loss may be minimal due to tolerance or fast recovery ability of the plants. This stresses the importance of economic thresholds in thrips pest management (Fening *et al*., 2016). It is important to consider the individual methods reviewed below and probe into the synergistic effect of combining compatible methods in an integrated pest management approach.

2.10.1 Monitoring

Monitoring allows for early detection of thrips pests, the identification of hot-spot areas in the crop, the prediction of pest/disease outbreaks, the timing of control measures, and the assessment of the effectiveness of control measures (Shipp, 1995; Chen *et al*., 2004). It is critical to detect thrips early in a field and identify suitable control options to prevent their catastrophic feeding and virus transmission injury. This is because the spread of viruses by their thrips vector can occur even at low thrips densities and disease symptoms may manifest after several weeks in some hosts (Boonham *et al*., 2002). Hence, thrips monitoring is very important and can be achieved through sampling of plant parts or utilising sticky traps in the crop environment (Boonham *et al*., 2002; GhanaVeg Sector Reports, 2017; Amouzzou *et al*., 2022; Fening *et al*., 2020, 2022) to determine the action threshold that warrants control measures to be implemented.

2.10.1.1 Plant sampling

Large scale monitoring of thrips is done by directly inspecting individual plants in the field (Cho *et al*., 2000; Hodges *et al*., 2009). Emphasis should be on whole plants or plant parts such as leaves, buds, flowers, and fruits depending upon the life stage targeted and the thrips species (Shipp, 1995). *Thrips palmi* larvae and adults, for instance, prefer foliage, though adults tend to move towards younger leaves which requires observation to be focused on this area, especially on underside of leaves (Jayma and Mau, 2007). Plant taping or beating the plant onto a clean white surface (Cho *et al*., 2000) will give an idea of the population of thrips present at that time. It is advisable to scout at an early phenological stage, such as 4 -5 leaves because, after this stage, their population will increase rapidly with ideal weather conditions (Rueda and Shelton, 1995). Flowers can also be sampled from plants and kept in vials containing 70% alcohol, and thrips population could be counted with a hand lens in the laboratory (Cho *et al*., 2000; Palmer, 1990; Fening *et al*., 2016).

2.10.1.2 Trapping

Several traps have been evaluated for monitoring thrips populations including CC traps, water tray traps, and sticky traps (Layland *et al*., 1994; Chu *et al*., 2006; Aliakbarpour and Rawi, 2011; Fening *et al*., 2022), but sticky traps are recommended as they easily detect fluctuations in a population in addition to their low costs. Sticky traps are composed of sticky cards with varying colours which may act as an attractant, or the adult insects may passively be intercepted during flight or be blown on the card through wind transportation (Samler, 2012). They are available or easy to produce locally by adding a sticky glue to a card. Blue, yellow and white are recommended colours for monitoring thrips in commercial farms. Blue sticky trap was reported attractive to *F. occidentalis* (Chen *et al*., 2004; Broughton and Harrison, 2012), *T. tabaci* (Lu, 1990), *T. palmi* (Murata *et al.*, 2021), and white traps were reported attractive to *Frankliniella intonsa* (Mao *et al*., 2018). Fening *et al*. (2022) reported *T. parvispinus* was attracted to blue sticky traps than yellow. However, the specificity of thrips species to different colours appears to vary with the location and the stickiness of the traps as reported by different authors. For instance, even though white has been reported to be very attractive to *F. occidentalis* in Hawaii (Yudin *et al*., 1987) and Australia (Broughton and Harrison, 2012), Chen *et al*. (2004) found white not attractive to this species in China. This could be due to locational differences, reflectance, or differences in the stickiness of the traps. Chen *et al.* (2004) locally improvised the white trap and coated it with Tanglefoot (aerosol formula; The Tanglefoot Co., Grand Rapids, MI) to compare with commercial blue and yellow traps. This is similar to the work of Beavers *et al.* (1971). Comparability of such results becomes questionable as the effectiveness of commercial traps may not only be due to their colour reflectance but also to the stickiness of the traps. The mode of deployment (horizontal or vertical), the height and the number of traps needed per area equally determines the efficiency of sticky traps (Schauff, 2001; Gharekhani *et al*., 2014). The basic recommendation by Pasian and Lindquist (2011) is to hang or place traps vertically, at or slightly below the tops of crops for better results.

The addition of semiochemicals to traps can improve their selectivity and attractiveness to different species of thrips. This phenomenon have been demonstrated by several studies (Teulon *et al*., 2007; Akella *et al*., 2014; Shuangshuang, 2018).

2.10.2 Action thresholds

Pest monitoring offers the opportunity to determine thresholds for action or to ascertain the effectiveness of a control measure (Fening *et al*., 2016). Generally, there is a pest population density at which the application of a control measure is justified in pest management. Above this level, significant damage occurs if control measures are not instituted (Stern *et al*., 1957). Knowledge of thresholds can help in optimizing insecticide applications and other management tactics as well as saving money and time, and mitigating the evolution of thrips resistance to insecticides (Gill *et al*., 2015). Action thresholds vary with crop cultivar, aesthetic value, phenological stage of the crop, geographic region, insecticide efficacy and thrips species. Action thresholds for *T. palmi* have been developed for several crops (Kawai, 1986; Capinera, 2000; Yadav and Chang, 2013), with the density estimated at 0.11 or 1.05-1.50 thrips/flower for sweet pepper and eggplant, respectively (Kawai, 1986; Yadav and Chang, 2013). Good thresholds should, therefore, depend on the identification of the thrips species to distinguish harmful species from less harmful or beneficial ones (Palmer, 1990). Unfortunately, identification of thrips species is still a challenge worldwide due to their small sizes (Timm *et al*., 2008; Iftikhar *et al*., 2016a; OEPP/EPPO, 2018b), but most especially in Africa where most laboratories are underequipped, and the cost associated with reagents for molecular diagnosis such as specific primers and tag polymerase appears high.

2.10.3 Cultural control

Cultural control refers to the manipulation of the normal production environment to disfavour pest incidence and abundance. Several cultural options are available for use in thrips management such as intercropping, manipulation of planting dates, sanitation, fertilization, use of resistant varieties, and use of soil cover such ultraviolent reflective mulch. Whilst some studies detailed the ability for cultural control to reduce thrips populations and damage significantly (Nonaka and Nagai, 1983, Srinivasan, 2009; Pankeaw *et al*., 2011; Bethke *et al*., 2014; GhanaVeg Sector Reports, 2017; Razzak *et al*., 2019), others have documented no influence of cultural control on thrips, especially *T. palmi* (Jayma and Mau, 2007).

Studies on the manipulation of planting dates to avoid coincidences of peak thrips dispersal resulted in lowered thrips densities, reduced risk of feeding injury and reduced virus transmission rate (Brown et *al*., 1996; Culbreath *et al*., 2010). Associations of green pepper (*Capsicum annum* L.) with black bean (*Phaseolus vulgaris* L.) and cucumber (*Cucumis sativus* L.) as trap crops against soil cover (rice husks and silver coloured plastic mulch) on *T. palmi* revealed that black bean trap crop recorded lower thrips population compared to the highest population on cucumber, and the highest yield was recorded on the pepper plot (14,236 k/ha) (Salas, 2004). Similarly, a combination of reflective mulch and reduced pesticide application resulted in a US$4000 increase in the profit margin of thrips-infested tomatoes in Florida (Stuart *et al*., 2011). Ultraviolet-reflective (UV) mulch disrupt host-finding behaviour to supress thrips population and thrips vectored diseases such as TSWV (Reitz *et al*., 2003; Riley *et al*., 2017). The use of these physical barriers prevents thrips colonization, settling capacity and establishment on new cultivated farms (Cannon *et al*., 2007; Hodges *et al*., 2009). However, Reitz *et al*. (2003) reported a reduced *O. insidiosus* abundance with the use of UV mulches, thereby resulting in effects on predator-prey dynamics. Farm sanitation measures including the elimination of weeds considered as alternative hosts, within and around farms can reduce their population (Hodges *et al*., 2009; GhanaVeg Sector Reports, 2017).

2.10.4 Biological control

Biological control involves the use of natural enemies such as microbials (pathogens) and macrobials (predators and parasitoids) to reduce pest densities. In general, biocontrol agents are often enough to keep pest infestations under economic control (Mandal and Patnaik, 2008). However, for thrips, most are r-selected and their population attributes (such as shorter generation time, breeding structure that promotes aggregation and parthenogenetic behaviour) can enable them to outnumber natural enemy populations and their ability to control thrips pests (Funderburk *et al*., 2000; Funderburk, 2002) and also because of the few natural enemies that feed on them (Bethke *et al*., 2014). This has caused several authors (Davidson and Andrewartha, 1948; Tamò *et al*., 1993; Parrella and Lewis, 1997; Srinivasan, 2009) to take a stand that natural enemies have minimal effect on thrips. The use of natural enemies for thrips management is discussed under section 2.4.3.

2.10.5 Chemical control

Chemical control is often considered as the major line of defence by farmers where pesticides are used as "silver bullets" when insect pests are noticed in the field (Lewis *et al*., 1997). For sure, progress has been made using insecticides in controlling thrips pests (Cermeli *et al*., 2002; Seal, 2005; Singh *et al*., 2013). Seal *et al*. (2013) evaluated several insecticides for their effectiveness in controlling *T. palmi* from 1994-2006 on eggplants and snap beans. Different chemical classes were included in the experiment amid others: pyrethroids, neonicotinoids, fermentation products, glycoside, benzoylphenyl-urea, organophosphates, and carbamates. Spinosad showed 80-95% efficacy on *T. palmi* with the other classes showing varying levels of efficacies. Thrips species on bean, chilli, cucumber, leek, onion, peas and potato have mainly been suppressed by formetanate, methiocarb and profenofos in Mauritius (Abeeluck *et al*., 2009). The synthetic insecticides, Cydim super EC® (Dimethoate 400g/l + Cypermethrin 36g/l), Viper 46 EC® (Acetamiprid 16g/l + Indoxacarb 30g/l) and Protocol® (Lambda cyhalothrin 15g/L + Acetamiprid 20g/L), the botanical neem seed kernel extract (Azadirachtin), the microbial Ecopel ® (*Bacillus thuringiensis* var. *kurstaki*) and the physically acting insecticide Eradicoat T GH® (Maltodextrin 282g/L) offered effective control of thrips than the control (unsprayed) plot on eggplant grown for export in Ghana (GhanaVeg Sector Reports, 2017).

In recent times, the use of synthetic pesticides has received much attention due to their harmful effects on consumers, non-target organisms, the environment, and public health (Amoah *et al*., 2006; Bempah *et al*., 2011; Abass *et al*., 2016; Renukadevi *et al*., 2018; Mohammed *et al*., 2019). Even consignments of several horticultural products from some developing countries have been rejected by international markets because of concerns regarding alarming pesticide residue levels (Bempah *et al*., 2011). Despite the rampant use of these pesticides, control of thrips is still not fully achieved (Hata *et al*., 1991; Monteiro *et al*., 1995). Among the reasons are that they lay their eggs in leaf tissue which act as a physical barrier to pesticide penetration, the larvae are normally hidden within leaf tissues or flower petal making them unavailable during spray and pupae stages spend about 40% of the lifecycle in the soil allowing them to escape pesticide sprays. Moreover, some species are very tolerant to most frequently used synthetic insecticides (Zhang and Young, 1998) and some field populations have developed resistance to these insecticides (Seal *et al*., 2013).

From the perspective of safe use of pesticides, Integrated Pest Management (IPM) specialists and environmentalists are currently calling for a look into pesticides that are friendlier and can maintain a balance with the ecosystem as well as their rotations (Subba and Ghosh, 2016; Renukadevi *et al*., 2018), for producing healthy and good quality crops. The effect of Dimethoate 30EC and Kartodim 315EC and their combinations with garlic extract in managing thrips in watermelon fields in Rivers State, Nigeria was evaluated by Burubai *et al*. (2011). He concluded that Dimethoate 30EC plus garlic solution and Kartodim 315EC plus garlic solution with per cent infestation averaging 4.0 and 5.8, respectively, were most effective in reducing thrips infestation and increasing watermelon yield than single doses of the individual organophosphates.

Renukadevi *et al*. (2018) evaluated different botanical extracts (Neem oil 1%, neem seed kernel extract, NSKE 5%, *Andrographis paniculata* leaf extract 10%, *Mirabilis jalapa* root extract 10% and leaf extracts of *Lantana camara* 10% and *Vitex negundo* 10%) on two life stages of *T. palmi*. Both NSKE and neem oil recorded more than 40 per cent mortality after 48 hours of treatment against the second instar and adults of *T. palmi* and all botanicals were significantly more toxic to second instar larvae than adults. A combination of neem and Spilanthes extracts gave more than 70% control and higher yields (27.55 t/ha) compared to other treatments against *T. tabaci* in tomato (Subba and Ghosh, 2016). Some of the most commonly and widely used plant products for *T. palmi* control include neem, pyrethrin, rotenone, lemon oil (limonene, linalool), ryania, sabadilla and nicotine (Renukadevi *et al*., 2018), but the higher cost of production coupled with frequent application, especially for large farm sizes, sometimes make botanicals more expensive to use.

2.10.6 Integrated Pest Management (IPM)

Thrips are generally not easy to control and if management is essential, the use of an integrated programme that combines good agricultural practices, natural enemies' conservation, and less-toxic insecticides that are effective is recommended (Bethke *et al*., 2014; GhanaVeg Sector Reports, 2017). The development of an effective and sustainable management system for thrips requires evaluating and combining several compatible methods from the standpoint of IPM, where pesticide use must be the last resort and should be kept at a minimum. The above-described methods including monitoring, cultural, biological, and chemical control are recommended in IPM. An experiment conducted by Sunitha and Narasamma (2018) illustrated solar light traps containing insecticide molecules (Spinosad 45SC at 0.1ml/l and Emamectin benzoate 5% SG at 0.25g/l) were significantly superior in reducing thrips population, producing highest yield, net returns and higher cost-benefit ratio over the treatments with insecticides alone in Capsicum. Seal (2004) used an integrated method combining cultural, chemical, and biological agents to manage *T. palmi*. He concluded that Spintor® 2SC (spinosad) (4 or 8 oz/acre) mixed with spreader-sticker (Cohere®, nonionic blend) and organosilicone surfactants as well as Novaluron (an insect growth regulator) provided significant control of *T. palmi* larvae on cucumber planted on white plastic mulch raised beds, with a 5-feet non-planted buffer area separating each replicate. The minute pirate bug populations were higher in cucumber, eggplant, and squash than other vegetable crops.

CHAPTER THREE

3.0 DIVERSITY AND ABUNDANCE OF THRIPS ON SELECTED EXPORT VEGETABLES IN SOUTHERN GHANA

3.1 Introduction

Several vegetables comprising eggplant, gourds, chillies, guar beans, okra, tinda, yard-long beans, and marrows are grown in Ghana for export to serve as a source of foreign exchange for the country (Gyau and Spiller, 2007; GEPC, 2010), and employment for actors in the vegetable export value chain. Despite the benefits, these vegetables are hosts to several species of insects including thrips. Thrips are tiny fringe-winged insects of the order Thysanoptera, with over 6,161 described species from two suborders and nine families [Tubulifera (Phlaeothripidae) and Terabrantia (Uzelothripidae (2 species), Fauriellidae (5 species), Merothripidae (20 species), Heterothripidae (93 species), Stenurothripidae (=Adiheterothripidae) (24 species), Melanthripidae (79 species), Aeolothripidae (222 species) and Thripidae (2,201 species)] (Mound *et al*., 1980; Buckman *et al*., 2013; Iftikhar *et al*., 2016b; ThripsWiki, 2019).

These insects are either harmful or beneficial as biological control agents or pollinators. Non-beneficial thrips are mostly pests that damage vegetables, including those cultivated for export, resulting in lower yields (through direct feeding and oviposition or virus transmission) (Boonham *et al*., 2002; Iftikhar *et al*., 2016b) or preventing these vegetables from meeting the export requirements of international trade due to their presence in the exported commodities as quarantine pests (GhanaVeg Sector Reports, 2016, 2017). For instance, the continual interception of thrips, amongst other harmful organisms (quarantine pests), in exported commodities led to a ban on some Ghanaian export vegetables (aubergine, garden eggs, pepper and gourds) in October 2015 (GhanaVeg Sector Reports, 2017; Fening and Billah, 2019).

Interestingly, although the melon thrips, *T. palmi*, has been intercepted frequently on some exported vegetables from Ghana to the EU (see Table 2.4), yet it is not known to occur in Ghana (EPPO, 2019; CABI 2019; Fening *et al*., 2022). Rather, a closely related species, the tobacco thrips, *T. parvispinus* has recently been reported for the first time in Ghana on ridged gourd using DNA barcoding (Fening *et al*., 2022).

The fundamental step in any diversity or pest management study is proper identification of the species. However, thrips identification has long been a challenge due to their small sizes and inconspicuous differentiating features which are only visible under a microscope (Timm *et al*., 2008; Iftikhar *et al*., 2016a). This makes the study of this group of insects technically difficult for researchers and have contributed to increasing misidentification issues on Thysanoptera (Timm *et al*., 2008). Identification of thrips have previously depended solely on examination of morphological characters under high magnification (Palmer, 1990; Schauff, 2001; Rachana *et al*., 2022), but is now being complemented by molecular analysis (Mehle and Trdan, 2012) (if possible) to improve the accuracy of thrips identification schemes.

The need to clarify the status of thrips species on Ghanaian export vegetables has prompted this diversity studies to inform management decisions, as thrips vary in insecticide susceptibility and natural enemy interactions. This research not only contributes to updating Ghana's pest-risk database and pests list but also helps guard against the unintended introduction of invasive species and identifies the thrips species which may be of quarantine importance.

3.2 Materials and methods

3.2.1 Study area and geographical location

The study was conducted in parts of Southern Ghana, which encompasses the country's Central, Eastern, and Greater Accra regions (Plate 3.1). This location falls under the Coastal Savannah and Deciduous Forest agroecological zones of Ghana and was chosen as it is the epicentre of vegetables grown for export. Southern Ghana has two rainy seasons: the main rainy season, which runs from April to July, and the minor rainy season, which runs from September to November, making it ideal for growing a variety of exotic and local vegetables, although, exported vegetables are normally supplemented with irrigation. From September 2019 to January 2021, a survey was conducted in selected vegetable export farms (companies) shown in Table 3.1.

Table 3.1. Vegetable export companies visited during the study.

Region	Location	Export farm
Central Region	Pamfokrom	PARAM FARMS
	Gomoa Nsuaem	SRIGHAN FARMS LTD (OUT GROWER)
	Buduatta	JORO FARMS
	Swedru	SRIGHAN FARMS LTD
Greater Accra	Tuba	AT MAHLI VENTURES, PARAM FARMS
	Ada	KABSCODA CO. LTD
	Toje	MOONLIGHT FRESCO LTD
	UG school farm	OUT-GROWER (PARAM FARMS)
	Atomic Farming area	DHILLON FARMS (OUT-GROWER)

Eastern Region	Dago	AB FARMS
	Kyekyewere	JOEKOPAN ENTERPRISE
	Adeiso	TROSKY FARMS
	Suhum	AB FARMS (OUT-GROWER)

3.2.2 Sampling design for collection of thrips

The sampling design was modified from Oparaocha and Okigbo (2003) and Ebratt-Ravelo *et al*. (2019). Four vegetable export growing localities [based on an exporter list provided by the Plant Protection and Regulatory Services Directorate (PPRSD)] were selected from each region; Greater Accra region, Central and Eastern regions (Plate 3.1) and the presence or absence of thrips on the crops was noted. Thrips samples were then collected from export vegetables (eggplant, bitter gourd, turia, guar beans, marrow, and chilli) with average farm sizes of 2 acres (Plate 3.2). In each crop field, 40 plants were selected randomly in an X-pattern and thrips were sampled from five leaves, five flowers and five fruits to form a sampling unit (Ebratt-Ravelo *et al*., 2019). The sampled parts were collected into zip lock bags and each sample was given a unique identification code that included information such as the location, crop type/stage/varieties, date, and geographical points of each crop. The geographical points and altitude were taken using My Altitude and Elevation-GPS app., version 5.03 (216) with an Android mobile phone. These samples were taken to the laboratory, placed on ice for 1 minute to inactivate them and an alcohol-moistened brush with a white plastic plate was used to collect thrips adults and immatures into 1.5 ml eppendorf tubes, filled with 70% alcohol. They were then separated into morphospecies, counted, and preserved in 80% alcohol pending identification.

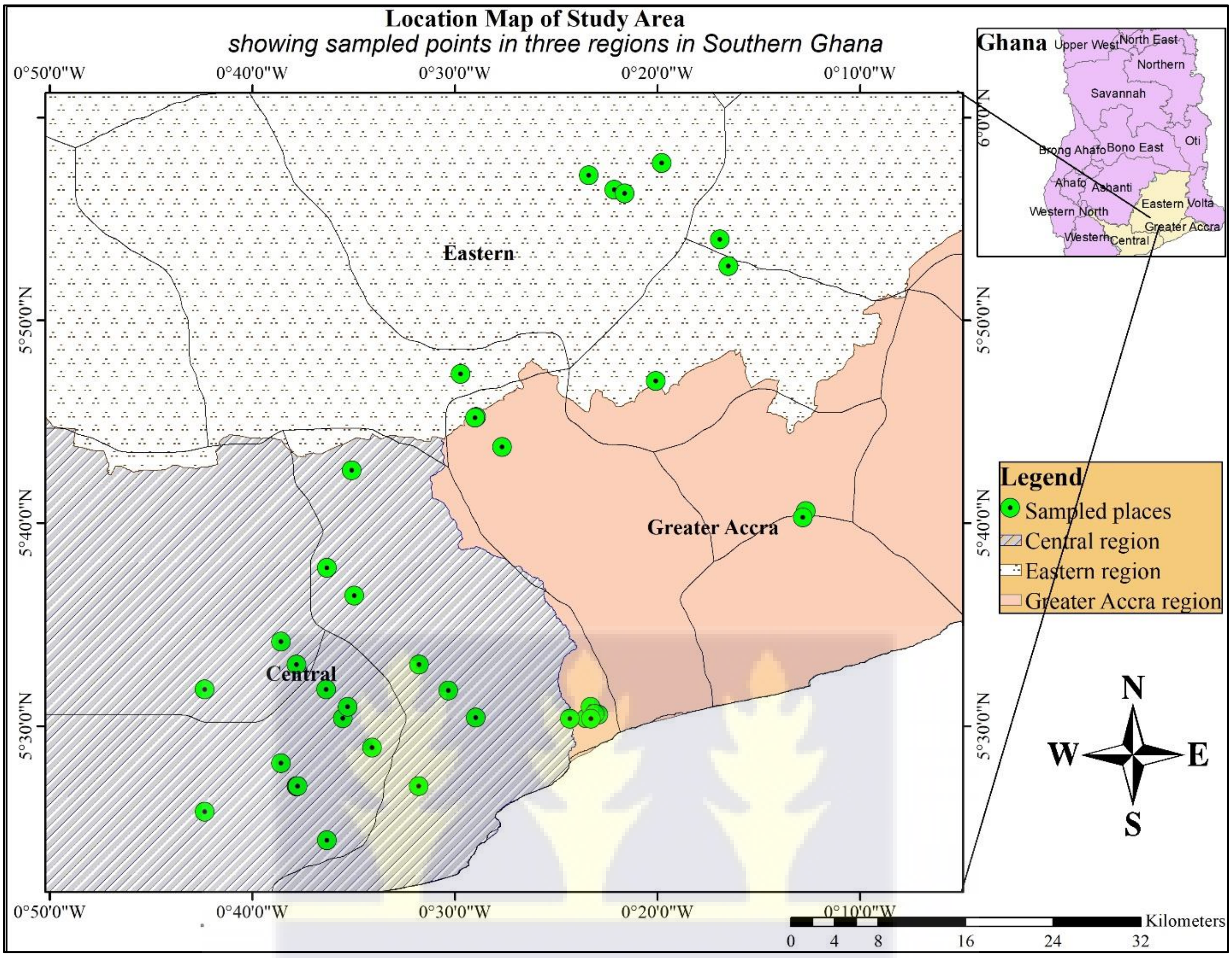


Plate 3.1. Map showing the study area with sampled points.

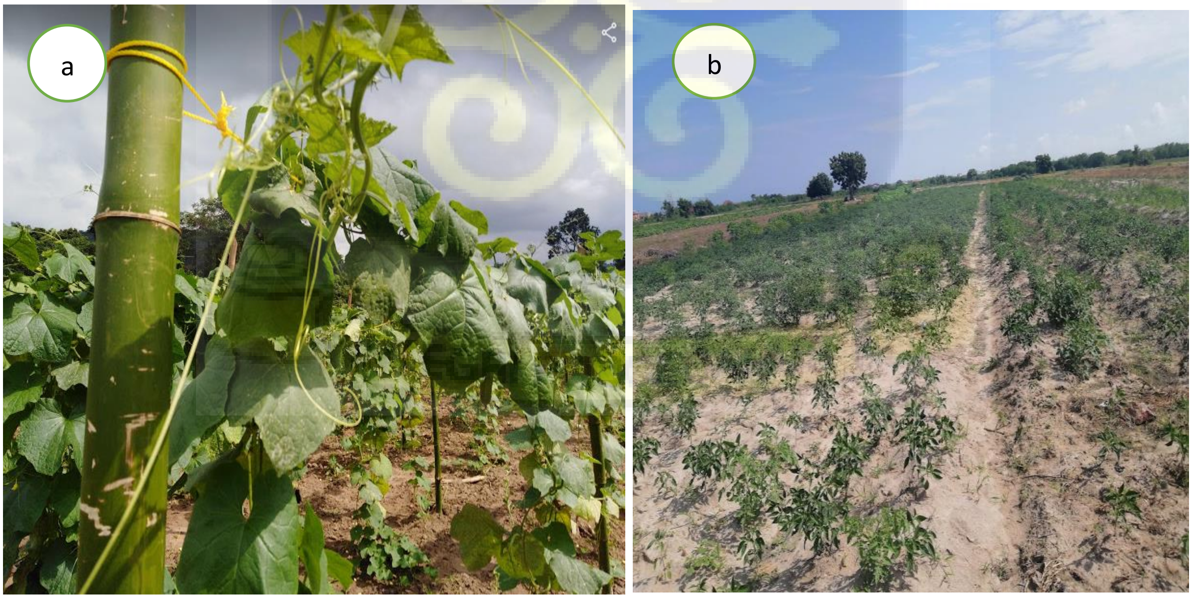


Plate 3.2. Some collection sites. (a) turia and (b) chillies at Param Farms, Pamfokrom.

3.2.3 Identification of specimens

3.2.3.1 Morphological identification

Preparation of samples for morphological identification followed methods by Palmer (1990), Muvea *et al*. (2014) and Yong (2015), involving maceration, dehydration and mounting of the specimens.

3.2.3.1.1 Maceration

The samples from field storage tubes were placed in watch glasses and the collecting fluid was replaced with 10% potassium hydroxide (KOH). A micro-pin was used to gently hole the insect abdomen behind the hind coxae to allow fast entry of the KOH (Palmer, 1990). The specimens were transferred to a test tube and heated (Plate 3.3) for 30-45 minutes to easily soften the insects and expel the body contents, allowing them to become transparent. Darker specimens took longer (1 hour) to clear. Potassium hydroxide was washed off by passing the specimens through 50% and 70% alcohol concentrations. Specimens were placed for 10 minutes in each concentration after which acetic acid was introduced and left to stand for 10-15 minutes before being rinsed off with 50% and 60% alcohol, respectively. Xylene was then introduced and left for 15 minutes to clear the fatty contents of the insects. This was washed off with alcohol concentrations of 50% and 60% for 10 minutes each. The specimens were stained with acid fuchsin for 10 minutes and later washed with 50% and 60% alcohol concentrations.

3.2.3.1.2 Dehydration

The samples were then subjected to a variety of alcohol concentrations, starting at 50% and increasing to 70%, 85%, 90%, and 95%, to gradually dehydrate them. To avoid any contact with moisture during the final mounting, specimens were immersed in each of the above concentrations for 10 minutes. 95% alcohol was then replaced with clove oil after 30 minutes, and the specimens were ready for mounting.

Plate 3.3. (a) Equipment and reagents used in the preparation of slides and (b) heated specimens in a test tube.

3.2.3.1.3 Mounting of slides

A small mounting block was prepared using a carton sized to fit the dimension of the slides. A clean microscopic slide was positioned on the mounting block and a drop of Canada balsam was placed onto the centre. A specimen was then placed into this position, with its dorsum facing upwards. The antennae were straightened, and the wings and legs were spread out using a minutien pin to prevent them from covering the body (Davis, personal communication). A clean cover slide was lowered and inverted gently onto the specimen. The mounted slides were spaced out in insect preserving boxes for two weeks until the specimens were held firmly, and the liquid completely dried out.

3.2.3.1.4 Taxonomic identification of specimens

Taxonomic identification was done using keys by several authors (Palmer, 1990; Moritz, 1994; De Borbón and Agostini, 2011; Yaseen, 2014; Tyagi *et al*., 2015; Rachana *et al*., 2022; Thrips-ID, 2022). These keys use morphometric characters of the thrips to identify them to the species level. Specimens were confirmed by LuCID keys; pest thrips of the world (Moritz *et al*., 2004a), thrips of California (Hoddle *et al*., 2012) and pest thrips of East Africa (Moritz *et al*., 2013). Identified specimens were further confirmed by Mr Davis, a retired taxonomist at the University of Ghana, Department of Animal Biology and Conservation Science. For purposes of referencing, slides were positioned such that the head of the specimen faced the determiner, and a label was affixed on the right-hand side bearing information on the host plant, locality, country, date, and collector's name (Coll), whilst the left side contained the specimen's name, author's name, and determiner's name (Det). Characters were examined and illustrations were taken with a Leica DM 500 microscope with DIC illumination using LAS EZ software (Plate 3.4). Representative morphotypes were put in absolute alcohol and stored at 4 ºC to confirm the identity of the species using molecular techniques (DNA barcoding).

Plate 3.4. Morphological identification with Leica compound microscope.

3.2.3.2 Molecular identification of thrips species

Identification of thrips was carried out using the Thermo Scientific Phire Plant protocol following the manufacturer's instructions. About 5mg of thrips were placed into a microcentrifuge tube containing DNA extraction buffer. The thrips in the tube were ground with a micropestle to homogenise the mixture and the homogenate was spinned for 30 seconds at maximum speed (8,000 rpm/1,180 xg). 0.5µL of the supernatant was used for the Polymerase Chain Reaction (PCR) reaction. PCR was carried out to amplify the Cytochrome Oxidase subunit one (CO1) gene in a total reaction mixture of 20 µL consisting of 0.5 µL DNA template, 10 µL Biomix, 8.5 µL of water and 0.5 µL each of 100 µM forward (LC01490: 5'-GGTCAACAAATCATAAAGATATTGG-3') and reverse primers (HCO2198: 5'-TAAACTTCAGGGTGACCAAAAAATCA-3') with the following cycling conditions: initial denaturation (95°C for 3 minutes), denaturation (30 cycles at 94°C for 30 seconds), annealing (55°C for 30 seconds), extension (72°C for 1 minute) and a final extension (72°C for 10 minutes) on a thermal cycler. The DNA amplicons were visualised on a 1% (w/v) agarose gel stained with Ethidium bromide to observe bands under UV illumination on an Alphalmager® gel documentation system. The PCR products were sequenced by INQABA Biotech (Pretoria, South Africa). The raw sequences were assembled and edited manually using the SnapeGene app version 5.3.2. Consensus forward and reverse sequences were queried with nucleotide BLAST search in National Center of Biotechnology Information (NCBI) GeneBank Database. Additionally, sequences for previousely identified respective thrips species were generated from the GenBank and Pairwise comparisons for similarity were done by aligning the sequences using MUSCLE in Species Demarcation Tool v 1.2 (SDT v. 1.2) (Muhire *et al.*, 2014).

3.2.4 Analysis of Data

The thrips specimens identified were sorted according to the region of collection and the type of crop from which they were sampled. To quantify the biodiversity and assess the distribution patterns across different regions and crops, several ecological indices were calculated: The Shannon-Wiener Diversity Index (H′), which measures the diversity within a community, considering both the number of species (richness) and the evenness of their distribution. Simpson's Dominance (D), reflecting the degree to which a few species dominate the overall population. Chao 1 Species Richness, an estimator that predicts the total number of species present based on the observed data and the distribution of rare species. These calculations were conducted using the Past 3 software (version 3.21), a comprehensive statistical package tailored for ecological data analysis, as cited by Ebratt-Ravelo *et al*. (2019). This enabled a detailed examination of the diversity and abundance of thrips populations per region and per crop. To statistically compare the abundance and diversity of thrips across different crops within each region, the Student's t-test was applied. This statistical method helps in identifying significant differences between two groups, providing insights into the variability of thrips populations among the studied crops and regions.

Additionally, the geographical distribution of the sampled locations was visualized using ArcGIS software (version 10.7.1). This mapping tool facilitated the spatial representation of data, allowing for a visual assessment of thrips distribution patterns across Southern Ghana. The combination of these analytical and visual tools provided a comprehensive overview of thrips biodiversity and abundance, contributing valuable insights for agricultural management and pest control strategies.

3.3 Results

3.3.1 Export vegetables sampled for thrips species from the Eastern, Central and Greater Accra regions of Ghana

The sampled vegetables grown for export were found to host different thrips species on the leaves, flowers, and fruits (Table 3.2). However, the thrips population on Guar beans was generally low and Guar beans was equally not cultivated in all the regions. In general, more thrips (46.05%) were collected from *Luffa acutangula* than the rest of the plants sampled (Table 3.3). Similarly, *L. acutangula* recorded more thrips within each region than any of the sampled host plants. The distribution of abundance was not equal in each crop since most species were abundant with moderate dominance and some species were represented as “singletons” in some regions (Table 3.4).

Five thrips species were identified on chilli, out of which, all the five were found on eggplant, four each were found on turia, marrow and guar beans and two were found on bitter gourd. On eggplant, eight thrips species were identified of which four were found on marrow, turia and guar beans, five on chilli and two on bitter gourd. On turia, all the four identified species were found on the other export vegetables, except for bitter gourd which had only two species. The two thrips species identified on turia were equally found on all the other vegetables.

Table 3.2. Export vegetables sampled during the study with their associated thrips status.

Common name of crop	**Scientific name of crop**	**Thrips status**
Chilli	*Capsicum frutescens*	Present
Eggplant	*Solanum melongena*	Present
Turia (ridged gourd)	*Luffa acutangula*	Present
Marrow	*Lageneria siceraria*	Present
Guar beans	*Cyamopsis tetragonoloba*	Present
Bitter gourd	*Momordica charantia*	Present

3.3.2 Species structure and abundance of thrips

The South-East Asian or tobacco thrips, *Thrips parvispinus* (Karny), the cotton thrips, *Frankliniella schultzei* Trybom, and the onion thrips, *Thrips tabaci* Lindeman, were among the thrips species collected and identified from export vegetables across localities/export companies during this study (Table 3.2). Identified thrips were members of both the Tubulifera and Terabrantia suborders, however only one species was from the family Phlaeothripidae in the suborder Tubulifera. The rest of the identified species were from the Suborder Terabrantia representing the Thripidae and Aeolothripidae families from the genera *Thrips*, *Frankliniella* and *Megalurothrips,* amongst others. 47.30% (n = 815) of all described species was *Thrips parvispinus*, making it the most abundant species identified across the regions. This was directly followed by *F. schultzei* (32.82%, n = 558) and *T. tabaci* (15.22%, n = 268). The predatory thrips, *F. vespiformis* was, however, the least abundant species recorded in the study (0.11%, n = 2) (Table 3.3). Within the regions, the highest number of thrips were identified from the Central region (n = 665) compared to all other regions on the bases of permanent slide mount.

Comparing thrips abundance on various hosts across the regions revealed that chilli recorded more thrips in the Central than Greater Accra and Eastern regions with *T. tabaci* as the most abundant species, however, significant differences were not observed between the regions; Accra-Eastern (*t* = 0.309, P = 0.762), Accra-Central (*t* = 0.308, P = 0.763) and Eastern-Central (*t* = 0.123, P = 0.902) (Table 3.4). *Thrips parvispinus* was the most dominant species on eggplant across all regions, however, the total thrips population was lower in the Greater Accra than the Eastern and Central regions. A t-test showed no significant differences between them; Accra-Eastern (*t* = 0.009, P = 0.993), Accra-Central (*t* = 0.037, P = 0.971) and Eastern-Central (*t* = 0.0275, P = 0.978). Turia had the highest population of thrips in the Central region with *T. parvispinus* as the dominant species (Appendix 1), however, differences in total thrips abundance on turia were not significant across regions ((Accra-Eastern (*t* = 0.068, P = 0.947), Accra-Central (*t* = 0.0678. P = 0.945) and Eastern-Central (*t* = 0.0678, P = 0.948)) (Table 3.5).

Table 3.3. Thrips species identified from export vegetables across localities in the Eastern, Central and Greater Accra regions of Ghana.

Scientific name	**Common name**	**Family**	**Subfamily**	**Genus group**
Thrips parvispinus Karny	Southeast Asian Thrips/Tobacco thrips	Thripidae	Thripinae	*Thrips*
Frankliniella schultzei Trybom	Cotton Thrips	Thripidae	Thripinae	*Frankliniella*
Thrips tabaci Lindeman	Onion thrips	Thripidae	Thripinae	*Thrips*
Megalurothrips sjostedti Trybom	African bean or cowpea flower thrips	Thripidae	Thripinae	*Megalurothrips*
Franklinothrips vespiformis Crawford	Vespiform thrips	Aelothripidae	Aelothripinae	*Franklinothrips*
Gynaikothrips uzeli Zimmermann	Leaf gall or weeping fig thrips	Phlaeothripidae	Phhaeothripinae	*Gynaikothrips*
Frankliniella sp	-	Thripidae	Thripinae	*Frankliniella*
Selenothrips rubrucintus Giard	Redbanded or cocoa thrips	Thripidae	Panchaetothripinae	*Selenothrips*

Table 3.4. Abundance of thrips by region (GAR = Greater Accra Region, ER = Eastern Region, CR = Central Region) and crop type.

Region	**Host plant**	***Thrips parvispinus***	***Frankliniella schultzei***	***Thrips tabaci***	***Megalurothrips sjostedtii***	***Franklinothrips vespiformis***	***Gynaikothrips uzeli***	***Frankliniella* sp**	***Selenothrips rubrucintus***	**Total number per crop**
GAR	*Capsicum frutescens*	20	15	20	2	-	-	4	-	61
	Solanum melongena	70	50	15	2	1	3	5	4	150
	Luffa acutangula	110	71	25	-	-	-	2	-	208
	Lagenaria siceraria	22	20	-	-	-	0	8	-	50
	Cyamopsis tetragonoloba	-	-	-	-	-	-	-	-	0
	Momordica charantia	22	20	-	-	-	-	8	-	50
ER	*Capsicum frutescens*	10	10	25	1	-	-	4	-	50
	Solanum melongena	79	52	15	3	1	3	5	3	161
	Luffa acutangula	120	79	25	-	-	-	2	-	226
	Lagenaria siceraria	15	18	-	-	-	-	6	-	39

Table 3.4 continued. Abundance of thrips by region (GAR = Greater Accra Region, ER = Eastern Region, CR = Central Region), altitudinal range and crop type.

Region	**Host plant**	***Thrips parvispinus***	***Frankliniella schultzei***	***Thrips tabaci***	***Megalurothrips sjostedtii***	***Franklinothrips vespiformis***	***Gynaikothrips uzeli***	***Frankliniella* sp**	***Selenothrips rubrucintus***	**Total number per crop**
	Cyamopsis tetragonoloba	-	-	-	-	-	-	-	-	0
	Momordica charantia	-	-	-	-	-	-	-	-	0
CR	*Capsicum frutescens*	13	20	28	1	-	-	4	-	66
	Solanum melongena	72	55	15	4	-	1	5	2	154
	Luffa acutangula	200	100	75	-	-	-	2	-	377
	Lagenaria siceraria	30	28	10	-	-	-	1	-	67

Table 3.4 continued. Abundance of thrips by region (GAR = Greater Accra Region, ER = Eastern Region, CR = Central Region), altitudinal range and crop type.

Region	**Host plant**	***Thrips parvispinus***	***Frankliniella schultzei***	***Thrips tabaci***	***Megalurothrips sjostedtii***	***Franklinothrips vespiformis***	***Gynaikothrips uzeli***	***Frankliniella* sp**	***Selenothrips rubrucintus***	**Total number per crop**
	Cyamopsis tetragonoloba	2	-	5	-	-	-	-	-	7
	Momordica charantia	30	20	10	-	-	-	1	-	61
Total		815	558	268	13	2	7	57	9	1727

Table 3.5. Comparison of thrips abundance between regions and crops.

Crops/region combination	*Capsicum annuum*		*Solanum melongena*		*Luffa acutangula*	
	t	P	*t*	P	*t*	P
Greater Accra-Eastern	0.30893	0.762	0.009	0.993	0.068	0.947
Greater Accra-Central	0.30893	0.76193	0.037	0.971	0.0678	0.945
Eastern-Central	0.12476	0.90249	0.0275	0.978	0.0678	0.948

T-test at 5% significant level

3.3.3 Diversity of thrips between regions and crop

The Shannon diversity index (H′) calculated for the Greater Accra, Eastern and Central regions indicated that there was generally low diversity on all of them (Table 3.6). However, diversity was highest in the Central (H′ = 1.232), followed by the Greater Accra (H′ = 1.209) and the Eastern region (H′ = 1.171). Comparing thrips diversity between the sampled crops revealed that, diversity was highest in *S. melongena* and *C. frutescens* but was low in *M. charantia* and *L. siceraria* and the least also had a few dominant species (*M. charantia*, H′ = 0.5983, D = 0.4082 and *L. siceraria*, H′ = 0.9812, D = 0.579) (Table 3.7).

The species richness expected by Chao 1 estimator, showed that generally no other species than those found in this study will be obtained if the sampling effort is increased, but there might be an increase of one or two more species on chilli and eggplant, respectively. Similarly, the Eastern region will not record any additional increase in species, whilst the Greater Accra and Central regions may record about 1 or 3 more species, respectively with increasing sampling effort (Tables 3.6 and 3.7).

Table 5. Shannon-Wienner diversity index (H′), Simpson's dominance (D), observed and expected thrips species richness with the Chao I estimator per crop.

Crop	Abundance	Observed richness	Chao 1	H′	D
Capsicum frutescens	176	5	6	1.325	0.701
Solanum melongena	465	8	10	1.308	0.654
Luffa acutangula	811	4	4	1.032	0.605
Lagenaria siceraria	156	4	4	0.981	0.579

Cyamopsis tetragonoloba	111	4	4	1.127	0.633
Momordica charantia	7	2	2	0.598	0.408

Table 3.7. Shannon-Wienner diversity index (H′), Simpson's dominance (D), observed and expected thrips species richness with the Chao I estimator per region.

Region	Abundance	observed richness	Chao 1	H′	D
Greater Accra	519	8	9	1.209	0.638
Eastern	476	7	7	1.171	0.646
Central	732	8	11	1.232	0.652

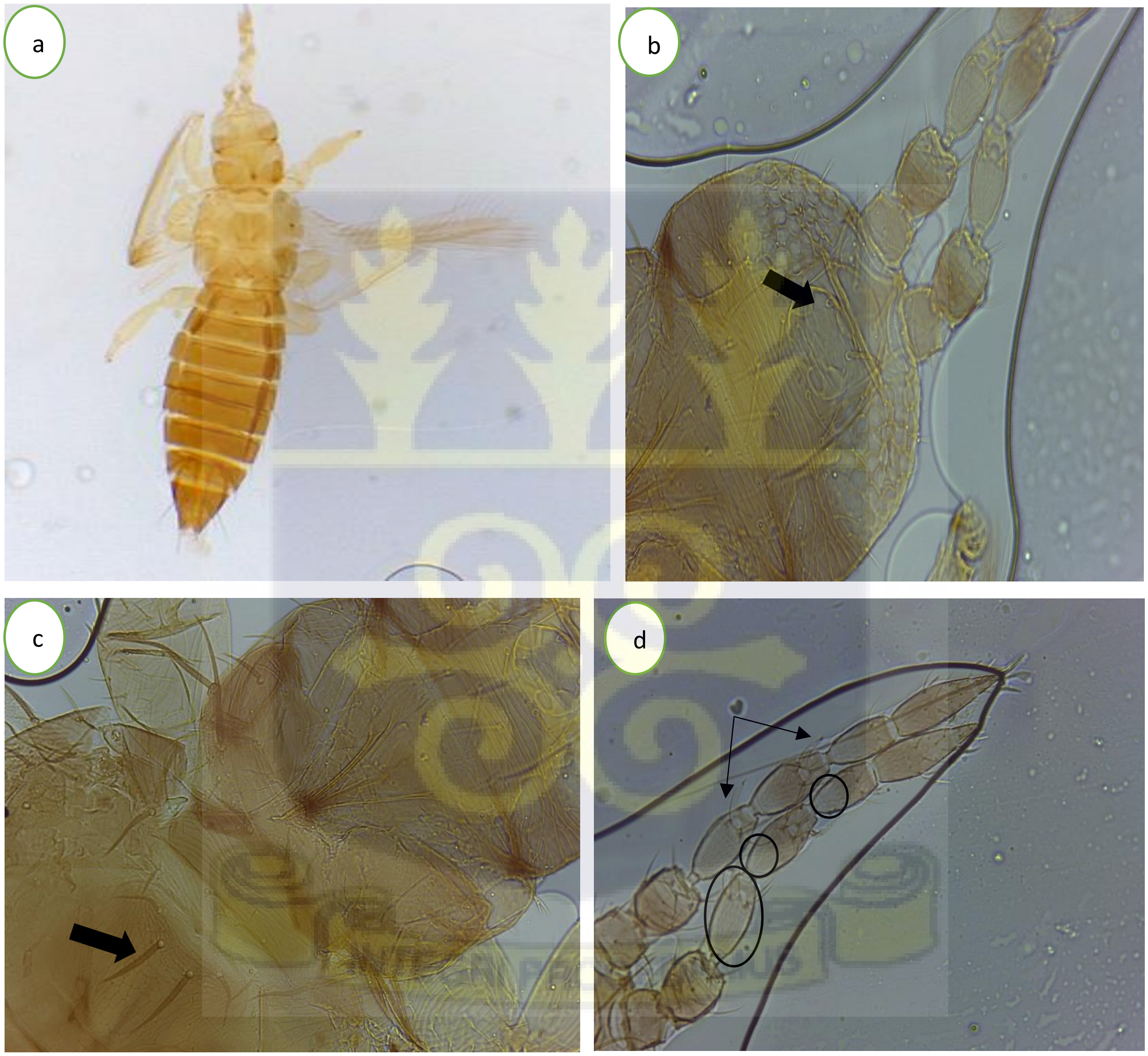
3.3.4 Morphological Identification of thrips

The morphological features used in confirming the identity of some of the thrips' species are presented below.

3.3.4.1 *Thrips parvispinus* Karny

The female *T. pavispinus* has a brown body with the head and thorax paler than the abdomen and the legs yellow (Plate 3.5a). The ocellar setae pair III is located on the anterior margin of the ocellar triangle. The head is wider than long (Plate 3.5b). The postocular setae I and IV are longer than III. The antennae have seven segments, with segments III and IV each having a forked sense cone, segment III and the base of both segments IV and V are all clear (Plate 3.5d). The pronotum has two pairs of posteroangular setae and two pairs of posteromarginal setae. The median setae in the metanotum are long and positioned behind the anterior margin with campaniform sensilla absent (Plate 3.5c). The forewing is brown with a pale or clear base and the first and second vein is continuous (Plate 3.5e).

The male is yellow with dark setae. The posterior margin of tergite VIII without a comb with a few laterally present microtrichia (Plate 3.5g) which differentiates it from *T. palmi*.



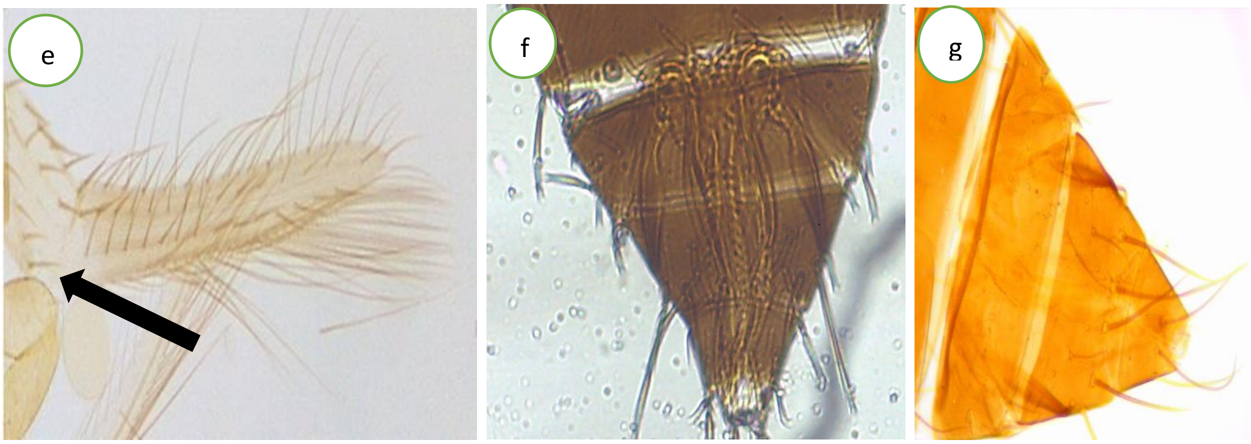
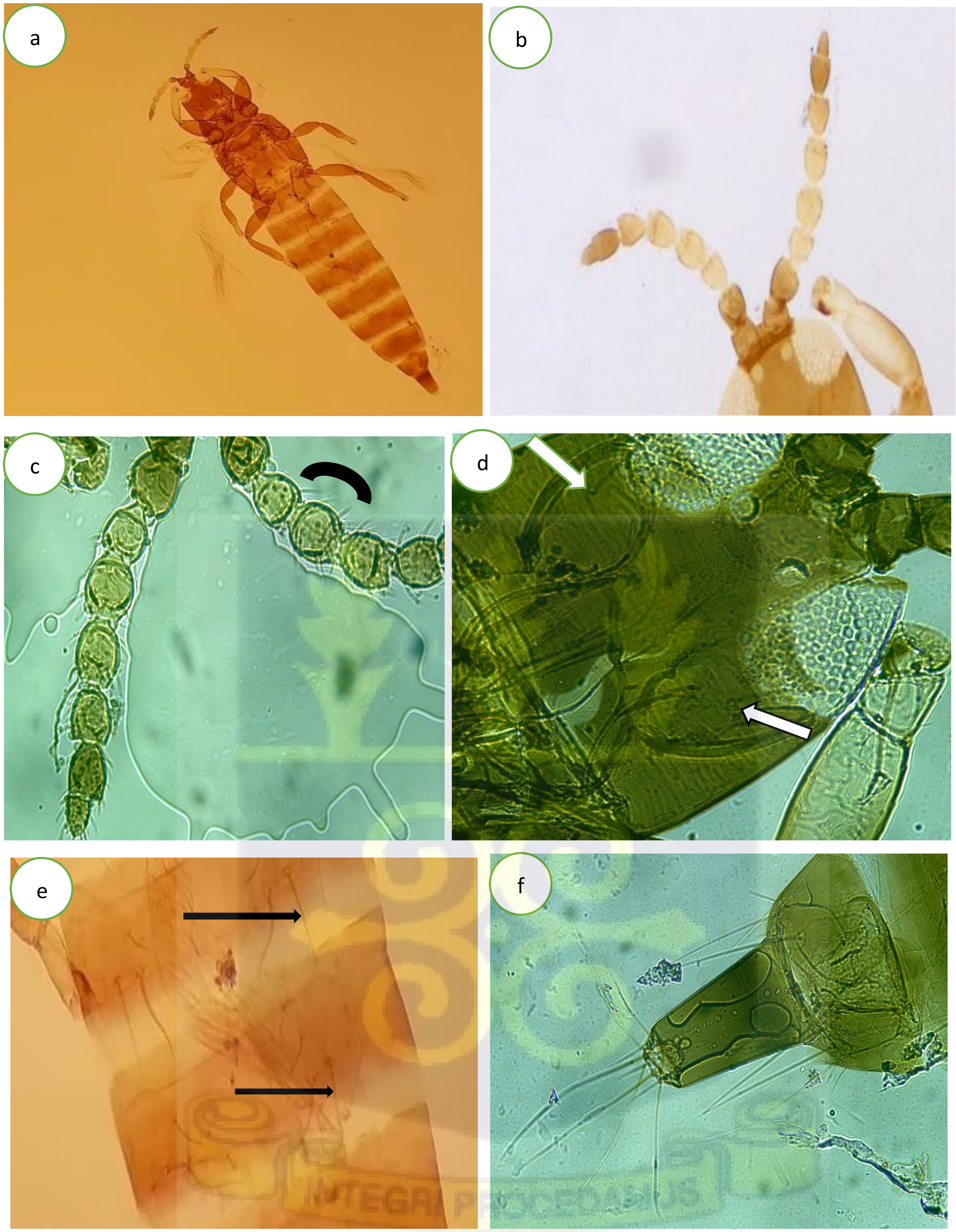


Plate 6. *Thrips parvispinus* (a) Female, (b) antenna, (c) Meso and metanotum, (d) antenna, (e) wing, (f) abdominal tergite VIII female, (g) abdominal tergite VIII male.

3.3.4.2 *Gynaikothrips uzeli* Zimmermann

The body of *G. uzeli* is brown with apices of tibiae yellow (Plate 3.6a). The antennae are 8-segmented, segment III has one sensorium, segment IV has three sensoria (Plate 3.6b and c), segments III–VI are mostly yellow, and segment VIII is brown (Plate 3.6b). The head is longer than wide, somewhat constricted behind the eyes. the postocular setae are long, with the tip weakly capitate behind the eyes (Plate 3.6d, white arrow). The maxillary stylets are retracted almost to the postocular setae, roughly one-third of the way across the head (Plate 3.6d). The pronotum has varied main setae. Tergites with a main pair of pale marginal setae and tergites II–VII with two pairs of sigmoid wing-retaining setae (Plate 3.6e). The last abdominal segment tubular (Plate 3.6f).


a
b
c
d
e
f

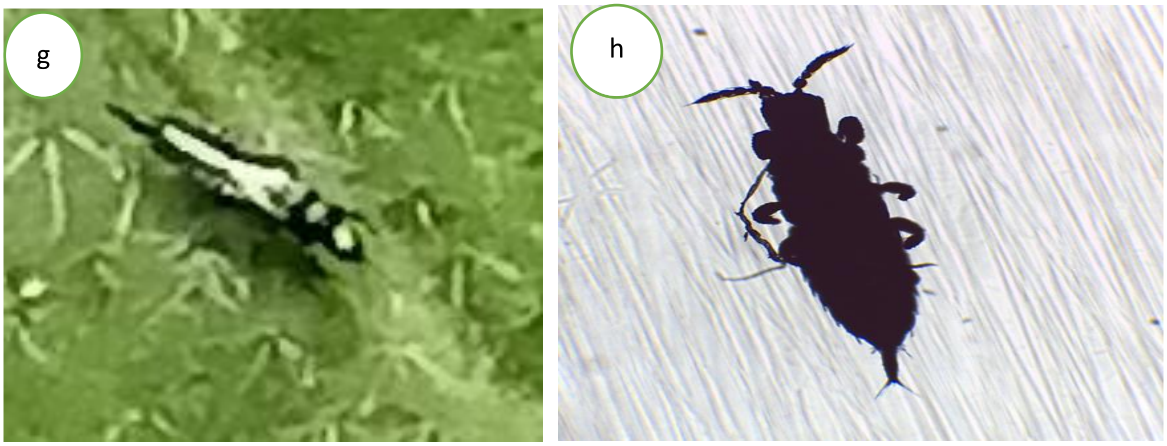


Plate 7. ***Gynaikothrips uzeli*** (a) Female, (b and c) antenna, (d) head, (e) major setae on abdominal segments, (f) tube-like last abdominal segment, (g and h) adult on eggplant leaf.

3.3.4.3 *Frankliniella schultzei* Trybom

The body of *F. schultzei* is variably brown or yellow and both forms were identified in this study (Plate 3.7a and b). The head is wider than long, with three pairs of ocellar setae. The ocellar pair III arises at a level essentially between anterior margin of the posterior ocelli, and setae bases are close together (Plate 3.7c). The postocular setae are slightly shorter than interocellar setae on the head of adult female *F. schultzei* (Plate 3.7d). *Frankliniella schultzei* has eight pairs of antenna segments, with segments III–IV having forked sensorium, and segment VIII longer than segment VII (Plate 3.7h). The metanotum has 2 pairs of setae at the anterior margin with campaniform sensilla absent (Plate 3.7e). The fore wing has 2 complete rows of veinal setae (Plate 3.7d). The abdominal comb is weakly developed on the 8th abdominal segment (Plate 3.7f).

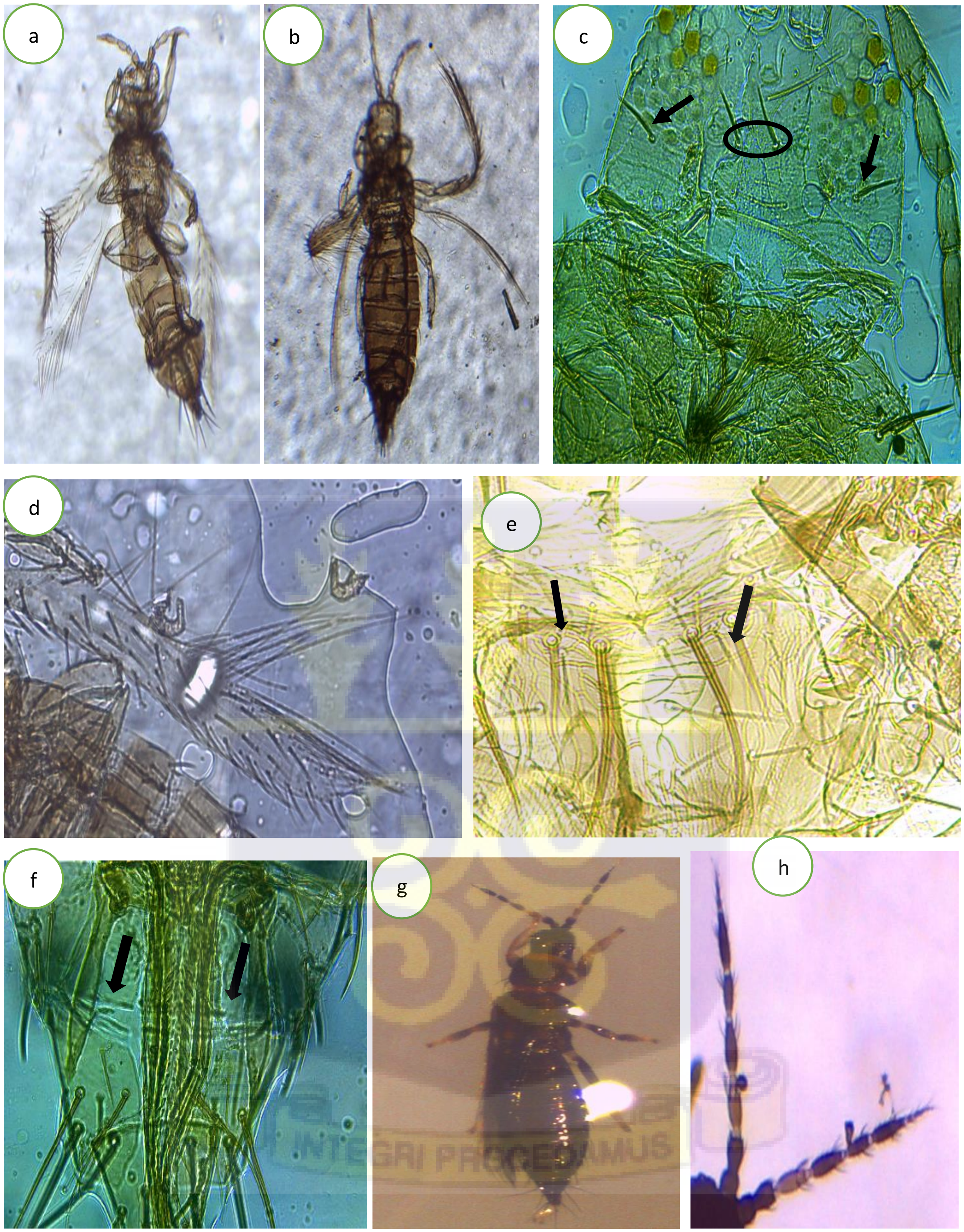
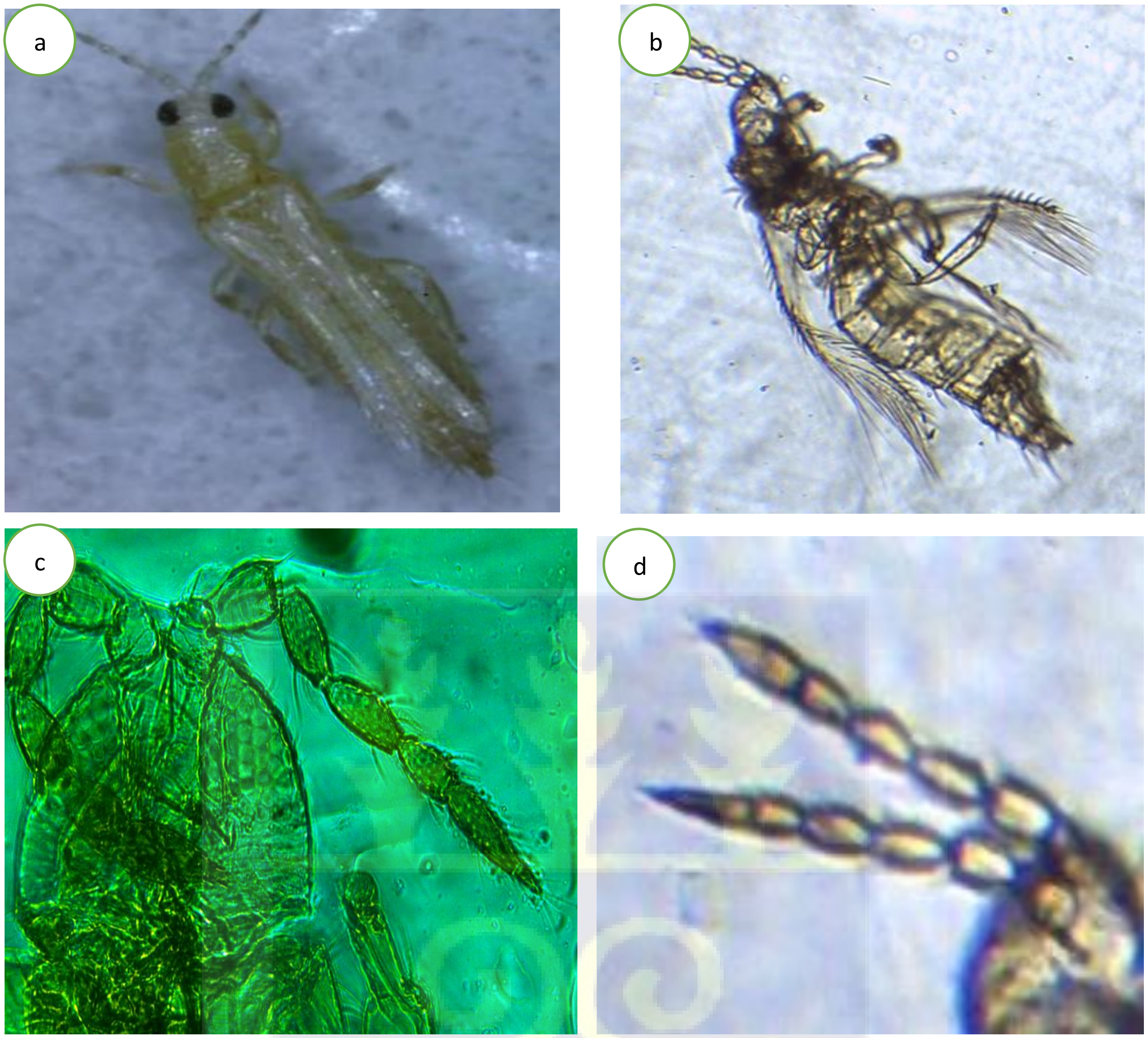

a
b
c
d
e
f
g
h

Plate 8. ***Frankliniella schultzei*** (a and b) Adult female, (c) head with postocular setae location, (d) wing, (e) metanotum, (f) abdominal tergite VIII female (g and f) unmounted dark-brown adult and 8-segmented antennae of *F. schultzei*.

3.3.4.4 *Thrips tabaci* Lindeman

The adult male and female of *T. tabaci* are fully winged with body colour and size variable from small and whitish yellow to large and brown depending on temperature during development (Plate 3.8a and b). The head is wider than long with a grey pigment on the ocelli. *Thrips tabaci* has seven-segmented antennae with segments III–IV each with forked sensorium (Plate 3.8c and d). The metanotum is variable, with medial irregular reticulation interspersed with lines which converge to midpoint at the posterior margin. The median setae on the metanotum arise behind the anterior margin without any campaniform sensilla present (Plate 3.8e). The abdominal tergite II with 3 lateral marginal setae, V–VIII with paired ctenidia, on VIII, the ctenidia is placed posterior to the spiracles (Plate 3.8f and g). The posteromarginal comb on abdominal tergite VIII is complete (Plate 3.8h).


a
b
c
d

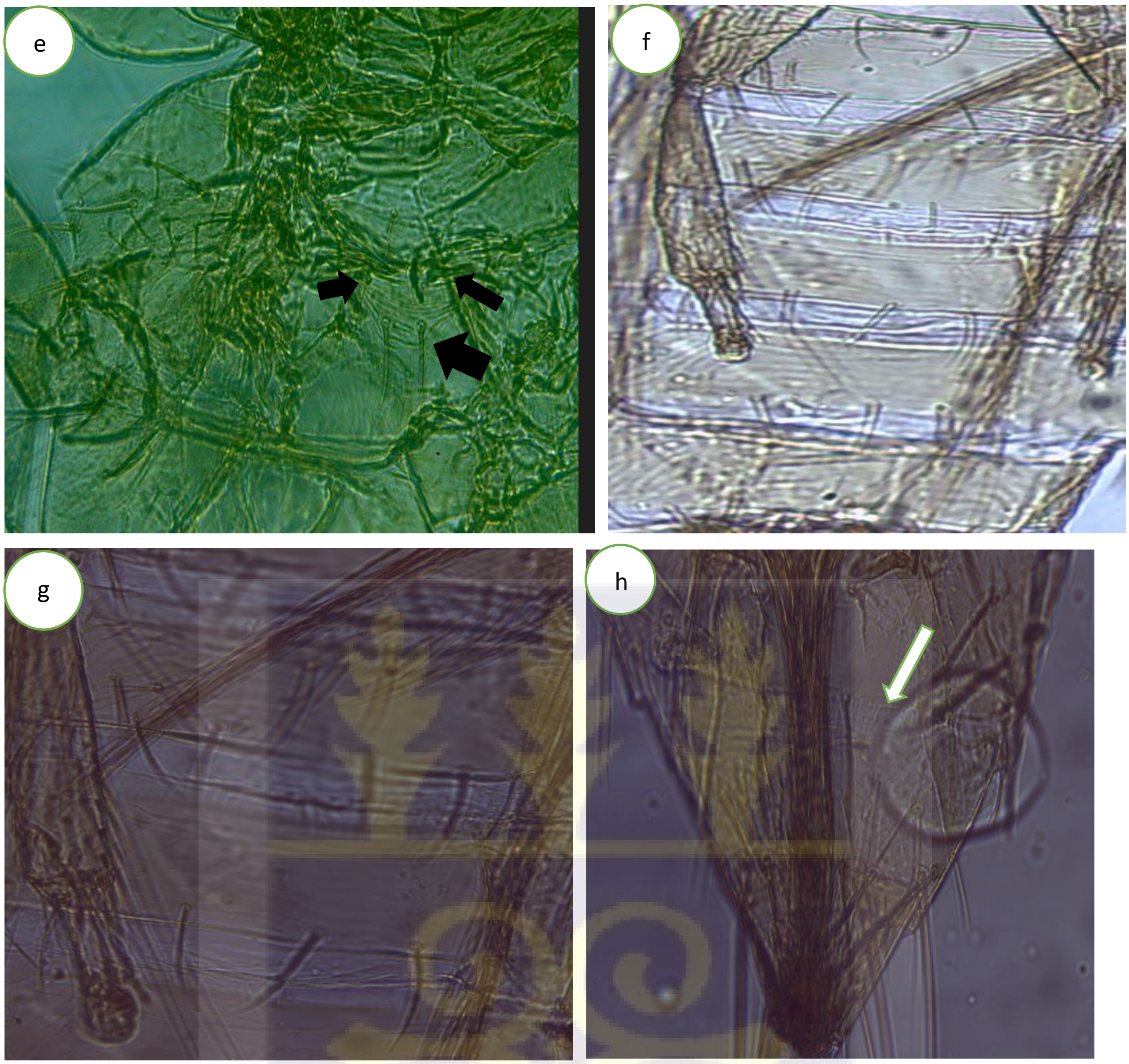


Plate 9. ***Thrips tabaci*** (a and b) Adult female, (c) head, (d) antenna, (e) Metanotum, (f) metanotum, (e) abdominal segments, and (f) abdominal tergite VIII female.

3.3.4.5 *Franklinothrips vespiformis* Crawford

The adult female has a wasp-like waist with the body, the legs, and the antennae mostly brown, but the abdominal segments II–III are sharply yellow or clear except for the anterior margins, whilst segment X is yellowish (Plate 3.9a and d). The antennae are 9-segmented and amazingly elongate, with segment III being the longest segment, with a constricted base. Antennal segments

I–III are yellow, and all the femora area yellowish at apices (Plate 3.9b). The head is sunk into the front border of the pronotum. The forewing is slender and rounded at apex, banded and brown, with a small sub-basal pale area, a broad median pale area, and a dim sub-apical pale spot (Plate 3.9c).

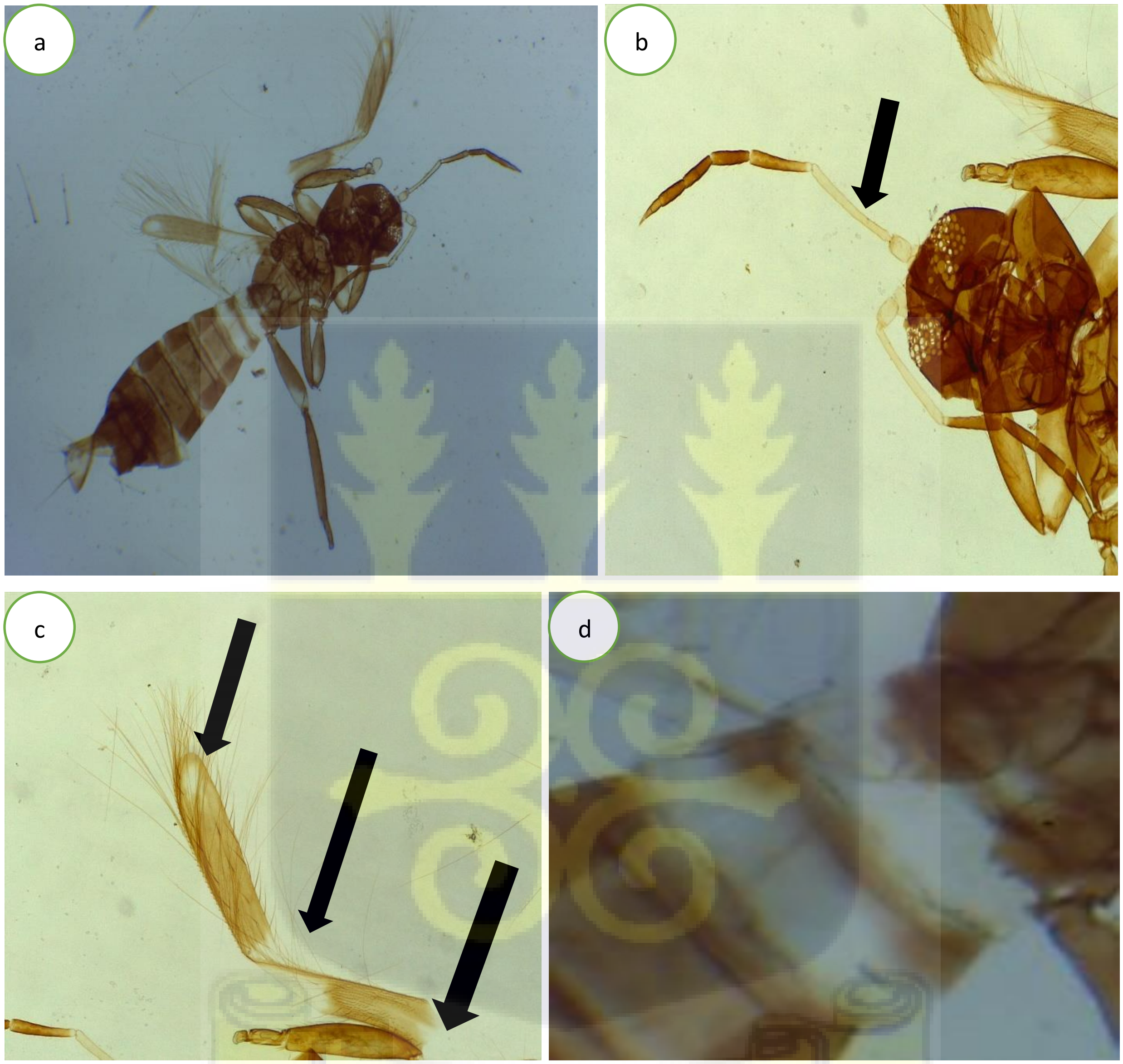
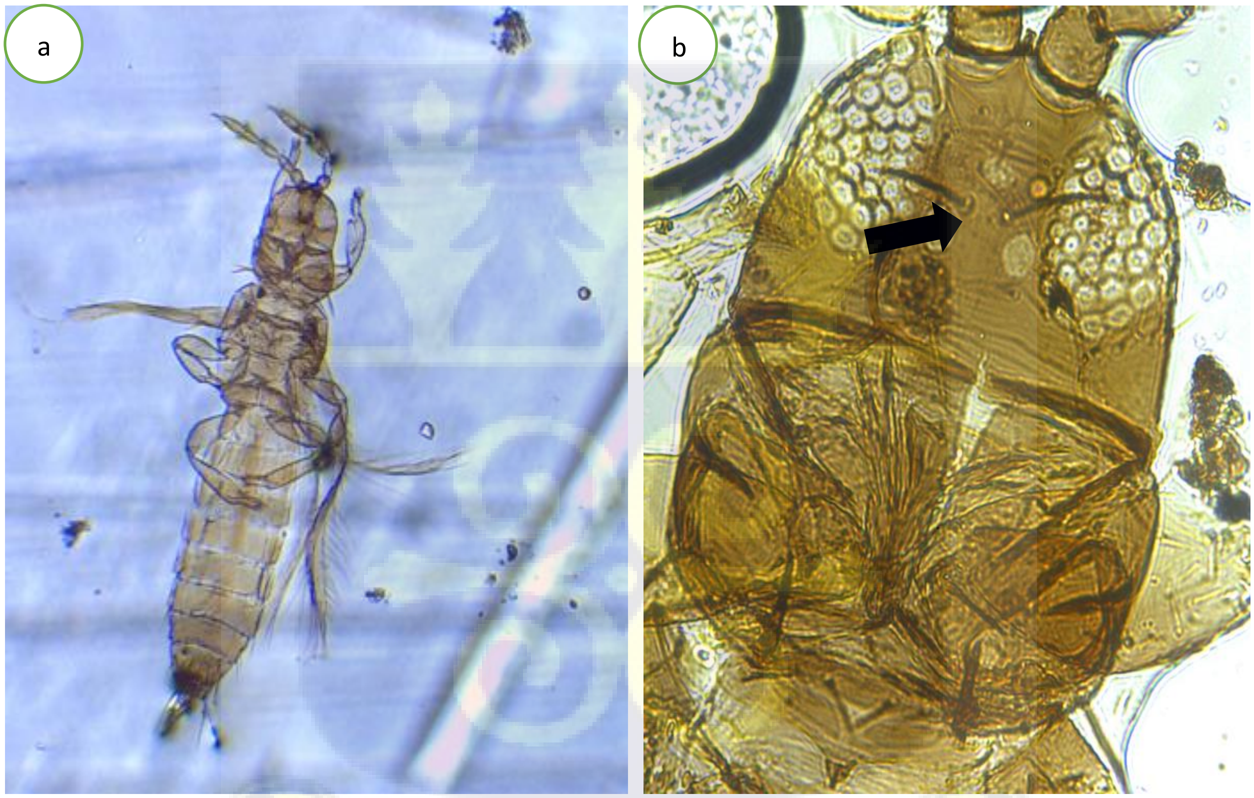


Plate 10. ***Franklinothrips vespiformis*** (a) Adult female, (b) head and antenna, (c) banded forewing, and (d) clear abdominal segments II and III.

3.3.4.6 *Frankliniella* sp.

This species is uniformly yellow in colour and has eight antennal segments, with segment VIII longer than VII (Plate 3.10a). The head is wider than long with three pairs of ocellar setae, pair III is very long and arise on the anterior margins of the ocellar triangle (Plate 3.10b). The postocular setae pair I is present. The metanotum has a median pair of setae which is long and positioned close to or at the anterior margin (Plate 3.10c). The posteromarginal comb on abdominal tergite VIII is complete, with short slender microtrichia arising from triangular bases (Plate 3.10e). The sternites III–VII has no discal setae (Plate 3.10d).



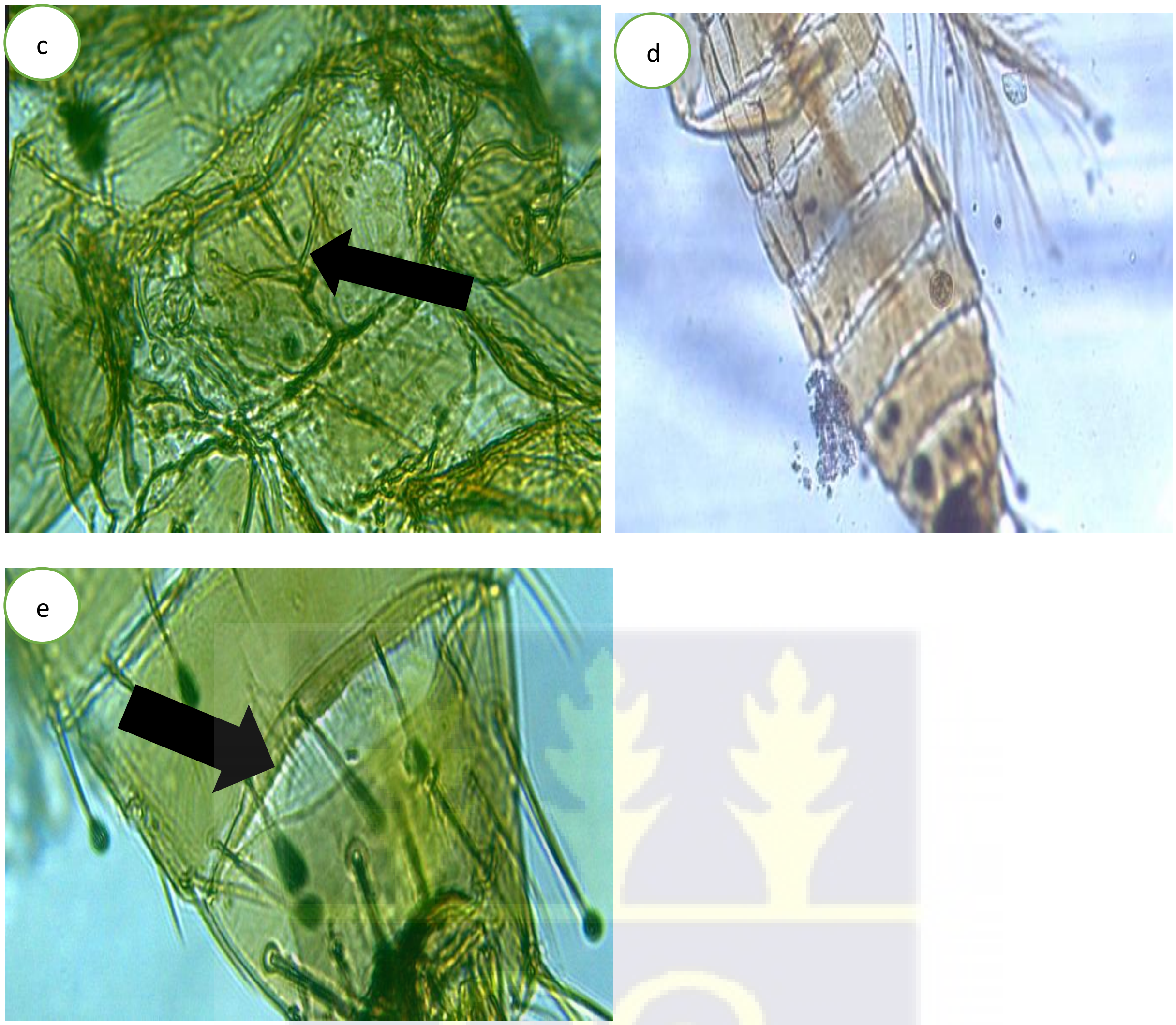


Plate 11. ***Frankliniella* sp.** (a) Adult female, (b) head and pronotum, (c) metanotum, (d) abdominal segments and (e) posteromarginal comb on abdominal tergite VIII.

3.3.5 Molecular identification of thrips

BlAST homology with NCBI generated respective thrips sequences to confirm two of the morphologically identified species in this study. *Gynaikothrips uzeli* was 99.84% similar to KX622230.1 sequence from China and 99.84% similar to those from India, whilst *Thrips parvispinus* was 99.64% similar to sequences from India and Indonesia, respectively (Table 3.8, Appendix 2). These high similarity indices confirmed the identities of species identified in this study to the closest sequence gene bank identities of similar species that have been identified in other areas where they occur. However, repeated attempts to confirm the other thrips species proofed futile.

Table 3.8. Blast results for thrips confirmation.

Raw sample	Sample ID	Query sequence length	Percentage of identical matches	Closest sequence gene bank identity	Primer	Species name	Common name	Country
Long dark thrips	S1_G_C	646	99.83	JN181200.1	LCO1490	*Gynaikothrips uzeli*	Weeping fig thrips	China
Long dark thrips	S2_G_E	645	99.83	KC881243.1	LC01490	*Gynaikothrips uzeli*	Weeping fig thrips	China
Long dark thrips	S3_G_A	633	99.84	KX622230.1	LCO1490	*Gynaikothrips uzeli*	Weeping fig thrips	India
Long Dark thrips	S4_G_A	633	99.96	KX622230.1	LCO1490	*Gynaikothrips uzeli*	Weeping fig thrips	India
Long dark thrips	S5_G_E	645	99.03	KC881243.1	LCO1490	*Gynaikothrips uzeli*	Weeping fig thrips	India
Yellow and black thrips	S6_P_A	658	99.64	OM085664.1	LCO1490	*Thrips parvispinus*	South-East Asian thrips	India
Yellow and black thrips	S6_P_C	675	99.64	KF144070.1	LCO1490	*Thrips parvispinus*	South-East Asian thrips	Indonesia

3.4 Discussion

There are few studies on Thysanoptera in Ghana especially on species richness, ecological function of thrips in fauna, host plants and thrips taxonomy. As a result, there is a scarcity of research that deepens our understanding of thrips diversity and species adaptations to their environment (Mound, 2005). According to Mound (2018), Thysanoptera diversity is greatest in the tropics, but most research have been centered in the temperate areas, especially because most Thysanopterists live in Europe and North America. Here, information on the diversity and abundance of thrips on Ghanaian export vegetables is presented.

In this study, majority of the identified thrips species were from the family Thripidae with a few from the family Phlaeothripidae. The most abundant species from the Thripidae family was the Asian species, *Thrips parvispinus* with two major pests' species which are known to be disease vectors including *Thrips tabaci* and *Frankliniella schultzei*. The family Thripidae contains all pest species of economic importance (Minaei, 2014) and the Genus *Thrips* is found in many parts of the world except the Neotropical region (Iftikhar *et al*., 2016a). It is, therefore, not surprising that these species were collected in this study. Similar species have been reported by Banfo (2009) and Yong (2015) including *T. tabaci*, *M. sjostedti* and *F. schultzei*. Yong (2015) also reported *T. palmi* from samples collected from Atomic Energy farming area in Accra, Ghana. However, all collections in the current study did not find *T. palmi*, rather, the invasive *T. parvispinus* whose adult males are very similar morphologically to *T. palmi* adults was identified. Earlier studies did not equally record this species in Ghana (EPPO, 2019; CABI 2019). However, a recent study by Fening *et al*. (2022) has for the first time reported the presence of *T. parvispinus* on ridged gourd from vegetable exporters farms in Ghana.

Gynaikothrips uzeli was also reported for the first time in the current study. Earlier studies described this species as one of the few species in Phlaeothripidae considered to be a pest of Ficus (Yaseen, 2014). In this study, however, it was collected on eggplant and physical examination of sampled plants showed several galls with curled leaves which are all characteristics of this species. Its presence on only eggplant out of all the sampled crops points to the eggplant morphology, even though it is a shrub, whilst Ficus is a tree, but further studies is needed to ascertain its pest status on eggplant. One potential predatory species, *Franklinothrips vespiformis*, was found in this study. *Franklinothrips vespiformis* has been reported a common predator of *T. palmi* on eggplant, cucumber and beans (Johnson, 2013), however, experimental evidence for its predatory feeding behaviour in Ghana requires confirmation.

Host plants play a crucial role in shaping thrips diversity by providing food, habitat, and also influences ecological interactions and geographical distribution (Mound, 2005; Pizzol *et al.*, 2017). Factors such as leaf morphology, chemical composition, and phenological stages of host plants create different habitats and microenvironments or niches that support diverse thrips communities (Ananthakrishnan, 1970). Thrips were collected on the leaves, flowers and fruits of different vegetables from different plant families in this study. The vegetables varied in total thrips abundance, suggesting crop-specific preferences. The higher thrips population on turia can be attributed to its morphology. The leaves are hairy, and fruits contain furrows which provide suitable areas for thrips concealment. Out of the eight thrips species identified on eggplant, four were found on marrow, turia and guar beans, five on chilli and two on bitter gourd. The concurrent occurrence of the same species on other crops points to their polyphagous nature. Palmer (1990) and Mound (2018) had listed several crops susceptible to thrips infestation in tropical Africa and

Table 2.4 adds to the lists including thrips-intercepted-hosts plants from African countries. Though some thrips are oligophagous, according to Kirk (1995), a majority of thrips are polyphagous and are able to maintain a small, lasting population on alternative crops such as left over weeds after a cropping season or other volunteer crops. In the sampled host agroecosystems, although phytophagy is the main food habitat in the family Thripidae, pollen grain consumption and predation on smaller arthropods could also be a food source that could affect composition of fauna (Bournier *et al*., 1979; Lewis, 1968; Trichilo and Leigh, 1988; Tan *et al*., 2016), in addition to favourable environmental conditions and agroecological barriers. Understanding these contributions is essential for managing thrips populations and conserving biodiversity in agricultural ecosystems.

The distribution of host plants across landscapes and geographical variation contributes to overall insect diversity at national, regional and global scales (Michielini *et al*., 2024). The Central region had the highest population of thrips sampled and species diversity was highest in the Central followed by the Greater Accra and Eastern regions. Suitable weather conditions in addition to higher availability of export vegetables might have contributed to such differences. Thysanoptera is expected to be more diverse in areas less altered by the action of man or in natural systems (Ebratt-Ravelo *et al*., 2019). If we want the total entomofauna of Thysanoptera of Ghana represented, then further exploration of natural habitats unaltered by man, where thrips diversity is likely related to plant heterogeneity is required. However, the targeted focus of this study linked to challenges associated with meeting export requirements of international trade for Ghanaian exported vegetables was of prime importance. Sanabria *et al*. (2008), however, stated that local or regional diversity is affected by the different elements of a landscape. Therefore, just as in perennial crops or silvopastoral systems where species richness is comparable with natural systems, cultivated systems could as well benefit from diversity of the total entomofauna (Ebratt-Ravelo *et al*., 2019).

No quarantine species were identified in this study. Even as this seems like good news for Ghana, more planning and collaboration with neighbouring countries is required so that we can be vigilant enough to document new species as and when they appear and take the necessary emergency preparedness, contingency and eradication plans. Even so, the identified species are classified as regulatory non-quarantine pests and their introduction to new areas, especially EU territories through international trade is prohibited. Hence, exporters need to adhere strictly to approved thrips management protocols and researchers needs to constantly probe into alternative options not currently recommended in the country for inclusion in the overall pest management plan.

3.5 Conclusion

This study contributes valuable insights into the thrips species present in Ghana's vegetable export agroecosystems, their ecological functions, and potential implications for crop health and trade. Moving forward, it is imperative to continue exploring thrips diversity and their interactions with host plants, alongside developing integrated pest management strategies that consider both local biodiversity and the requirements of international trade. This will ensure the sustainable production of export vegetables and the preservation of Ghana's agricultural biodiversity.

CHAPTER FOUR

4.0 PERFORMANCE OF DIFFERENT COLOURS OF STICKY TRAPS IN MONITORING THRIPS POPULATION

4.1 Introduction

Eggplant (*Solanum melongena* L.) and chilli pepper (*Capsicum frutescens* L.) are important vegetables cultivated for export in Ghana (GhanaVeg Sector Reports, 2016), but they are damaged by thrips and other insect pests (Owusu-Ansah *et al*., 2001; GhanaVeg Sector Reports, 2017). Thrips pests infestations reduces yield (Welter *et al*., 1990; Shipp *et al*., 1998; Bacci *et al*., 2008; Srinivasan, 2009; Muniappan *et al*., 2012), aesthetic value (Shipp *et al*., 1998; Tan *et al*., 2016) and have phytosanitary implications (EUROPHYT, 2015, 2016, 2017; GhanaVeg Sector Reports, 2017). Their broad host range, small size, high fecundity and thigmotactic behaviour make thrips extremely difficult to control (Hata *et al*., 1991; Monteiro *et al*., 1995). Thrips management options currently rely on synthetic chemical insecticides (Tanzubil *et al*., 2008; Omo-Ikerodah *et al*., 2009; Amouzou *et al*., 2022), with about 4-15 sprays per cropping season (Nderitu *et al*., 2001), which is not based on reliable pest monitoring. Furthermore, as a result of the repeated application of these pesticides, several negative effects on non-targets, consumers, and public health have emerged (Amoah *et al*., 2006; Bempah *et al*., 2011; Seal *et al*., 2013).

One essential component of integrated pest management (IPM) for sustainable and need-based pest management is accurate and reliable monitoring of the target pest (Afreh-Nuamah, 2003).

Thrips detect and orient towards their host plants using scent and colour as cues (Terry, 1997) and the use of colour has been exploited in thrips pest management. Coloured sticky traps among the various thrips monitoring approaches (Layland *et al*., 1994; Chu *et al*., 2006; Broughton and Harrison, 2012; Tang *et al*., 2016), have been demonstrated as a cost-effective tool for the monitoring of thrips and provide quick indications of thrips population fluctuations over time. They have been used for several thrips species including *F. schultzei*, *F. occidentalis* and *S. dorsalis* (Chen *et al*., 2004; Chu *et al*., 2006; Mainali and Lim, 2010).

Following the national action plan outcome held in 2015, sticky traps were recommended for thrips monitoring in Ghana, and vegetable producers and exporters currently use yellow, blue, or both colour for thrips monitoring (GhanaVeg Sector Report, 2017; Amouzou *et al*., 2022; Fening *et al*., 2022). Thrips, on the other hand, respond differently to different trap colours (Muvea *et al*., 2014; Allan and Gillett-Kaufman, 2018; Mao *et al*., 2018). A recent study by Fening *et al*. (2022) revealed that blue sticky traps had a significantly higher number of thrips than the yellow sticky traps in ridged gourd farms of six exporters in Ghana. Thus, very little information exists on thrips preference to different colour of sticky traps in Ghana. Going forward, information on the effectiveness of sticky traps of different colours and thrips-species-specific sticky traps could be incorporated into thrips-integrated pest management programmes to curb the global spread of these pests. This will provide the relevant empirical data for a long-term monitoring plan and first-hand information for policymakers to adopt to be an integral part of a sustainable nationwide pest monitoring scheme for exporters.

4.2 Material and methods

4.2.1 Site selection

The experiment was conducted in Tuba (Plate 4.1) which lies in the Ga South municipality in the Greater Accra region of Ghana (Streets of Ghana, 2021). The region has a bimodal rainfall pattern (April to July and August to October) with rainfall averaging 800-1270 mm annually. The temperature ranges between 25.1 and 28.4 ºC annually, with 75- 78% relative humidity. The soils are sandy and clayey loams (MoFA, 2020), with clayey predominant in Tuba.

During the rainy season, especially the major raining season (April to July), farmlands in Tuba are usually flooded with excess water or by the occasional opening of the Weija dam when it is full. This situation forces farmers to escape these flooding seasons by planting in reduced rainfall periods and irrigating their fields which they have greater control over it. Therefore, this study was conducted for two cropping seasons [August to November (season 1) and January to March (season 2)] of 2020/2021.

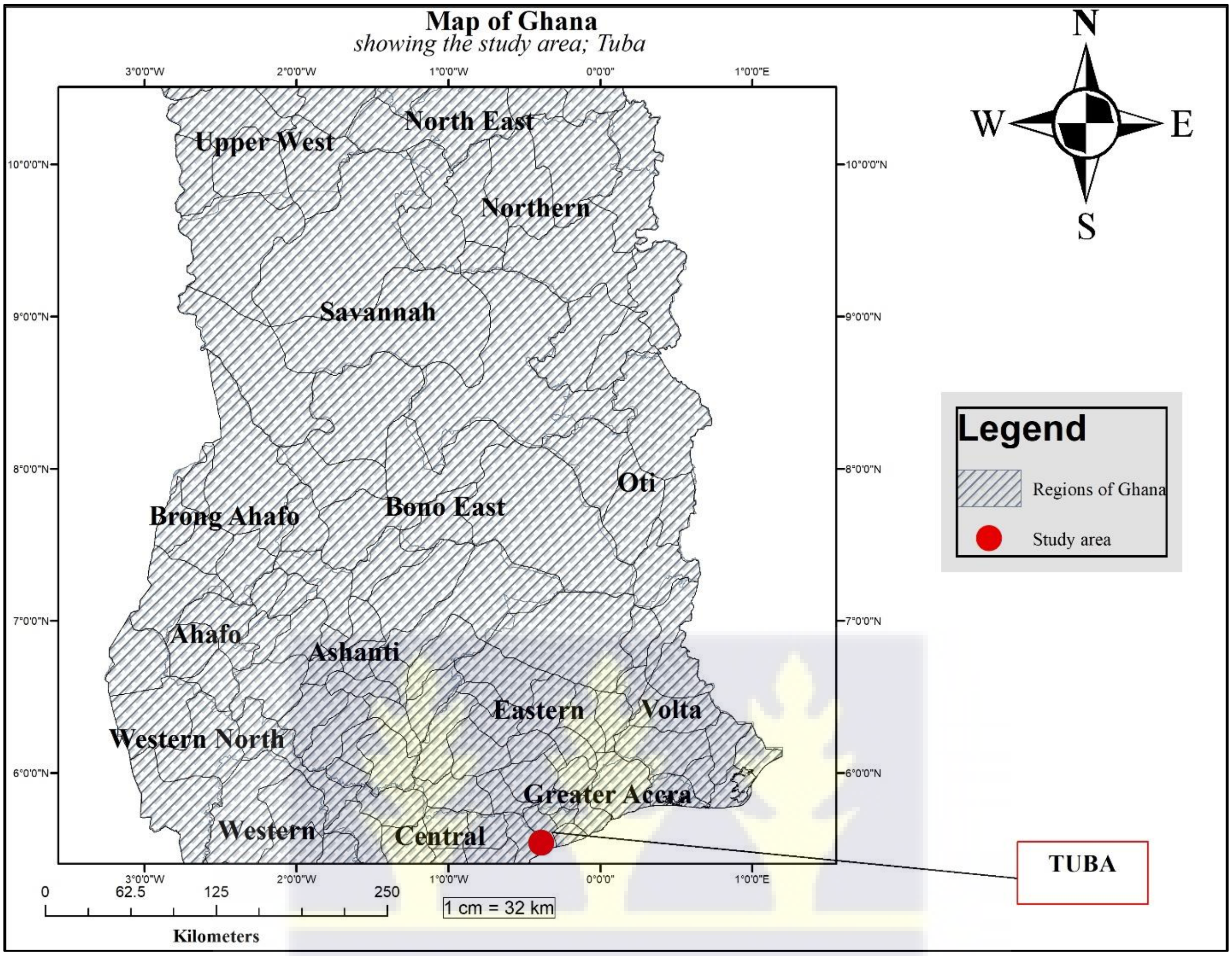


Plate 12. Map of Ghana showing the study site.

4.2.2 Farm selection

Chilli (Latitude 5° 30' 21.3618", Longitude 0° 16.54368") and eggplant (Latitude 5° 30' 20.72268", Longitude 0° 23' 19.57344") commercial farms with previous history of thrips incidence and damage were used for this study. The farms were separated at least 100 m from each other and cultivated under irrigation with a moveable black hose where crops were watered at four-day intervals. Prior to the study, the fields were under tomato and okra cultivation. Other characteristics of the farms are summarized in Table 4.1.

Table 4.6. Characteristics of the commercial farms.

Characteristics	Chilli farm	Eggplant farm
Variety	bird's eye	Ravaya
Size	2 acres	2.5 acres
Planting distance	60 x 60 cm	1 x 1 m
Plant height	10-15cm	15-20cm
Insecticides used	K-Optimal EC (Acetamiprid (20g/l) + Lambda-cyhalothrin (16g/l) and Attack 1.9 EC (Emamectin-benzoate (19g/l))	Attack 1.9EC and K-Optimal EC

4.2.3 Setting of traps

The methodology for trap placement was modified from Tang *et al*., (2016) and Allan and Gillett-Kaufman, (2018). Each field was divided into 8 blocks (replicates). In each replicate, all trap colours (blue, yellow, or white sticky card) representing three treatments were randomly set at the centre for the respective crop (Plate 4.2). Each of the sticky cards had a dimension of 22.5 cm by 12.5 cm and was spaced 3 m apart (Allan and Gillett-Kaufman, 2018). The sticky cards were tied vertically on stakes using a wire (Plate 4.3) and adjusted weekly to the height of the canopy. The study began 4 weeks after transplanting and lasted for ten weeks in each cropping season. Traps were replaced every seven days between 5:30 am and 7:00 am and retrieved traps were transferred to the laboratory to be further processed.

4.2.4 Environmental data collection

A data logger [EasyLog USB Data Logger (EL-USB-2)] was installed at the centre of the farms to record environmental data (temperature and relative humidity) at intervals of one hour daily. This logger was placed in an inverted plastic cup, tied with polyethene bags to prevent damage during rainy periods.

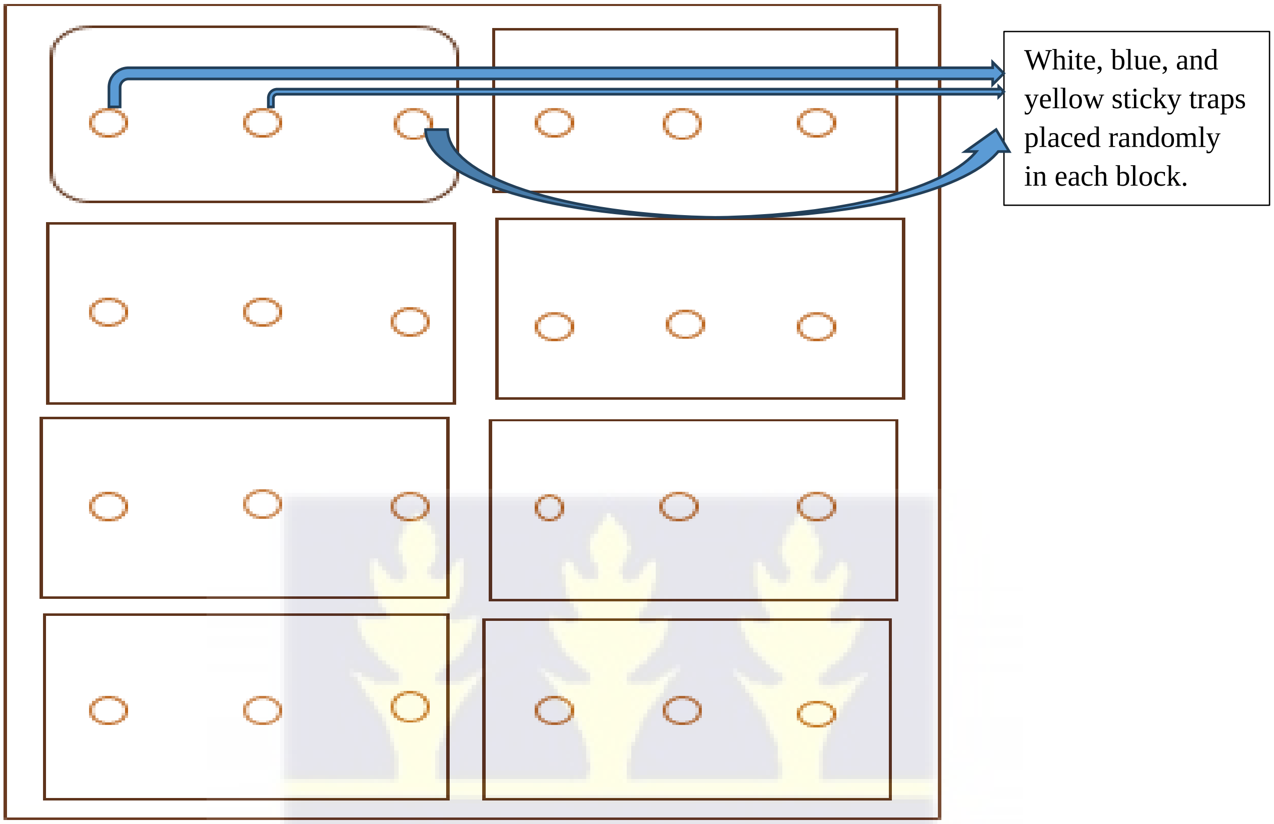


Plate 13. Experimental design modified from Allan and Gillett-Kaufman, 2018.

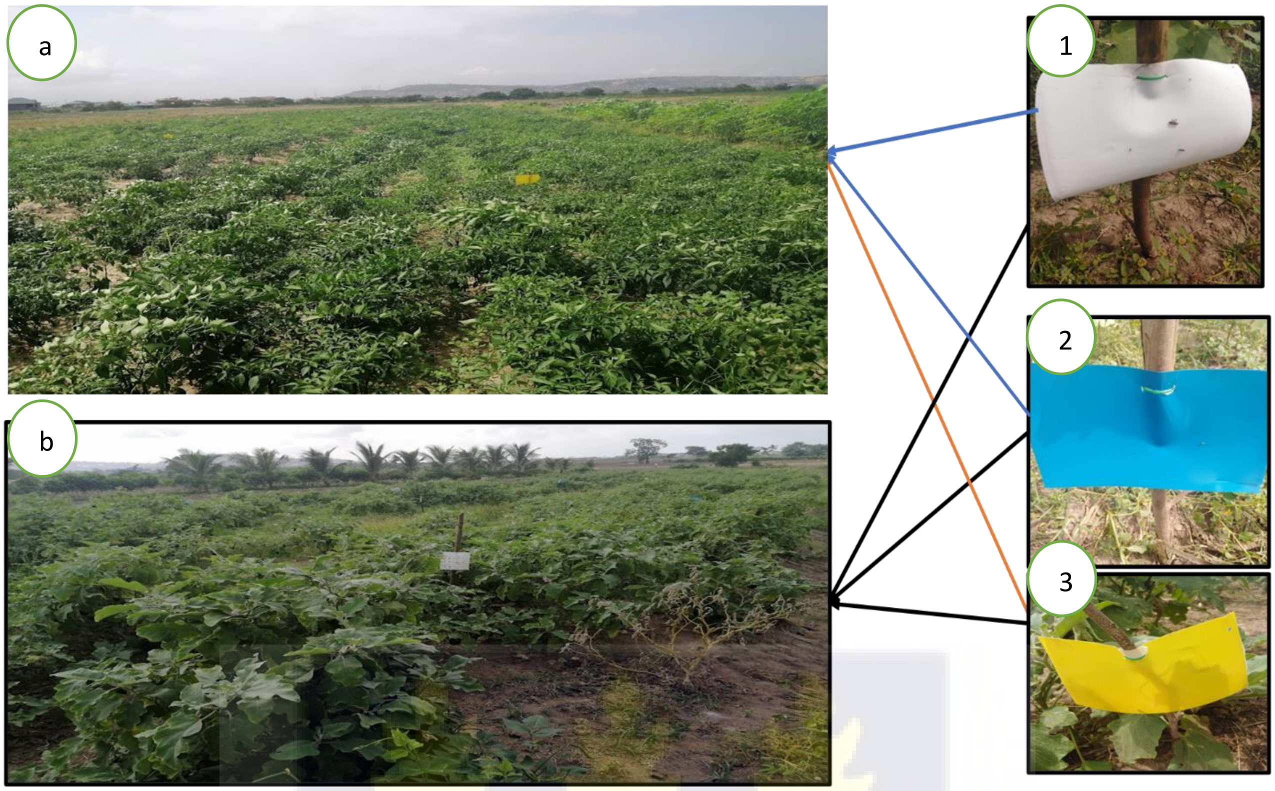


Plate 14. Commercial fields and colour traps used for the experiment. (a) chilli, (b) eggplant, (1) white sticky trap, (2) blue sticky trap and (3) yellow sticky trap.

4.2.4 Processing of retrieved traps

In the laboratory, thrips were recovered from sticky cards following methods by Muvea *et al*., 2014. The glue on sticky cards was dissolved with Kerosene for 12 minutes after which minutien pin was gently used to collect thrips into Eppendorf tubes filled with 70% alcohol. Sampling of thrips for identification was modified from Morsello *et al*., 2008, where, the total number of adult thrips was counted, and a random subsample of 30 thrips was removed for identification of the species. The proportion of each species within the subsample was multiplied by the total number of thrips captured on that trap to estimate the total number of each species present on the trap. A microscope slide was prepared for each trap collection after maceration, clearing and mounting. Clove oil and Canada balsam were used as clearing and mounting media, respectively. Thrips were identified to species using keys by Palmer (1990). Voucher specimens are held at the Entomology Museum of the African Regional Postgraduate Programme in Insect Science, University of Ghana. Other non-targets including captured natural enemies were counted and recorded for each collection.

4.2.5 Analysis of data

The data on trap performance was analysed with a generalized linear model (GLM) with a negative binomial log link distribution for individual thrips species. The factors included trap colour, crop type, and environmental factors (relative humidity and temperature). Since the dependent variables were not normally distributed, a GLM which provides a flexible and robust framework for determining relationships between diverse types of data was used. It has three components; the random, the systematic, and the regression component which uses a link function to explain the linear relationship between the dependent and predictor variables allowing more flexibility in complex relationships. The sampling time was used as an offset in the GLM since it was not significant, to improve the prediction of the variables. Differences in thrips species within host plants were analysed with a Kruskal-Wallis test. Comparisons between means were made using the Dunn's test at the 5% significance level. Differences in thrips species between host plants were not significant, therefore, data from host plants on the individual thrips species was pooled for analysis. The non-target catch data was analysed by GLM with a negative binomial distribution. The dataset was stratified based on the cropping season to allow for season-specific analyses, which were done with the student, t-test. Before the analysis, the cumulative daily lowest and highest temperature was averaged to give the average weekly temperature which was then used for the analysis. Statistical analysis was done with SPSS (Version 16.0) software which offers advanced statistical procedures for evaluating the effects of multiple independent variables simultaneously. It provides a robust GLM capabilities, which allows one to specify models with various distributions (normal, Poisson, binomial) and link functions (log, identity). This flexibility was crucial for accurately modelling the relationship between predictors and thrips species populations in the dataset.

4.3 Results

4.3.1 Species of thrips trapped during the experiment

The species of thrips identified on retrieved sticky traps included the Southeast Asian thrips, *Thrips parvispinus* Karny (Thysanoptera: Thripidae), the cotton thrips, *Franklinella schultzei* Trybom (Thysanoptera: Thripidae) and the onion thrips, *Thrips tabaci* Lindeman (Thysanoptera: Thripidae). These three species were found on both crops for the two growing seasons.

4.3.2 Effects of host plant, sticky traps, and environmental factors on thrips species dynamics

4.3.2.1 *Thrips parvispinus* Karny (Thysanoptera: Thripidae)

Throughout the sampling period, the prevalence of *Thrips parvispinus* significantly surpassed that of *Frankliniella schultzei* and *Thrips tabaci*. The population of *T. parvispinus* peaked during flowering in the first cropping season and during the vegetative (1263.75 ± 190.90) and flowering (1341.29 ± 183.85) periods in the second season, respectively (Figures 4.1 and 4.2). The host plants, that is chilli and eggplant did not have a significant effect on *T. parvispinus* catches in the first season ($\chi^2_{(1, N = 54)} = 2.39$, P = 0.122) and the second season ($\chi^2_{(1, N = 54)} = 2.89$, P = 0.322). However, the effect of sticky traps on *T. parvispinus* catches was significant for both cropping seasons ($\chi^2_{(2, N = 54)} = 6.91$, P = 0.032 and $\chi^2_{(2, N = 54)} = 1.10$, P = 0.042). Among the traps, white sticky traps attracted more *T. parvispinus* which was significantly different from the population on blue traps, and not on yellow traps in the first season ($\chi^2_{(1,\ N = 18)}$ = 3.62, P = 0.049), but differed significantly from both blue and yellow traps in the second season (Figure 4.3). The interaction between sticky trap colour and *T. parvispinus* was significant (Appendices 3 and 4). All tested environmental factors predicted the abundance of *T. parvispinus*. Temperature highly contributed significantly to the abundance of *T. parvispinus* in the first and second seasons, respectively ($\chi^2_{(1,\ N = 54)}$ = 29.14, P < 0.001 and $\chi^2_{(1,\ N = 54)}$ = 39.14, P < 0.001). During the first season, the lowest and highest hourly temperature was 22.5 °C and 40.5 °C, respectively, with the highest mean weekly average of 30.46 °C. In the second season, the lowest and highest hourly temperature was 24.5 °C and 49.5 °C, respectively, with the highest mean weekly average of 35.86 °C. Here, an increase in mean temperature from 33.82 °C to 35.39 °C, led to a sharp decline in their population from 1263.75 ± 190.90 to 669.58 ± 154.26. But when the temperature reduced to 34.11 °C, *T. parvispinus* population increased sharply to 916.56 ± 154.26 and this increase or decrease varied across the sampling weeks and physiological stage of the plants (Figure 1). Likewise, as the relative humidity reduced from 80% to 78%, *T. parvispinus* population increased with peaks at 75% RH, however, an increase in relative humidity from 80% to 81.5% led to a reduction in its abundance in the first season (Figure 1). The effect of relative humidity was significant for both seasons ($\chi^2_{(1,\ N = 54)}$ = 6.95, P < 0.008 and $\chi^2_{(1,\ N = 54)}$ = 4.80, P = 0.006) (Table 4.3). Comparing the abundance for both seasons revealed, the population was significantly higher in the second season (t-test = 6.88, P < 0.001) (Appendix 5).

4.3.2.2 *Thrips tabaci* Lindeman (Thysanoptera: Thripidae)

The onion thrips, *T. tabaci* recorded its highest peak population during the fruiting/flowering stage in the first and second cropping seasons (Figures 4.1 and 4.2). The population of *T. tabaci* on sticky traps was not significantly affected by the host plants for both seasons ($\chi^2_{(1,\ N = 54)}$ = 2.96, P < 0.083

and $\chi^2_{(1, N = 54)} = 3.77$, $P = 0.071$), though the abundance was higher on eggplant (187.19 ± 16.35). The specificity of sticky traps in attracting *T. tabaci* was likewise not significant for the first and second cropping seasons, respectively ($\chi^2_{(2, N = 54)} = 3.01$, $P = 0.086$ and $\chi^2_{(2, N = 54)} = 1.21$, $P = 0.997$). All traps, white, yellow, and blue recorded some *T. tabaci* numbers, with white and blue having higher catches than yellow traps for both seasons (Figure 4.3). However, the micro climatic weather parameters were effective predictors of *T. tabaci* abundance throughout the sampling period. Temperature highly predicted the abundance of *T. tabaci* significantly in the first ($\chi^2_{(1, N = 54)} = 64.07$, $P < 0.000$) and second ($\chi^2_{(1, N = 54)} = 24.97$, $P = 0.045$) cropping seasons. An increase in temperature translated to an increase in *T. tabaci* abundance up to a certain optimum value, above which a reduction in *T. tabaci* numbers was seen with any increase in temperature afterwards. Similarly, relative humidity significantly predicted *T. tabaci* abundance in both seasons ($\chi^2_{(1, N = 54)} = 7.72$, $P < 0.005$ and $\chi^2_{(1, N = 54)} = 7.14$, $P = 0.005$), where an increase in relative humidity from 60-78% led to a slight increase in *T. tabaci* numbers which subsequently levels off (Figure 4.1). Differences existed in the abundance of *T. tabaci* between seasons where the population in the second season was significantly higher than the first (t-test = 7.75, $P = 0.001$) (Appendix 5).

4.3.2.3 *Franklinella schultzei* Trybom (Thysanoptera: Thripidae)

Franklinella schultzei was present throughout the sampling period and its population varied across the sampling dates, with weeks 4 and 8 (22/07/2020 and 19/09/2020) recording the peak abundance. This peak coincided with the flowering of the host plants, however, chilli and eggplant had no significant effect on *F. schultzei* numbers in the first and seconds, respectively ($\chi^2_{(1, N = 54)} = 2.36$, $P = 0.124$ and $\chi^2_{(1, N = 54)} = 2.42$, $P = 0.120$) (Tables 4.2 and 4.3). The specificity of sticky traps in capturing *F. schultzei* was significant for both seasons ($\chi^2_{(2, N = 54)} = 7.07$, $P < 0.029$ and

$\chi^2_{(2,\ N\ =\ 54)} = 39.74$, $P < 0.000$). *F. schultzei* showed a preference for yellow sticky traps and its attractiveness was significantly different from white and blue sticky traps in the first season ($\chi^2_{(1,\ N\ =\ 18)} = 2.83$, $P = 0.040$), but did not differ from the white trap in the second season (Figure 4.3). Weather parameters were able to predict *F. schultzei* abundance. Temperature highly contributed significantly to the abundance of *F. schultzei* in the first and second seasons, respectively ($\chi^2_{(1,\ N\ =\ 54)} = 37.89$, $P < 0.001$ and $\chi^2_{(1,\ N\ =\ 54)} = 5.98$, $P = 0.015$). As the temperature reduced throughout the experimental period, *F. schultzei* numbers increased and vice versa (Figure 4.1). Contrary to this trend, an increase in relative humidity led to a slight increase in *F. schultzei* population. The effect of relative humidity on *F. schultzei* was significant for the first ($\chi^2_{(1,\ N\ =\ 54)} = 5.54$, $P = 0.019$) and second ($\chi^2_{(1,\ N\ =\ 54)} = 18.62$, $P < 0.001$) seasons, even though an increase in relative humidity did not always translate to a reduced *F. schultzei* population. A t-test revealed a higher population in the second than in the first season (t-test = 6.47, P = 0.008) (Appendix 5).

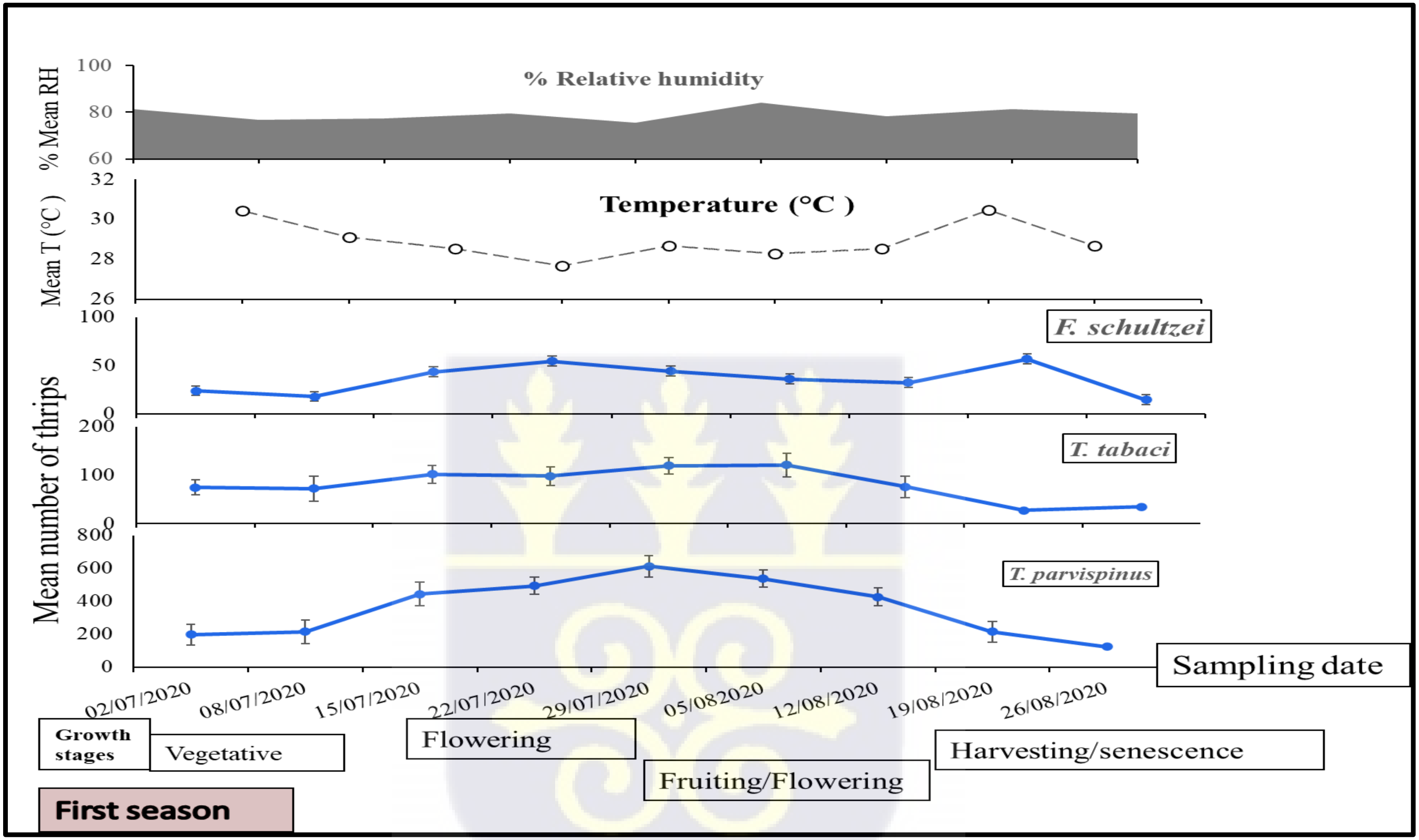


Figure 4.1. Effect of temperature and relative humidity on the weekly population dynamics (Mean ± SE) of *T. parvispinus*, *T. tabaci* and *F. schultzei*, respectively, in the first season of 2020.

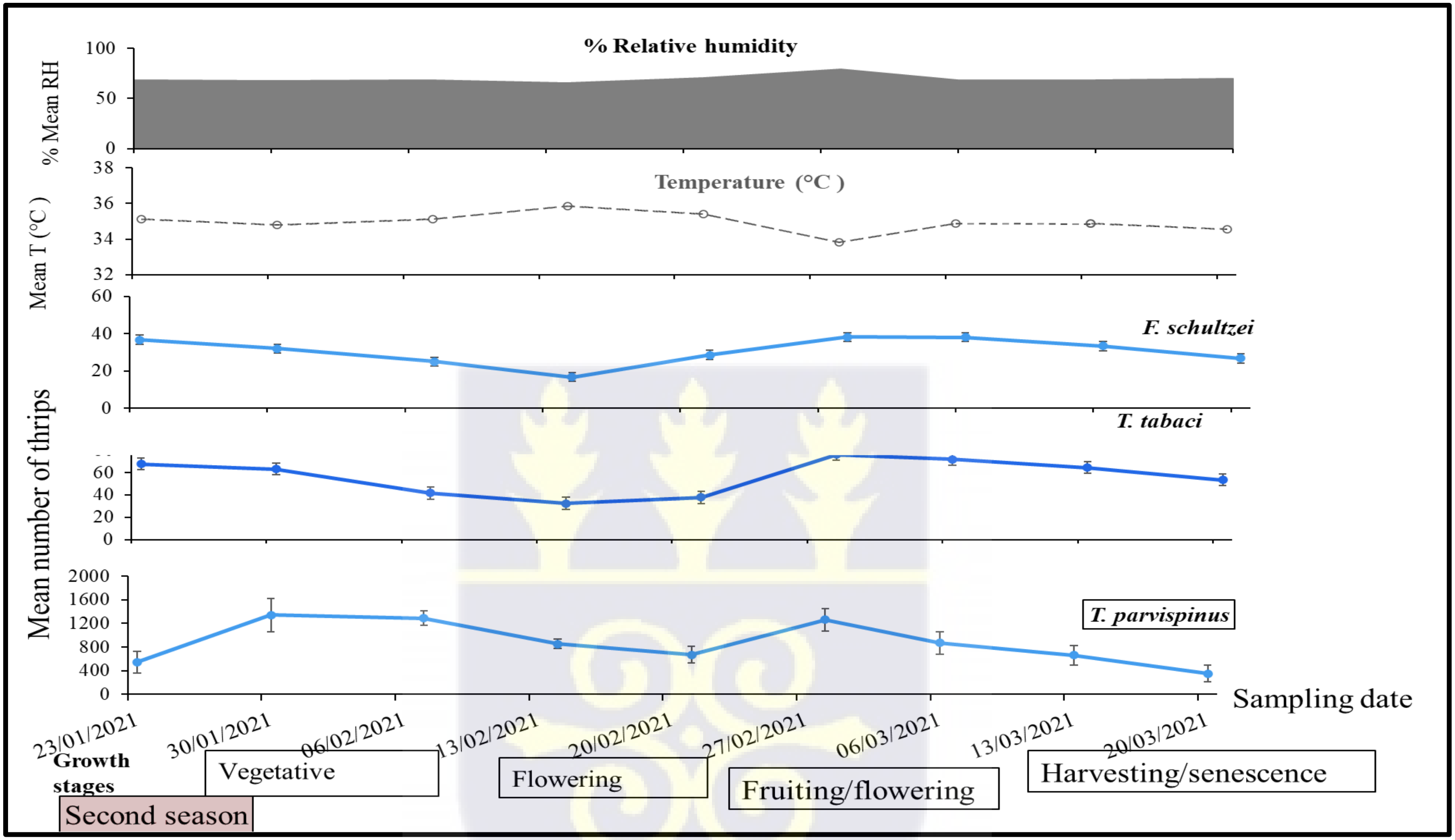


Figure 4.2. Effect of temperature and relative humidity on the weekly population dynamics (Mean + SE) of *T. parvispinus*, *T. tabaci* and *F. schultzei*, respectively, in the second season of 2021.

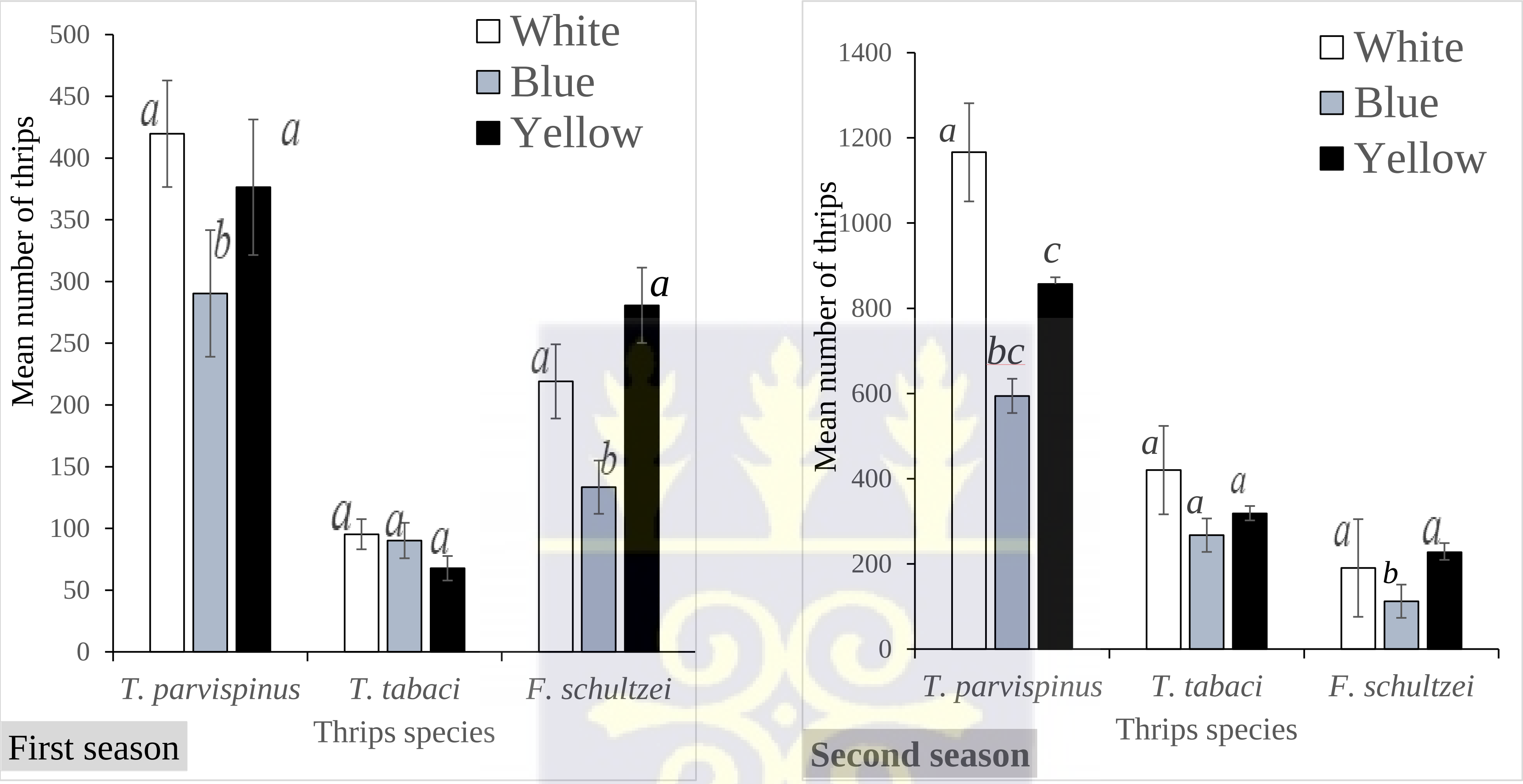


Figure 4.3. The attractiveness of sticky traps on mean (± SE) number of thrips species in the first and second cropping seasons of 2020/2021.

Table 4.2. Mean number of thrips species (± SE) collected on sticky traps on chilli and eggplant fields in the first and second cropping seasons of 2020/2021.

Thrips species	First season		Second season	
	Eggplant	Chilli	Eggplant	Chilli
T. parvispinus	408.04 (44.94)a	316.19 (36.22)a	935.95 (81.73)a	808.92 (115.84)a
T. tabaci	97.37 (11.30)b	63.41 (7.61)b	374.38 (32.69) da	295.95 (34.12)ba
F. schultzei	200.78 (21.41)ab	183.33 (25.89)ab	187.19 (916.35)b	149.99 (18.09)b
Total	706.19 (71.62)	562.93 (66.22)	1406.58 (150.23)	1180.59 (147.83)

Standard errors are in parenthesis. Means with the same letters within columns are not significantly different ($P < 0.05$; Dunn test).

Table 4.3. Summary of generalised linear model showing the relationship between trap colour, crop type and environmental factors on *thrips* species in the first and second cropping seasons of 2020/2021.

Thrips species	Parameter	First season				Second season			
		Estimate	SE	Chi-square	P	Estimate	SE	Chi-square	P
T. parvispinus	(Intercept)	-5.977	5.58	1.01	0.315	-95.88	5.52	-3.93	0.23
	Crop type	0.43	0.27	2.39	0.122	0.49	0.21	2.89	0.322
	Trap colour	0.65	0.34	6.91	0.032	0.76	0.07	1.10	0.042
	Temperature	0.76	0.14	29.14	< 0.001	0.81	0.15	39.14	< 0.001
	Relative humidity	-0.18	0.07	6.95	0.008	-3.19	0.03	4.80	0.006
T. tabaci	(Intercept)	-16.54	5.66	8.02	0.003	193.86	100.55	3.769	0.052
	Crop type	0.49	0.28	2.96	0.083	-0.81	1.99	3.77	0.071
	Trap colour	0.59	0.34	3.01	0.086	-0.005	0.001	1.21	0.997
	Temperature	1.10	0.14	64.07	< 0.001	-4.21	2.44	24.966	0.045
	Relative humidity	-0.19	0.07	7.73	0.005	-0.64	0.22	7.738	0.005
F. schultzei	(Intercept)	-10.14	5.53	3.24	0.067	131.65	45.16	8.24	0.004
	Crop type	0.43	0.28	2.37	0.124	-0.98	0.63	2.42	0.120
	Trap colour	0.48	0.33	7.07	0.029	-5.81	0.93	39.74	< 0.001
	Temperature	0.85	0.137	37.89	< 0.001	-2.59	1.06	5.98	0.015
	Relative humidity	-0.16	0.07	5.54	0.019	-0.54	0.13	18.62	< 0.001
Total thrips	(Intercept)	-8.22	5.53	2.04	0.154	113.02	26.87	17.94	< 0.001
	Crop type	0.44	0.27	2.54	0.111	-0.45	0.28	2.44	0.118
	Trap colour	0.54	0.33	5.17	0.075	-0.67	0.34	8.96	0.011
	Temperature	0.85	0.14	38.21	< 0.001	-2.15	0.62	11.99	0.001
	Relative humidity	-0.17	0.06	6.58	0.010	-0.48	0.08	38.57	< 0.001

Dependent Variables: *T. parvispinus*, *T. tabaci*, *F. schultzei* and Total thrips. Model: (Intercept), Trap colour, Crop type, Temperature, and Relative humidity, weeks = offset.

4.3.3 Effects of host plant, sticky traps, and environmental factors on non-target organisms in trap catches

In addition to the thrips species detailed in section 4.3.1, the study documented a diverse array of arthropods across various insect orders on the host plants and sticky traps, with their populations influenced by environmental conditions. These insects have been grouped into various insect orders as shown in Figure 4.4. The insect orders included Coleoptera (mainly flea beetles and ladybirds), Hymenoptera (Ants and wasps), Lepidoptera (moths), Hemiptera (Minute pirate bug, big-eyed bug, whiteflies, and leaf hoppers), Blattodea (cockroach), Diptera (flies, hoverfly) and Orthoptera (grasshoppers). In the first season, the effect of host plant, sticky trap and weather factors (temperature and relative humidity) were significant on the catches of the insect orders Hymenoptera ($\chi^2_{(1, N = 54)} = 19.84$, $P < 0.001$, $\chi^2_{(2, N = 54)} = 63.35$, $P = 0.001$, $\chi^2_{(1, N = 54)} = 5.596$, $P = 0.018$, $\chi^2_{(1, N = 54)} = 13.40$, $P < 0.001$), Hemiptera ($\chi^2_{(1, N = 54)} = 29.95$, $P < 0.000$, $\chi^2_{(2, N = 54)} = 66.88$, $P = 0.000$, $\chi^2_{(1, N = 54)} = 58.77$, $P = 0.000$, $\chi^2_{(1, N = 54)} = 9.74$, $P = 0.002$), Blattodea ($\chi^2_{(1, N = 54)} = 18.90$, $P < 0.000$, $\chi^2_{(2, N = 54)} = 36.96$, $P = 0.000$, $\chi^2_{(1, N = 54)} = 6.97$, $P = 0.008$, $\chi^2_{(1, N = 54)} = 8.53$, $P = 0.003$), and Diptera ($\chi^2_{(1, N = 54)} = 10.762$, $P = 0.001$, $\chi^2_{(2, N = 54)} = 8.491$, $P = 0.014$, $\chi^2_{(1, N = 54)} = 67.34$, $P = 0.000$, $\chi^2_{(1, N = 54)} = 8.19$, $P = 0.004$). However, though the effect of the host plant significantly contributed to the species abundance in the order Araneae ($\chi^2_{(1, N = 54)} = 7.48$, $P < 0.006$) and Orthoptera ($\chi^2_{(1, N = 54)} = 7.19$, $P < 0.007$), it was not significant for Coleoptera ($\chi^2_{(1, N = 54)} = 1.27$, $P < 0.260$) and Lepidoptera ($\chi^2_{(1, N = 54)} = 2.48$, $P = 0.115$). Likewise, the specificity of sticky traps in attracting species in the orders Araneae ($\chi^2_{(2, N = 54)} = 3.14$, $P = 0.208$) and Lepidoptera ($\chi^2_{(2, N = 54)} = 3.90$, $P = 0.142$) were not significant, but were significant for Coleoptera ($\chi^2_{(2, N = 54)} = 11.492$, $P = 0.003$). A similar trend was followed in the second season, except that the white sticky trap recorded higher species in the order Diptera than the rest (Figure 4.4). The population of trapped arthropods varied on different crops. More Hymenoptera, Lepidoptera and Coleoptera were collected on Chilli than eggplant for both seasons (Tables 4.4 and 4.5).

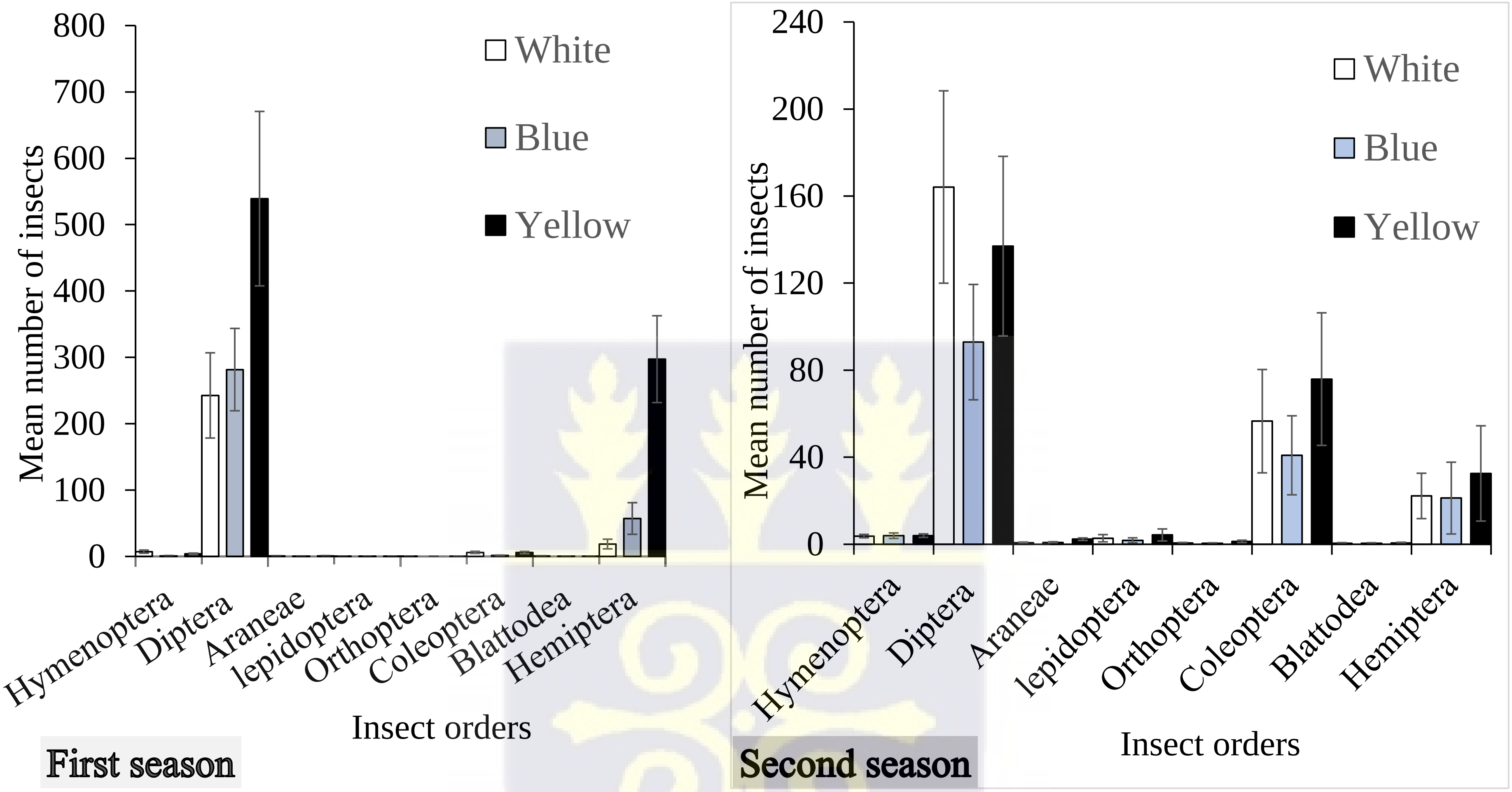


Figure 4.4. Effect of sticky trap on the mean catches (± SE) of species in the different arthropod orders in the first and second cropping seasons of 2020/2021.

Among the non-target catches, some of the attracted species were of interest for their role in the biological control of thrips and other insects. Therefore, the effect of the tested parameters was assessed on the individual natural enemies including Ladybird beetles (*Cheilomene*s *lunata* and *Cheilomenes propinqua*), minute pirate bug (*Orius insidiosus*), spiders and hoverflies (Figure 4.5). Yellow sticky traps captured the highest number of Ladybird beetles, minute pirate bug and hoverflies but differences were not significant, except for ladybird population where yellow traps recorded significantly higher population than the rest ($\chi^2_{(2, N = 54)} = 14.51, P < 0.001$). Blue sticky traps recorded consistently the lowest number of natural enemies, followed by white traps throughout the sampling period. More hoverfly, spiders, and *O. insidiosus* were collected on eggplant than on chilli, whilst the ladybird population was higher on chilli (Table 4.3).

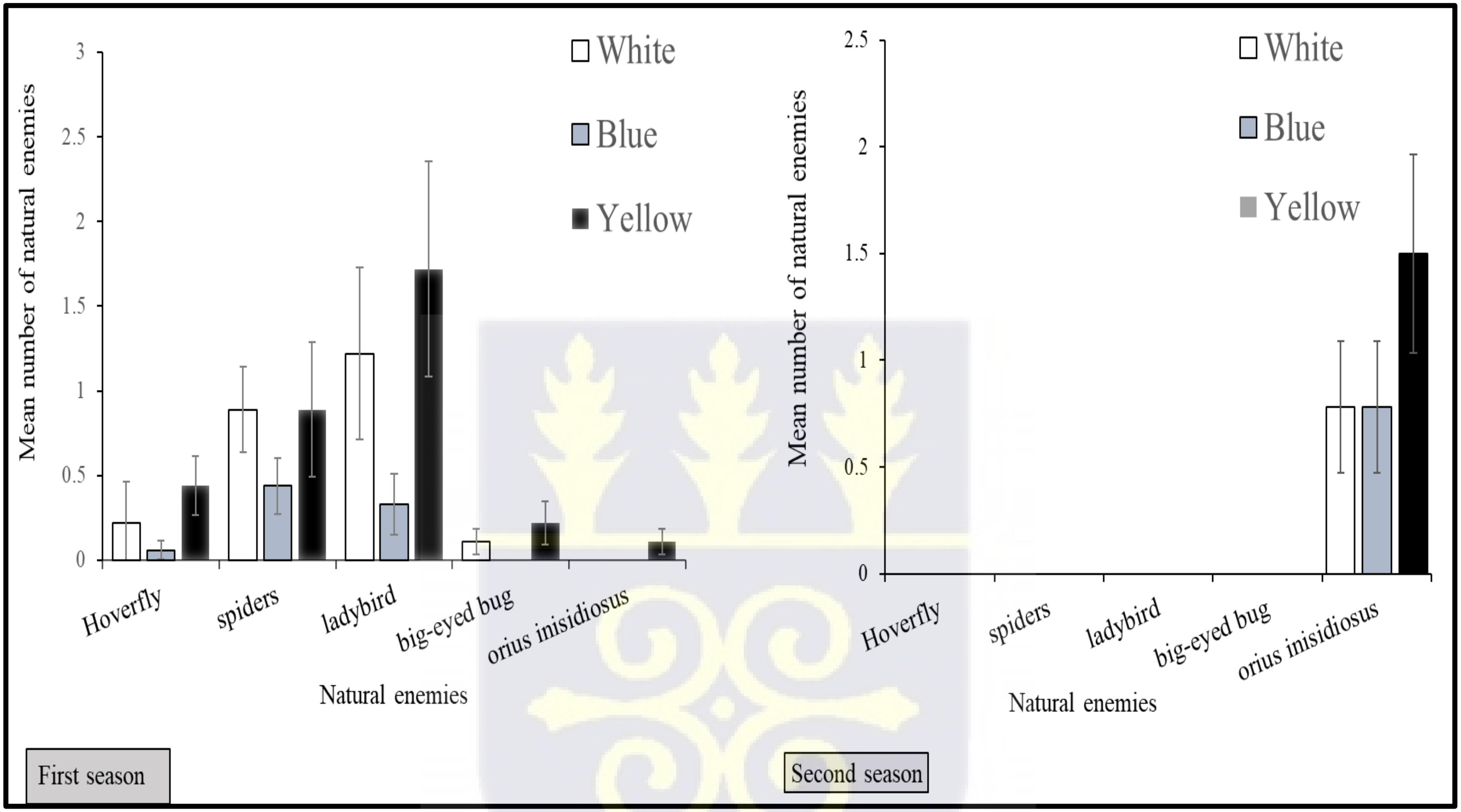


Figure 4.5. Effects of sticky traps on the mean numbers of natural enemies in the first and second cropping seasons of 2020/2021.

Table 7. Weekly mean insect orders and natural enemies collected on sticky traps on chilli and eggplant fields in the first cropping season of 2020.

Crop type	Insect orders								Natural enemies				
	Hymenoptera	Diptera	Araneae	Lepidoptera	Orthoptera	Coleoptera	Blattodea	Hemiptera	Hoverfly	Spiders	ladybird	Big-eyed bug	Orius spp.
Eggplant	1.11 (0.32)	232.26 (48.76)	1.04 (0.285)	0.11 (0.06)	0.37 (0.13)	3.33 (0.70)	0.04 (0.04)	18.37 (4.97)	0.33 (0.17)	1.04 (0.29)	0.56 (0.24)	0.15 (0.08)	0.14 (0.04)
Chilli	6.85(1.69)	476.67 (93.87)	0.44 (0.15)	0.26 (0.13)	0.07 (0.05)	5.63 (1.53)	0.59 (0.25)	230.41(49.17)	0.15 (0.12)	0.44 (0.15)	1.63 (0.50)	0.07 (0.05)	0.04 (0.19)
Total	7.96 (0.94)	708.93 (55.01)	0.74 (0.17)	0.34 (0.07)	0.44 (0.07)	8.96 (0.85)	0.63 (0.13)	248.78 (28.48)	0.48 (0.10)	1.48 (0.17)	2.19 (0.28)	0.22 (0.05)	0.23 (0.03)

Standard errors are in parenthesis.

Table 8. Weekly mean insect orders and natural enemies collected on sticky traps on chilli and eggplant fields in the second cropping season of 2021.

Crop type	Insect orders								Natural enemies				
	Hymenoptera	Diptera	Araneae	Lepidoptera	Orthoptera	Coleoptera	Blattodea	Hemiptera	Hoverfly	spiders	ladybird	Big-eyed bug	Orius spp.
Eggplant	3.48 (0.64)	202.15 (37.96)	1.46 (0.42)	0.85 (0.26)	0.74 (0.33)	37.22 (17.55)	0.42 (0.15)	45.11 (10.20)	-	-	-	-	0.59 (0.02)
Chilli	4.31 (0.91)	60.56 (11.81)	1.15 (0.35)	5.07 (2.10)	0.78 (0.31)	78.33 (20.66)	0.56 (0.31)	5.56 (1.390					1.44 (0.36))
Total	7.79 (0.55)	262.71 (21.95)	2.61 (0.27)	5.92 (1.13)	1.52 (0.23)	115.55 (14.09)	0.98 (0.18)	50.67 (10.47)	-	-	-	-	2.03 (0.21)

Standard errors are indicated in parenthesis.

4.4 Discussion

4.4.1 Species of thrips trapped during the experiment

The three species of thrips [*Thrips parvisinus* Karny, *Franklinella schultzei* Trybom and *Thrips tabaci* Lindeman] identified in this study were all found on chilli and eggplant, indicating the possibility of more than one thrips species to occupy a single crop at a particular time. This result agrees with Palmer (1990) who stated that several thrips species were able to coexist in a single crop. Mixed infestation of thrips has been reported on cucumber, *Cucumis sativus* L. in Hawaii (Rosenheim *et al*., 1990) and on chilli, eggplant and bell peppers in Cameron Highlands (Tan *et al*., 2016). Thrips can occupy a wide range of ecological niches and the identified species in this study were found on different parts of the plants, including leaves, flowers and fruits. Their presence on these crops can as well be attributed to their opportunistic and polyphagous nature which allows them to feed on mixed diets to meet their nutritional requirements (Bournier *et al*., 1979; Mound and Teulon, 1995). All three species belong to the Thripidae family which are naturally known to inhabit plant tissues. Physical examination revealed silvering, scaring and wilting of the affected plant parts which are all symptoms of the damages caused by thrips, confirming their pest status. This confirms the idea that knowing the thrips species present on a crop is key in determining the appropriate method of control or specific insecticide a farmer should use. For instance, *Thrips tabaci,* unlike other thrips species, is not very susceptible to insecticides due to its ability to easily develop resistance (Gill *et al*., 2015) and care must be taken when selecting insecticides for its control.

4.4.2 Effects of host plant, sticky traps, and environmental factors on thrips species population dynamics

4.4.2.1 *Thrips parvispinus* Karny (Thysanoptera: Thripidae)

The finding of the current study indicates that *T. parvispinus* had the highest population compared to that of *F. schultzei* and *T. tabaci*, even though Fening *et al*. (2022) recently reported this species in Ghana. Invasive species can cause the extinction of local species, loss of species diversity (Badii, 2014), and are able to easily colonize new areas, especially when a suitable natural enemy is not yet identified and this could exactly be the case with *T. parvisipinus*. The results are in line with Tan *et al*. (2016) who found *T. parvispinus* as one of the most abundant species on chilli, eggplant and bell peppers in Cameron Highlands, Malaysia. In this study, *T. parvispinus* was more attracted to white compared to blue and yellow traps, with its population varying throughout the growing season. In an earlier study in Ghana, *T. parvispinus* was more attracted to blue than yellow sticky trap on ridged gourd (Fening *et al*., 2022). The specificity of sticky traps to thrips species has been documented (Chen *et al*., 2004; Broughton and Harrison, 2012; Muvea *et al*., 2014) and the attractiveness of white traps to several thrips species (*F. occidentalis*, *F. intonsa*) have been reported in many parts of the world (Yudin *et al*., 1987; Broughton and Harrison, 2012; Mao *et al*., 2018). However, the non-attractiveness of white sticky traps reported in a few other studies (Beavers *et al*., 1971; Chen *et al*., 2004) could be due to differences in the stickiness of the traps as they were locally improvised and coated with Tanglefoot (aerosol formula; The Tanglefoot Co., Grand Rapids, MI). The result of this study is particularly important for vegetable exporters and their out-growers in Ghana as they currently use yellow or blue traps for thrips monitoring. With the emergence of a new species, *T. parvispinus*, which seem to have displaced the local thrips species, exporters risk their produce being rejected if the right colour trap is not included in the overall thrips pest management plan. Although, *T. parvispinus* is not of quarantine importance at the moment, but the close resemblance of the male with *T. palmi* adult (Per. Comm. NT. Ngosong) could pose a big threat to the export of vegetables to the EU, especially as sometimes the interception is based on the order (Thysanoptera) or Family (Thripidae) (Fening *et al*., 2022). Apart from the fact that the white sticky traps were more effective in attracting more of the *T. parvispinus* adults, its effects on other non-target organisms and beneficial insects were minimal than the yellow trap, which reduces it negative impact on the environment and could be recommended for *T. parvispinus* monitoring/control by farmers.

The population of *T. parvispinus* was not affected by the tested host plants in this study. This result contradicts that of Gharekhani *et al*. (2014) who reported marked differences in the population of thrips trapped on sticky traps set on different hosts (garlic, onion and tomato). Host specificity is also thrips species-specific and *T. parvispinus* showed no preference for both crops (since the higher numbers on eggplant were not significantly different). Interestingly, its population peaked constantly during the late vegetative and flowering/fruiting stages on both crops, confirming its status as a leaf and flower-feeder. These results attest to the nutritive value of pollen enclosed within the flowers (Tsai *et al*., 1996; Allan and Gillett-Kaufman, 2018), which enhances rapid reproduction to build up such numbers. During the vegetative stage, there are several leaf buds which are very preferable for thrips leaf feeders because, in addition to their high nitrogen content, they are softer and provide a more humid microclimate (Kirk, 1995). This opportunistic characteristic of *T. parvispinus* which has also been observed by Hutasoit *et al*. (2018) means it can easily invade and infest more areas where crops are grown in Ghana if an up-to-date action plan is not taken.

The development and distribution of *T. parvispinus*, just like any other insect is dependent on environmental factors (Yadav and Chang, 2014; Karthik *et al*., 2021; Skendžić *et al*., 2021). In the first season, the fluctuation in temperature and relative humidity particularly determined the abundance and dynamics of *T. parvispinus*, especially when temperatures were averagely 28 °C and relative humidity was 65 to 75 %. However, when temperatures became very high in the dry season (averagely 35 °C), and relative humidity became high in the first season (above 80%), the population of *T. parvispinus* decreased. This confirms the non-linear relationship that exists between temperature and insect species at temperature extremes (Stinner *et al*., 1974). Important to note is the fact that during harvesting when the plants were senescing, the reduction in *T. parvispinus* population observed in the first and second cropping seasons was not only attributed to the high temperatures but also to a natural phenomenon explained by Slansky and Scriber (1985) and Kirk (1995) that ageing plants have reduced water and nitrogen content which tends to reduce their suitability to harbour thrips.

4.4.2.2 *Thrips tabaci* Lindeman (Thysanoptera: Thripidae)

The onion thrips, *T. tabaci*, a globally reported pest of several vegetables were equally found in this study but was the least abundant of the three species. Gharekhani *et al*. (2014) earlier recommended yellow traps for onion thrips monitoring, whilst several other authors (Lu, 1990; Chen *et al*., 2004; Murata *et al*., 2021) recommended blue traps for the monitoring of *T. tabaci* and other thrips species. However, in this study, none of the sticky traps was superior in attracting *T. tabaci*. The slightly higher numbers on the white and blue colours could mean these two colours are slightly preferable for this species but the fact that significant differences were not observed implies that farmers could choose any of the tested colours, after considering the environmental implication of the different colours on non-target organisms and natural enemies.

Like *T. parvispinus*, the evaluated vegetables; chilli and eggplant did not affect the abundance of *T. tabaci*. *Thrips tabaci* population fluctuated throughout the experimental period and recorded peaks during the flowering/fruiting stage with lower numbers before and after flowering. Similar findings have been reported by Allan and Gillett-Kaufman (2018) who recorded a very high thrips population during bloom in olive orchards. Aside from the nutritional value of the flower components, migrating *T. tabaci* population from neighbouring plants could also have contributed to the increase observed during this period.

The effect of weather factors significantly determined the abundance of *T. tabaci* in this study. Very high relative humidity and temperature reduced *T. tabaci* abundance and vice versa. This result agrees with Waiganjo *et al*. (2008) who found optimum temperatures of 15.6-28.2°C to increase *T. tabaci* numbers and a negative correlation with very high relative humidity.

4.4.2.3 *Franklinella schultzei* Trybom (Thysanoptera: Thripidae)

Frankiliniella schultzei was the second most abundant species after *T. parvispinus* in this study and morphological identification revealed the presence of both the dark and yellow forms. *Frankliniella schultzei* was more responsive to yellow traps in this study. In other studies, however, Muvea *et al*. (2014) and Allsopp (2010) found *F. schultzei* to be more attractive to blue than yellow sticky traps on both French beans and plums. Nevertheless, there is also evidence that this species can be attracted to yellow (Aliakbarpour and Rawi, 2011) and other trap colours such as red.

During the first season, *F. schultzei* recorded its peak at flowering on both vegetables during which temperature was optimum at 28 ºC and relative humidity was 78%. However, the lowest population was recorded during flowering in the dry season. The latter contradicts the findings by Aliakbarpour and Rawi, (2011) who observed a high population of *F. schultzei* during mango bloom. The sharp decline in the population during this period was due to the very high temperatures, above 35 ºC and very low relative humidity which negatively affected their abundance. Once these conditions passed, there was a very sharp rise in *F. schultzei* population (temperature, 34 ºC and relative humidity, 55%) which resulted in their population increasing during the fruiting stage. The importance of environmental factors such as temperature and relative humidity in determining the presence, abundance, and dynamics of *F. schultzei* in this study cannot be ignored.

4.3.3 Effects of host plant, sticky traps, and environmental factors on non-target catches

Yellow sticky traps attracted more non-targets including insects in the orders; Hymenoptera, Diptera, Coleoptera and all-natural enemies such as spiders, ladybirds, and big-eyed bugs. The abundance of natural enemies was lowest on blue followed by white traps. The results are in accordance with Chu *et al*. (2006) who reported a large number of non-target insects captured on yellow sticky traps, in addition to the targeted thrips pest, *Scirtothrips dorsalis* (Thysanoptera: Thripidae). Jacobson (1997) earlier attested that yellow sticky traps attracted several other arthropods in addition to the main pest and this justifies the preference for yellow sticky traps by farmers. Similarly, Tang *et al*. (2016) and Muvea *et al*. (2014) reported more beneficial insects including ladybird beetles and *Orius* species on yellow than on blue traps. Generally, sticky traps are composed of sticky cards with varying colours which may actively act as attractants, or passively intercept insects during flight or insects may be blown to the cards through wind transport (Samler, 2012). The trapped insects die eventually, making it a fast, low-cost, and efficient way of monitoring pest populations or mass trapping for control purposes. However, their ability to also attract unintended arthropods including biocontrol agents makes them unsustainable environmentally or poses biodiversity concerns. Nonetheless, the selectivity of sticky traps can be improved by adding semiochemicals such as pheromones to ensure that only targeted insects are trapped (Akella *et al*., 2014; Muvea *et al*., 2014). However, with regards to thrips, only pheromones for a few thrips species have been developed and are available commercially, making the use of sticky traps still a potential threat to biodiversity.

The tested host plants did not affect the population of non-target insects. The higher abundance of these arthropods in the second than the first season could be due to the very few natural enemies observed in the second season.

4.5 Conclusion

Efficient monitoring is the cornerstone of integrated pest management (IPM) strategies, reducing the need for chemical controls and supporting sustainable agricultural practices. This study aligns with existing research that different species of thrips are attracted to specific colour of sticky traps. Whilst white traps are recommended in this study for effective monitoring of the thrips population, it is crucial to consider the thrips species in question. Blue and white traps attracted fewer non-target insects compared to yellow traps. The effect of the host plant did not affect the thrips population significantly in this study and environmental factors significantly influenced the abundance of thrips species and other non-target abundance, with different species responding differently to these factors. Optimum temperatures and relative humidity of 28 to 31 ºC and 60 to 78 %, respectively showed a linear relationship between the trapped insects with temperature and RH, whilst extreme environmental factors negatively affected their abundance. Integrating these findings can enhance the effectiveness and timely implementation of IPM strategies, making them more responsive and adaptable to specific pest situations and climatic conditions.

CHAPTER FIVE

5.0 DEVELOPMENTAL POTENTIAL OF THE SOUTH-EAST ASIAN THRIPS, THRIPS PARVISPINUS KARNY (THYSANOPTERA: THRIPIDAE) UNDER DIFFERENT TEMPERATURE REGIMES

5.1 Introduction

Thrips parvispinus (Thysanoptera: Thripidae), native to Asia is a serious pest of vegetables such as chillies and eggplant in the tropics (Vos *et al*., 1991; Soto-Adames, 2020). Its damage has resulted to yield losses of 85-100%, and 23%-85% on chilli peppers in India and Indonesia, respectively (Johari *et al*., 2014; Prasannakumar *et al*., 2021; Sridhar *et al*., 2021). Furthermore, it was considered a pest of quarantine significance whose introduction to new areas was restricted before the year 2000. However, its interception at the US port in 2006 and its recent damage potential indicate a possibility of restoring its quarantine status in the future. It has since spread from Asia to other parts of the world (Mound and Collins, 2000), including Africa, with reported cases in Tanzania, Uganda, and Reunion (EPPO, 2000; Soto-Adames, 2020). This invasive species has been recently reported for the first time in Southern Ghana as the dominant species attacking ridged gourd from six exporters farms (Fening *et al*., 2022). In addition, a current comprehensive study on the diversity of thrips in Ghana identified *T. parvispinus* as the dominant thrips species infesting and causing damage to several economic crops such as chillies, gourds, and eggplant (Nkafu *et al*., 2024; Nkafu *et al*., unpublished). A recent survey across Ghana also revealed that *T. parvispinus* was the main thrips species found on many food crops and ornamental plants (Per. Comm KO. Fening).

In addition to the availability of suitable host plants, the distribution of *T. parvispinus*, just like other insect pests is regulated by environmental factors such as temperature which influence their biology (Yadav and Chang, 2014; Karthik *et al*., 2021). Temperature is the single most important environmental factor that influences insect development, survival, reproduction, and distribution (Bale *et al*., 2002; Skendžić *et al*., 2021). Its effect is currently unpredictable, especially in the era of climate change where global temperatures have been predicted to increase by 1.4-5.8 ℃ by 2100, in addition to increased frequency and intensity of extreme events (IPPC, 2001; Bale *et al*., 2002). Specifically, based on the climate scenario, it was realised that temperatures will rise by 2.1-2.4 ºC in Northern Ghana, 1.7-2.0 ºC in Ashanti, Western, Eastern, Central and Volta regions and 1.3-1.6 ºC in Bono, Bono East, and Ahafo regions of Ghana by 2050 (Asante and Amuakwa-Mensah, 2015). This increase will certainly aggravate *T. parvispinus* damage activity as tropical conditions are already favourable for its development and might result in range expansions, disruption of pest-natural enemy synchrony, and facilitated development which promotes several generations per year (Hong *et al*., 2019).

Generally, each insect species has an optimum temperature range within which development is fastest and a lower and upper temperature beyond which development will fail to occur (Stinner *et al*., 1974; Briere *et al*., 1999; Yadav and Chang, 2014). Studying the biology of an insect under wider temperature conditions is useful in understanding the dynamics of its population; assessing survivors at different stages and determining optimum, lower, and upper-temperature thresholds (Gutierrez e*t al*., 2007; Yadav and Chang, 2014) for development of each life-stage. However, the biology of *T. parvispinus* has only been studied by a few authors (Hutasoit *et al*., 2018) and its relationship to temperature remains understudied. Therefore, it is paramount to understand the relationship between temperature and the population growth potential of the invasive *T.*

parvispinus, especially in Ghana where it has newly been detected. The main objective is to study the biology of *T. parvispinus* and provide the thermal requirements of different life stages under varying temperature conditions.

The thermal requirements (such as the lower and upper temperature threshold, optimum developmental temperature and thermal constant k) and demographic parameters of an insect is estimated using linear regression models (Nielson *et al*., 2008) and non-linear models such as Sharpe and DeMichele, Hilbert and logan, Wang and logan models, among others (Logan *et al*., 1976; Sharpe and DeMichele, 1977; Wang *et al*., 1982) which are better predictor of insect development at extreme temperatures. Thermal requirements allow for the development of temperature-based models used to calculate life table parameters (Azrag *et al*., 2017), map out population indices (Tonnang *et al*., 2013) and predict pest distributions under different scenarios (Khadioli *et al*., 2014). The information generated in this study will help us to understand the biological parameters of *T. parvispinus* and to develop a temperature-dependent phenology model which will better inform decision-making on the timing of agroecological specific pest management interventions for this pest, in the context of climate change.

5.2 Materials and methods

The experiment was carried out in the Biotechnology Research Centre of the School of Agriculture at the University of Ghana, Legon, located in Accra, Ghana (Plate 5.1).

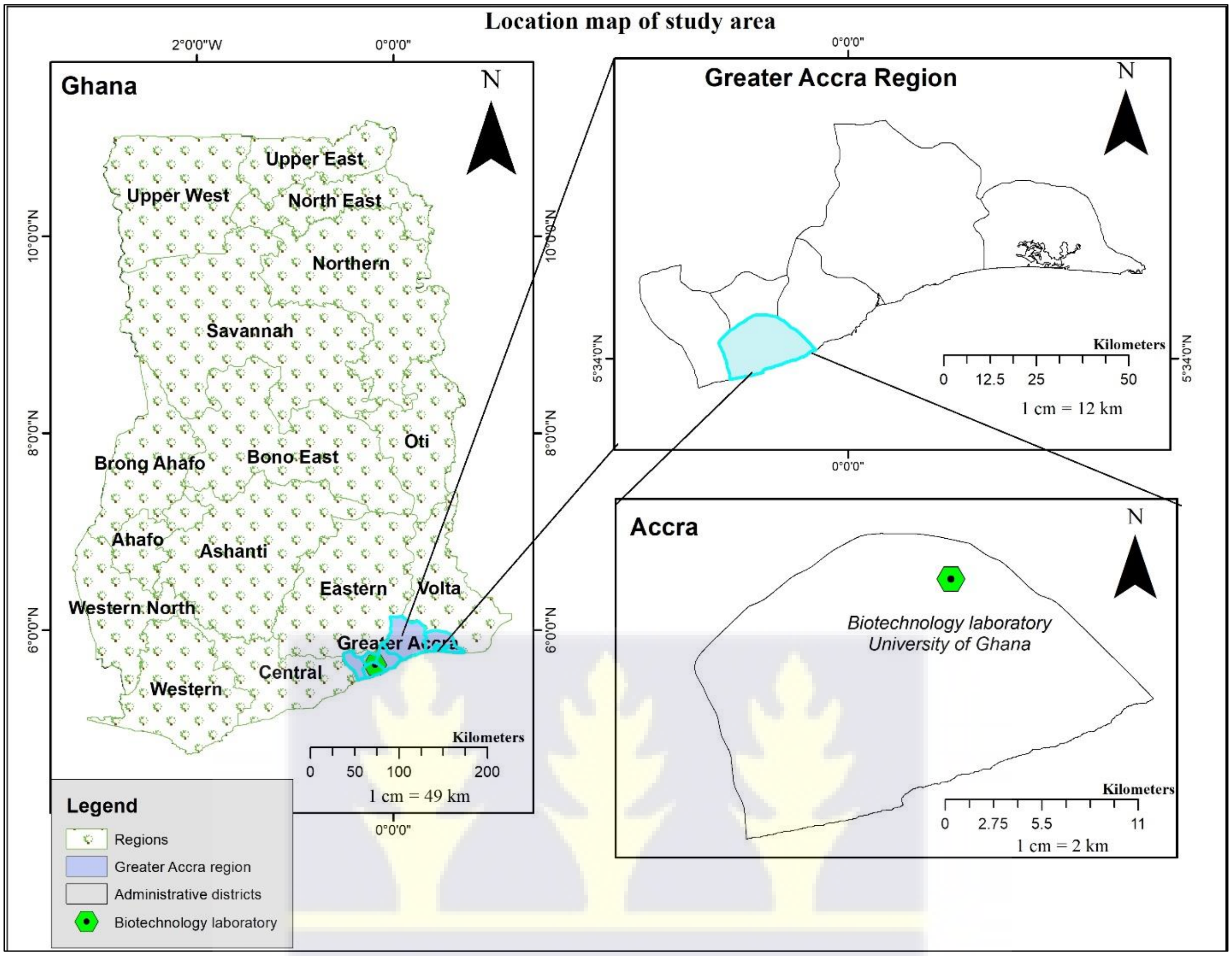


Plate 15. Map of study location.

5.2.1 Establishment of *Thrips parvispinus* culture

Adult males and females of *T. parvispinus* collected from chilli-infested plants in Tuba (latitude 5.50599, longitude -0.405303) were cultured on 6 weeks old eggplant leaves initially planted in plastic polybags in the greenhouse. The culture was maintained at room temperature (27±2 °C), relative humidity of 65%-80% and photoperiod of L12:D12 h. Moisten camel hairbrushes were used to place adults on leaves in small white plastic cups (diameter = 6.5 cm and height = 3.5 cm) (Plate 5.2). The bottom was lined with moist filter paper, 22.5 cm long and 12.5 cm wide, and folded thrice to prevent leaves from drying out. The insects in the cups were closed with tightfitting plastic lids whose tops were perforated with tiny insect pins (thickness = 2 mm, length = 1.5 cm) to allow sufficient aeration. The closed cups were sealed with sellotapes to prevent the escape of the insects, labelled and place in the incubator. New eggplant leaves were provided at 4 days intervals when the old ones showed signs of deterioration and/or drying out. At the end of the second larval instars, the larvae were transferred to separate cups lined with five folds of tissue paper as pupation sites with no leaves. Adults that emerge from here were transferred to new leaves to oviposit for the circle to continue.

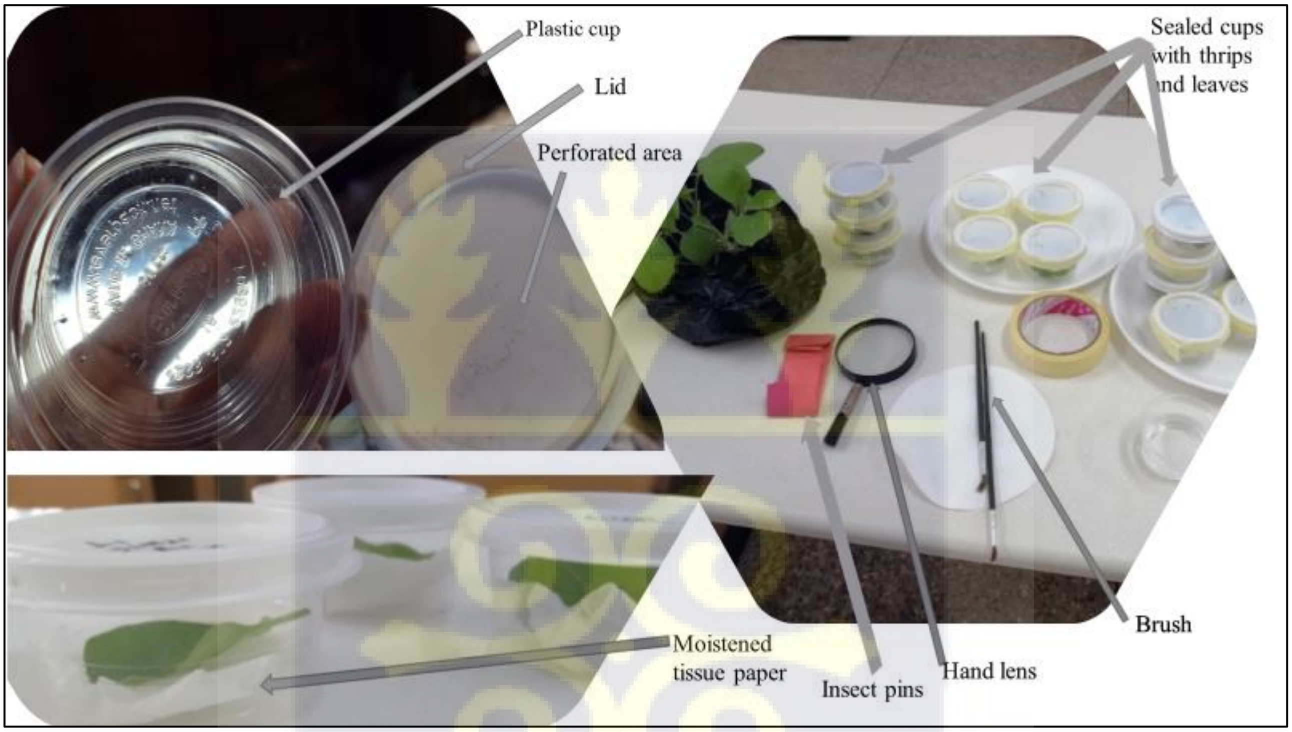


Plate 16. Experimental setup with materials used for thrips rearing.

5.2.2 Cohort life table studies

5.2.2.1 Experimental conditions

The effect of temperature on the development, survivorship, mortality, and oviposition were studied on cohorts of single life stages of *T. parvispinus* in controlled incubators at six constant temperatures (15 ºC, 20 ºC, 25 ºC, 30 ºC, 35 ºC and 40 ºC). The photoperiod was kept at 12L:12D and the relative humidity was 70±5. The temperature and relative humidity in the incubators were regularly monitored with data loggers.

5.2.2.2 Effect of temperature on the development time and survival of eggs, larvae, and pupae

Eggplant leaves exposed to the stock culture for <24 h were examined under a dissecting microscope for egg count, divided into two and placed in cups whose bottoms were covered by water-soaked tissue paper to prevent desiccation of eggs and leaflets (Yadav and Chang, 2012b), and placed in the incubators. The duration of egg development was determined by the appearance of the larvae. After hatching, a group of 30 newly emerged first instar larvae (<24 h old) were transferred into cups containing a single six-week-old leaf, covered with a lid, and sealed with Sellotape as described in section 5.2.1 (Plate 5.3). The experiment was replicated ten times with a total of 300 first instar larvae being observed at each temperature. The insects were monitored daily with a magnifying lens (Hama Lupe "Basic 75", rund, Durchmesser: 75 mm) for development and survival until each individual in a cohort died or moved to the next stage. A similar procedure was followed for the cohorts of the second larval instars, the propupa and the pupa stages. However, each cohort had a group of 25-second instar larvae, 20-propupae and 18 pupae, respectively with ten replications for each temperature. Rather than using eggplant leaves, tissue paper was used as substrate for pupation at the propupal and pupal stages.

Plate 17. (a) Daily monitoring of thrips development, (b) assessed cups containing thrips, (c) plastic cups containing thrips placed at 25 ºC and (d) plastic cups containing thrips placed at 30 ºC.

5.2.2.3 Effect of temperature on oviposition and longevity of adults

Six pairs of *T. parvispinus* adult males and females (<24 h old) were placed on a six-week-old eggplant leaf in each cup, lined with moist tissue paper and kept at the respective temperatures with five replications. Therefore, a total of 60 adult males and females were examined at each temperature, with the same conditions as above. The leaves containing laid eggs were replaced daily until all individuals in a cohort died. Longevity was recorded for males and females. A light under the glass stage of a dissecting microscope was used to view and count thrips' eggs in the leaves (Trichilo and Leigh, 1988).

5.2.2.4 Effect of temperature on *Thrips parvispinus* under fluctuating conditions

A similar procedure as sections 5.2.2.2 and 5.2.2.3 was repeated for a separate experiment under fluctuating temperatures at the School of Agriculture, Biotechnology Centre and the development time, longevity, mortality and oviposition of the cohort insects were monitored with observations recorded daily. The temperature was recorded daily with EasyLog USB Data Logger (temperature/relative humidity, EL-USB-2). This was done to confirm if the developed model can predict thrips phenological events with accuracy under fluctuating field conditions.

5.2.3 Identification of life stages

The different life stages, 1st instar larvae, 2nd instar larvae, propupae, pupae and adults were identified based on morphological characteristics reported by Palmer (1990), at the School of Agriculture, Biotechnology Research Centre, University of Ghana. Adult females were distinguished by their brown heads with black abdomens, whilst males were completely yellow in colour (Plate 5.4).

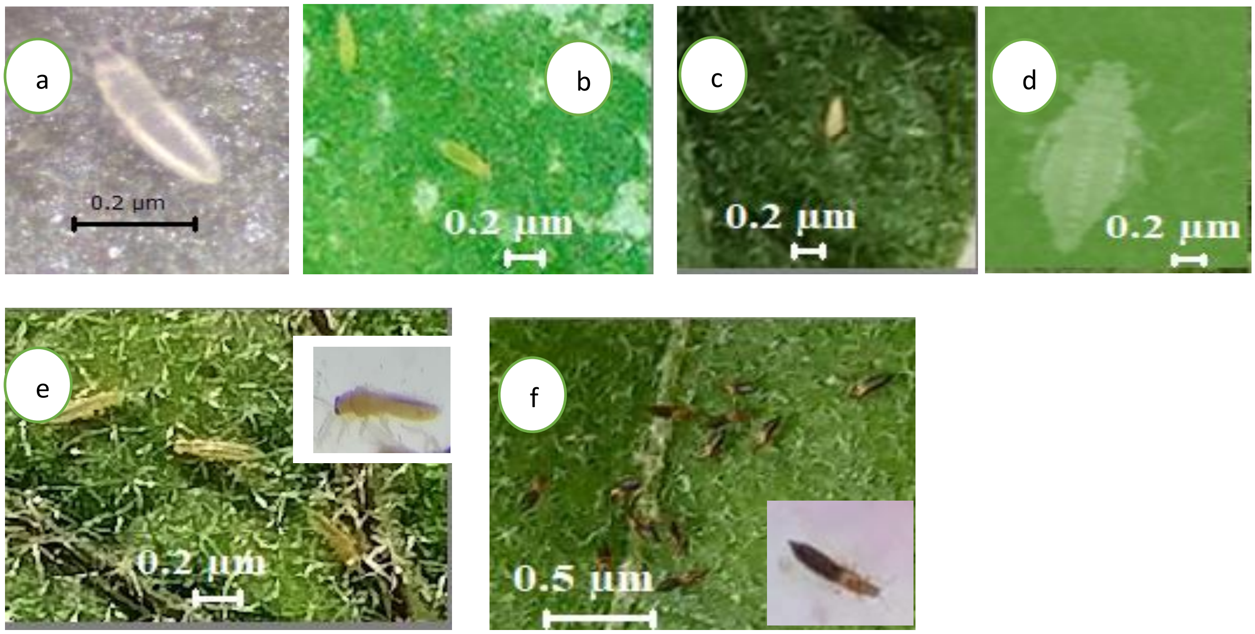


Plate 18. Life stages of *Thrips parvispinus* identified during the experiment. (a) 1st instar larva, (b) 2nd instar larva, (c) propupa, (d) pupa, (e) adult male, and (f) adult female.

5.2.4 Data analysis and model parameter fitting for *T. parvispinus*

The life table data collected in this study was used to develop a temperature-dependent phenology model for *T. parvispinus* using the insect Life Cycle Modelling (ILCYM) software (Version 3.0). ILCYM is a software package used for developing temperature-based phenology models with applications for local, regional and global analysis of insect populations and mapping (Tonnang *et al*., 2013). In this study, two modules of ILCYM were used: the “model builder” component for developing the phenology model and the “validation and simulation” module for estimating the life table parameters. In the model builder component, a number of linear and non-linear models are fitted to critically explain the effect of temperature on the development of an insect. It has in-built statistical criteria which combine the knowledge of the biology of the species under investigation to facilitate the best fitting function to describe the temperature-driven process and further combine the process into a phenology model for the investigated species (Tonnang *et al*., 2013). These criteria are Akaike's Information Criterion (AIC), which defines the goodness of an estimated statistical model and the coefficient of determination R^2, which is the proportion of variability explained by the model.

On the other hand, the validation and simulations module demonstrate the ability of the model to estimate phenological events in the lifecycle of the species under constant and fluctuating temperature conditions.

5.2.4.1 Development time and its distribution

The distribution of the development time of an insect under different temperatures is assumed to be the same shape for a normal distribution (Sharpe *et al*., 1977). Therefore, the data on development times were log-transformed to normalize the distribution (Fand *et al*., 2014).

To account for variability among individuals in a cohort, the concept of rate summation was used. The normalized data was arranged into a frequency distribution and the cumulative density function was applied to describe the relation between temperature and cumulative development time relative frequency (Tonnang *et al*., 2013). The cumulative frequencies of development of each life stage were plotted against the normalized development time by fitting a complementary log-log (CLL) distribution curve for the egg and first instar stages, a logit distribution for the second instar larval and the propupal stages, and a normal (probit) distribution for the pupa stage. Mathematically, the models or distribution functions are expressed as follows (Tonnang *et al*., 2013).

CLL distribution: $F(x) = 1 - \mathrm{Exp}(-\mathrm{Exp}(ai + \mathrm{b}\ln x)$ (1)

Logit distribution: $F(x) = \frac{1}{1+Exp(-(ai+b\ln x)}$ (2)

Probit distribution: $F(x) = \emptyset(ai + b\ln x)$ (3)

where, F(x) is the probability to complete development at time x, lnx is the natural logarithm of the days observed, a is the intercept corresponding to temperature i, and b is the common slope of the regression model.

5.2.4.2 Development rate

The non-linear relationship between temperature and development rate (1/development time) was described by the Logan, Sharpe and DeMichelle, and Allahyari models (Logan *et al.*, 1976; Sharpe and DeMichele, 1977) using the Marquardt algorithm. The Logan 1 model was fitted to the egg and propupal data, Sharpe and DeMichele and Allahyari models were fitted to the first and second instars, respectively, and the Hilbert and logan model was fitted to the pupal data. The mathematical expression for models is given as:

Logan 1: $r(T) = Y\left\{Exp\,(pT) - Exp\,\left(pTmax - \frac{Tmax-T}{V}\right)\right\}$ (4)

where r(T) is the rate of development at temperature T; Y, ρ and V are constants. The linear relationship between temperature and development rate was described by a linear regression model of the form:

$$r(T) = a + bT \qquad (5)$$

where r(T) is the development rate at temperature T, and, a and b represent the intercept and the slope of the regression line, respectively. The lower development threshold (T_{min}) which is defined as the temperature below which there is no measurable development were estimated using: T = -a/b, whilst the thermal constant k (in degree days) was calculated using k = 1/b (Azrag *et al.*, 2017).

Sharpe and DeMichele: $r(T) = \frac{P\frac{T}{T_0}Exp^{\left[\frac{Ha}{R}\left(\frac{1}{T0}-\frac{1}{T}\right)\right]}}{1+Exp\left[\frac{Hh}{R}\left(\frac{1}{Th}-\frac{1}{T}\right)\right]}$ (6)

where, r(T) represents the rate of development at temperature T (ºC), P is the development rate at optimum temperature To (ºC) assuming no enzyme inactivation, R is the universal gas constant

(1.987 cal degree^{-1} mol^{-1}), Ha is the enthalpy of activation of reaction catalysed by enzyme (cal mol^{-1}), Hh is the change in enthalpy at high temperature (cal mol^{-1}), and Th is the high temperature at which enzyme is half active.

Allahyari: $r(T) = p\left[\left(\frac{T-Tmin}{Tmax-Tmin}\right)^{n}\right]\left[1-\left(\frac{T-Tmin}{Tmax-Tmin}\right)^{m}\right]$ (7)

where, r(T) represents the rate of development at temperature T (°C), T_{max} and T_{min} are the maximum and minimum temperatures, respectively, P is the development rate at maximum temperature and n and m are model parameters.

Hilbert and Logan: $r(T) = \psi\left(\frac{T^2}{T^2+D} - Exp^{\left(Tmax-\frac{T}{Dt}\right)}\right)$ (8)

Where r(T) represents the development rate at temperature T, T is the temperature in degree Celsius, ψ and D are constants to be determined, and Dt determines the width of the upper boundary in which rates begin to decline rapidly.

5.2.4.3 Immature mortality

The survival rate of immature life stages was calculated from the cumulative frequency of cohort survivors and the mortality rates were estimated by the one-survivorship. The effect of temperature on the mortality of *T. parvispinus* immature life stages were fitted to the Wang model 7 for the egg data, polynomial model 4 for the first larval instar, Weibull function for the second instar, Wang model 5 for the propupa and the Marc model for the pupa stage (Wang *et al.*, 1982). Mathematically, the fitted functions are stated below.

Wang 7: $m(T) = 1 - \frac{H}{Exp\left\lfloor\left(1+Exp\left(-\frac{T-Topt}{B1}\right)\right)\left(1+Exp^{\left(\frac{Topt-T}{Bh}\right)}\right)\right\rfloor}$ (9)

Polynomial model 4: $m(T) = Exp^{\mathrm{b1+b2*T+b3}\sqrt{T}}$ (10)

Weibull: $m(T) = a * (|T-B|)^{n}$ (11)

Wang 5: $$m(T) = 1 - \frac{H}{Exp^{\left[\left(1+Exp\left(-\frac{T-Topt}{B}\right)\right)\left(1+Exp^{\left(-\frac{Topt-T}{B}\right)}\right)\right]}} \qquad (12)$$

Marc: $$m(T) = \left(1-Exp^{-Exp^{(a1+b1T)}}\right) + \left(1 - Exp^{-Exp^{(a2+b2T)}}\right) \qquad (13)$$

where, *m(T)* is the mortality rate at temperature T (ºC), Topt is the temperature optimum for survival (ºC), and B, H, B1, Bh, b1, b2, b3, a1, a2 are the fitted parameters to be estimated.

5.2.4.4 Longevity and oviposition of adult

The mean survival time was determined for both adult male and female. The inverse of the mean survival time was plotted against temperature and the cubic (Tanigoshi) and Wang-Lan-Ding models (Wang *et al*., 1982) were fitted to describe the relationship between temperature and longevity (senescence) of *T. parvispinus* adult female and male, respectively. The equations are given as:

Tanigoshi: $$r(T) = a_0 + a_1T + a_2T^2 + a_3T^3 \qquad (14)$$

Where, r(T) is the rate of senescence at temperature T (ºC), a_0, a_1, a_2, a_3 are the parameters of the model.

Wang-Lan-Ding: $$r(T) = k\frac{\left(1-Exp^{-a(T-T_{min})}\right)\left(1-Exp^{b(T-T_{max})}\right)}{1+Exp^{-r(T-C)}} \qquad (15)$$

Where, r(T) is the senescence rate at temperature T (ºC) and k, a, and c are model parameters.

The effect of temperature on the total number of eggs laid per adult female was described by the Simple gaussian function of the form:

$$f(T) = y0 + aExp^{-\frac{1}{2}\left(\frac{T-T_0}{b}\right)^2} \qquad (16)$$

Where, f(T) is the fecundity at temperature T (ºC), and yo, a and b are model parameters.

The exponential modified function was used to describe the relative oviposition (the age-specific oviposition rate) at each of the tested temperatures. The cumulative oviposition rate was plotted against normalized female age which is the age in days divided by the mean survival time. The expression is given as:

$$l(T) = 1 - Exp^{-aT^b} \qquad (17)$$

where, *l(T)* is the relative oviposition at temperature T (ºC), and a and b are the parameters of the equation to be estimated.

5.2.4.5 Life-table parameters

The life-table parameters were as well assessed. The gross reproductive rate (GRR), mean generation time (T), net reproduction rate (Ro), finite rate of increase (λ), intrinsic rate of natural increase (rm), and doubling time (Dt) was calculated for *T. parvispinus* using the 'stochastic simulation tool' in ILCYM (Curry *et al*., 1978). These estimates were based on the developed phenology model at the five-tested constant temperatures with ten repetitions of each. Forty degrees (40 °C) was not used for the simulation since the insect did not survive to the adult stage. An initial number of 100 individuals were used for simulation at each constant temperature (Khadioli *et al*., 2014). The life table parameters simulated were subjected to a one-way analysis of variance (ANOVA) and post hoc multiple comparisons using the Tukey test at 5% probability was used to separate means when significant differences were observed.

5.2.5 Validation of the phenology model

The developed model was validated by comparing the life table data obtained under fluctuating temperature studies with the model outputs from the constant temperatures study using stochastic simulation (Fand *et al*., 2014).

5.3 Results

5.3.1 Development time and its variation

The tested temperatures had a significant influence on the mean development time of the life stages of *T. parvispinus* ($P < 0.0001$) (Table 5.1). The mean development time generally decreased with increasing temperature for all life stages. The mean egg development time varied from 8.46 ± 0.16 days at 15 ºC to 1.82 ± 0.04 days at 35 ºC with a few hatching at 40 ºC. The mean developmental time for the first larval instar was 2.5 times shorter at 30 ºC than at 15 ºC, with the shortest development time at 35 ºC (1.66 ± 0.03), whilst at 40 ºC, it failed to develop to the next stage (Table 5.1). The development of the second instar was five times shorter at 25 ºC and 30 ºC than at 15 ºC. Similarly, both the propupa and pupa stages had two times and four times shorter mean development times at 30 ºC than at 15 ºC, respectively. It took much longer (37.7 days) for *T. parvisinus* to develop from the egg to the adult at 15 ºC compared to any other temperature. This time was shorter at 25 ºC, 30 ºC and 35 ºC, where development was much faster (Table 5.1). Adult longevity was the longest at 15 ºC with 14.54 and 11.21 days for the adult female and male, respectively. This was shortened to 4.84 and 2.95 days at 35 ºC for both females and males, respectively. Therefore, the adult females lived longer than the males at all temperatures.

The variability in the development of each immature life stage of *T. parvispinus* was better described by the complementary log-log, the probit and the logit models for the different life stages (AIC = 1124.45, 200.37, 110.00, 65.81, 137.46 and R^2 = 0.94, 0.99, 0.99, 0.98, 0.92, for the egg, first instar, second instar, propupa and pupa stages, respectively) (Figure 5.1). The slopes calculated for the different life stages were significant ($P < 0.0001$) (Table 5.2).

Table 9. Estimated mean development time and survival of *T. parvispinus* life stages at different constant temperatures.

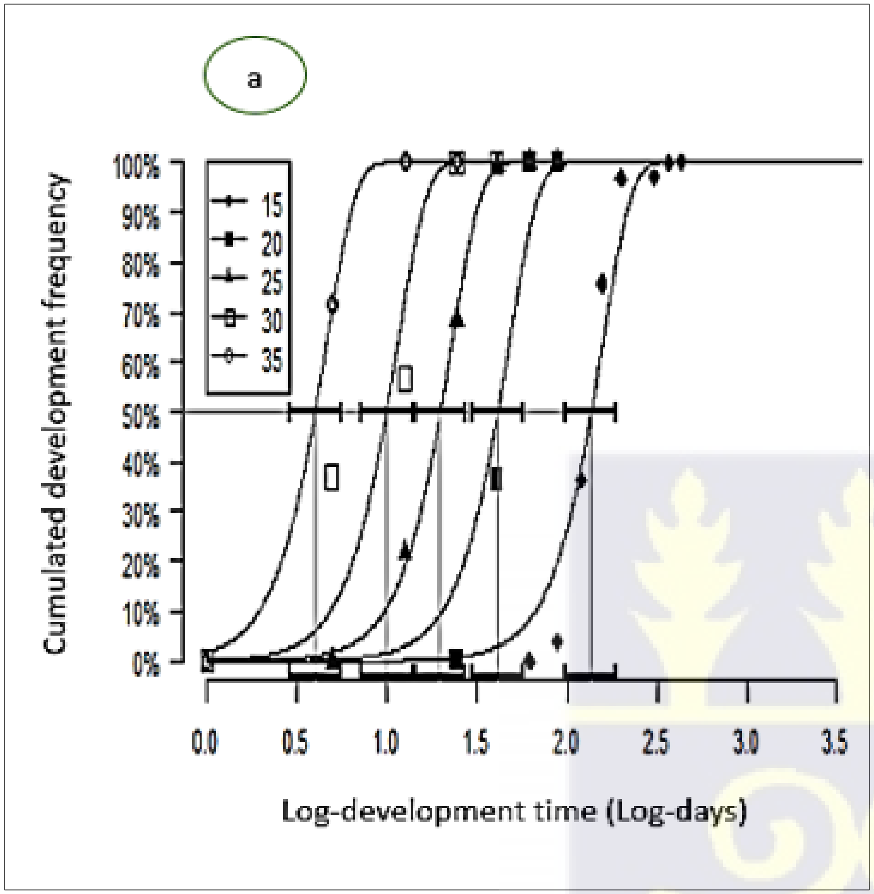
Temperature (ºC)	Immature stages											Adult longevity	
	Egg		1st instar		2nd instar		Propupa		Pupa		Egg to adult	Female	Male
	Mean development time (days)	Survival (%)	Mean development time (days)	Survival (%)	Mean development time (days)	Survival (%)	Mean development time (days)	Survival (%)	Mean development time (days)	Survival (%)	Mean development time (days)	Mean survival time (days)	Mean survival(days)
15	8.46 (0.16)	45.60	4.35 (0.08)	44.30	11.06 (0.01)	23.30	3.46 (0.08)	18.00	10.39 (0.15)	1.00	37.72 (0.48)	14.54 (0.06)	11.21 (0.08)
20	5.04 (0.08)	68.00	2.13 (0.05)	68.00	6.64 (0.06)	25.50	2.41 (0.03)	64.50	4.05 (0.09)	28.90	20.27 (0.31)	10.61 (0.05)	8.48 (0.06)
25	3.66 (0.07)	90.00	2.79 (0.06)	90.00	3.05 (0.05)	62.40	1.83 (0.04)	92.60	2.48 (0.06)	63.90	13.81 (0.28)	8.88 (0.05)	5.80 (0.05)
30	2.71 (0.06)	96.80	1.76 (0.04)	97.20	1.74 (0.02)	63.20	1.77 (0.03)	78.70	2.05 (0.05)	88.90	10.03 (0.20)	8.36 (0.04)	3.90 (0.04)
35	1.82 (0.05)	19	1.66 (0.03)	19.00	1.69 (0.02)	34.00	1.57 (0.02)	51.50	2.10 (0.06)	33.30	8.84 (0.18)	4.84 (0.03)	2.95 (0.05)
40	1.50 (0.01)		-	-	-	-	-		-		-	-	

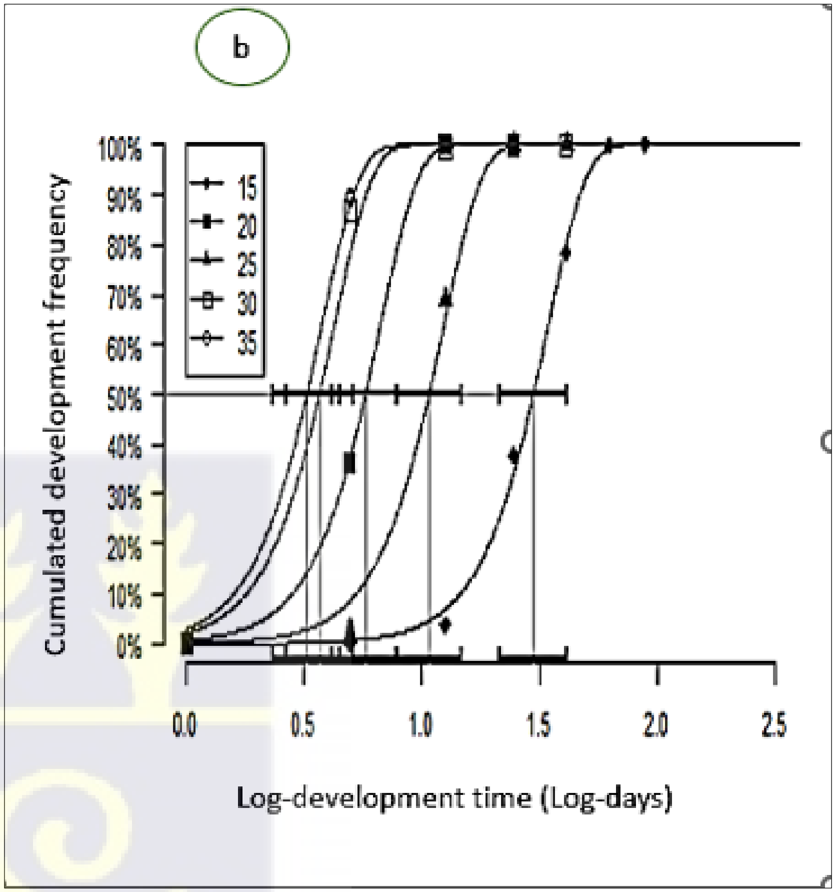
Standard errors are indicated in parenthesis.

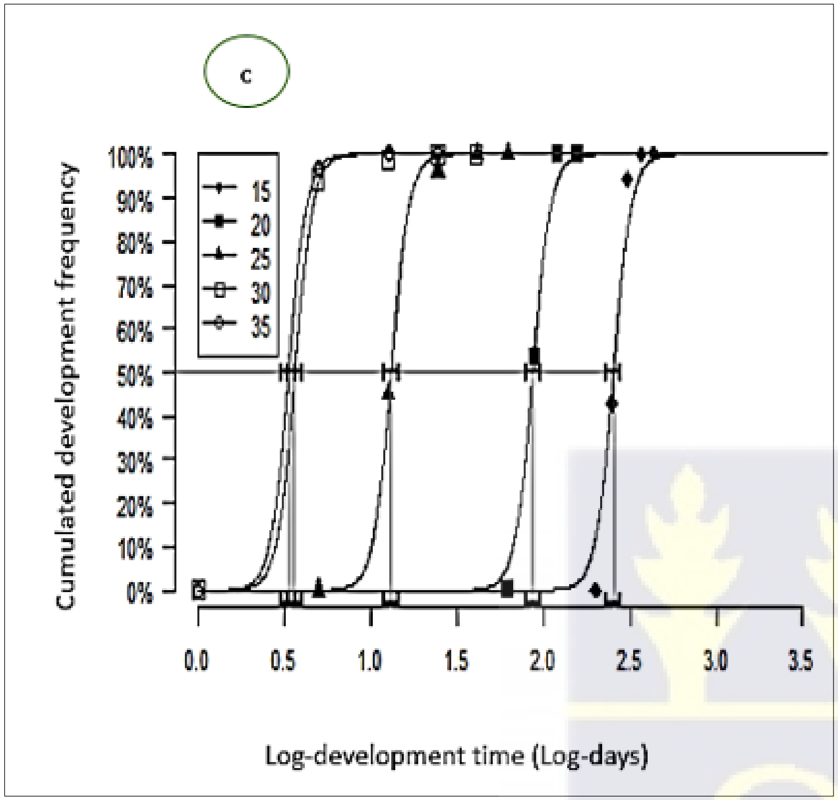
Table 10. Estimated parameters of the distribution functions fitted to normalized development time frequencies for immature life stages of *T. parvispinus*. Fitted functions: CLL model (egg and 1st instar), logit model (2nd larval instar and propupa), and probit model (pupa).

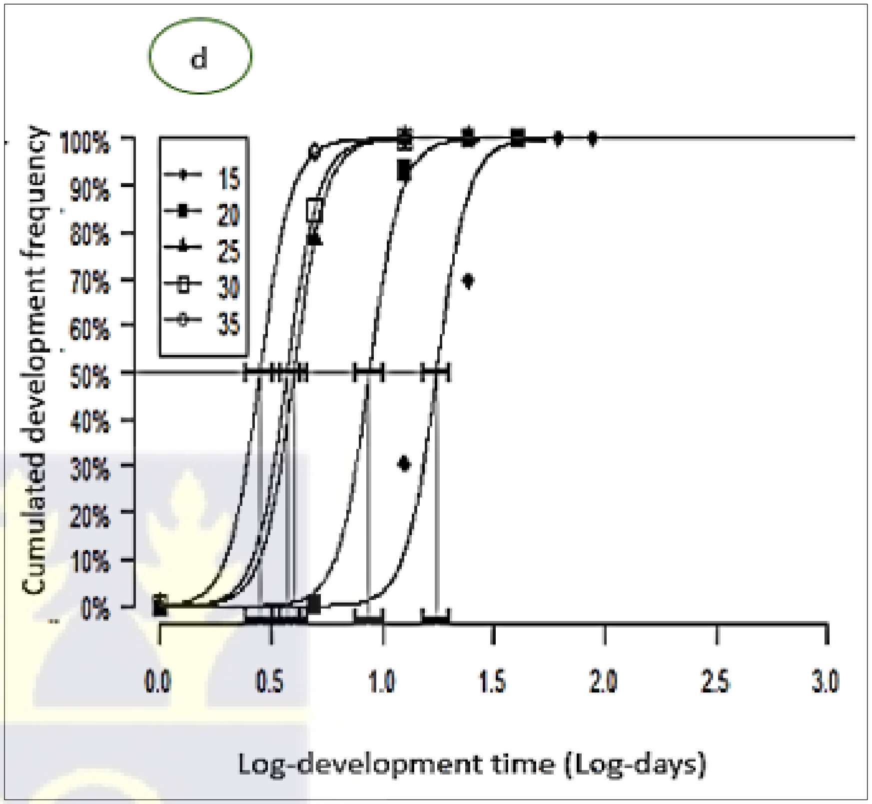
Temperature (°C)	intercepts (ai)						Slope (b)	AIC	R^2
Life stage	15	20	25	30	35	40			
Egg	-13.29 (0.26)	-10.14 (0.21)	-8.21 (0.17)	-6.39 (0.13)	-4.10 (0.13)	-2.00 (0.010	6.05 (0.12)	1124.45	0.94
1st instar	-9.31 (0.35)	-4.98 (0.19)	-6.62 (0.25)	-3.79 (0.16)	-3.47 (0.22)	-	6.09 (0.22)	200.37	0.99
2nd instar	-46.31 (3.94)	-37.33 (3.18)	-21.51 (1.81)	-10.76 (1.17)	-10.05 (1.27)	-	19.27 (1.63)	110.0	0.99
Propupa	-17.562 (1.41)	-13.26 (1.13)	-8.48 (0.78)	-8.05 (0.80)	-6.32 (0.90)	-	14.10 (1.09)	65.81	0.98
Pupa	-10.19 (0.62)	-5.22 (0.30)	-3.95 (0.23)	-3.12 (0.19)	-3.23 (0.22)		4.35 (0.23)	137.46	0.92

Standard errors are in parenthesis.


a
Cumulated development frequency
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
15
20
25
30
35
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
Log-development time (Log-days)


b
Cumulated development frequency
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
15
20
25
30
35
0.0
0.5
1.0
1.5
2.0
2.5
Log-development time (Log-days)


c
Cumulated development frequency
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
15
20
25
30
35
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
Log-development time (Log-days)


d
Cumulated development frequency
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
15
20
25
30
35
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Log-development time (Log-days)

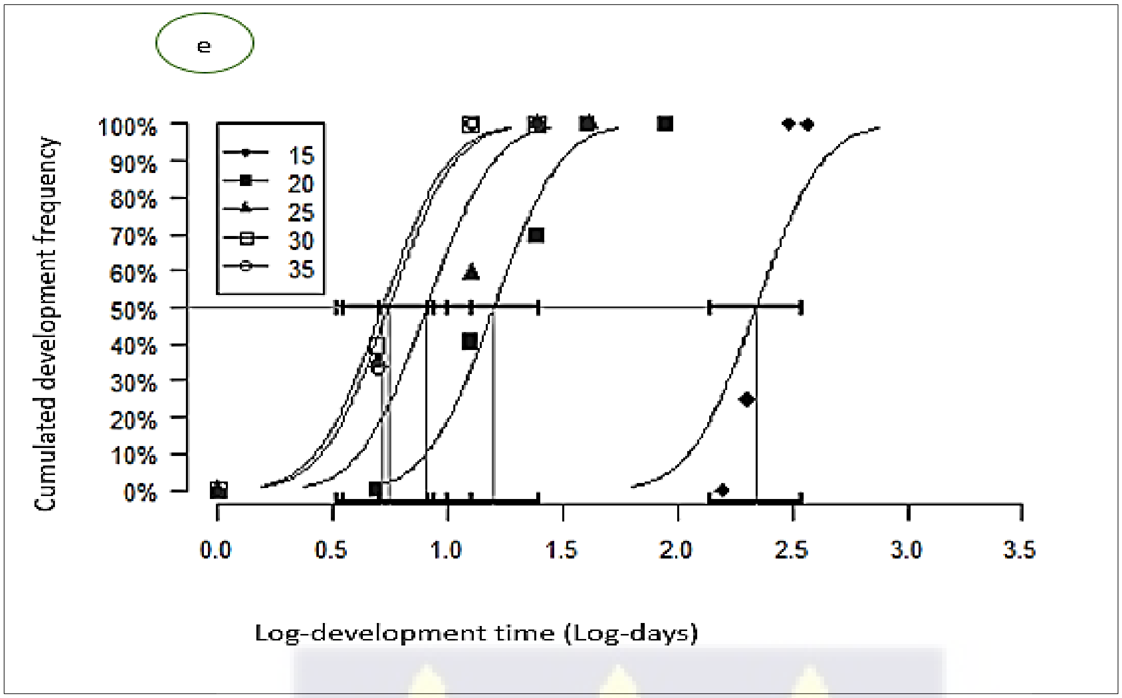
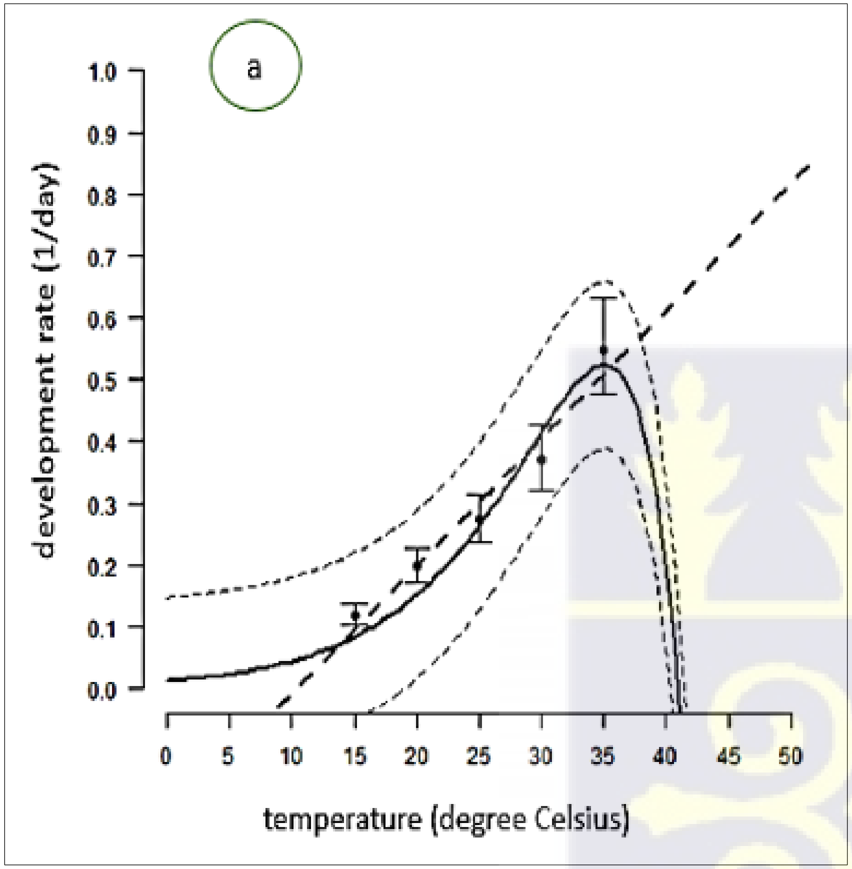


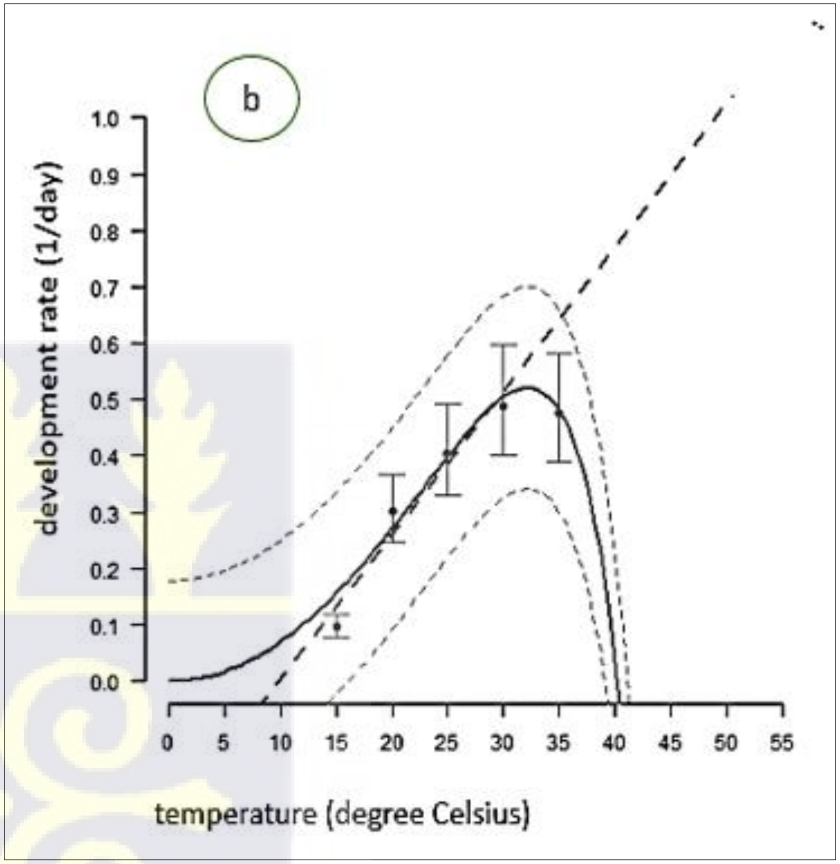
Figure 5.1. Cumulative development frequencies of *Thrips parvispinus* life stages, (a) eggs, (b) first larval instar, (c) second larval instar, (d) propupa, and (e) pupa. The bars indicate 95% confidence intervals for median development rates.

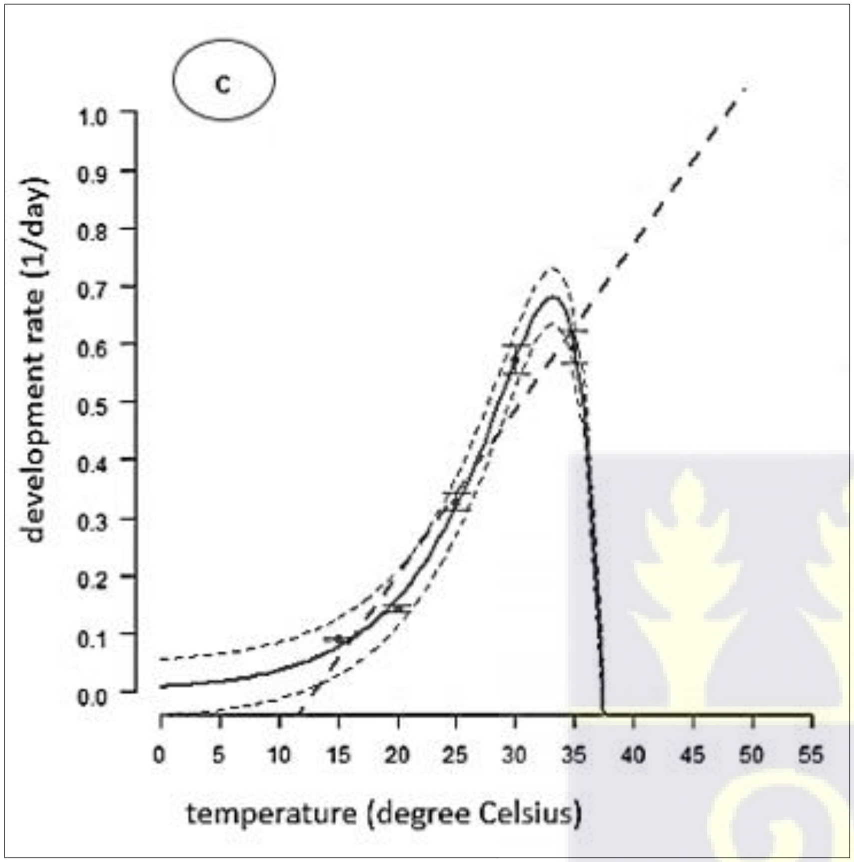
5.3.2 Development rate

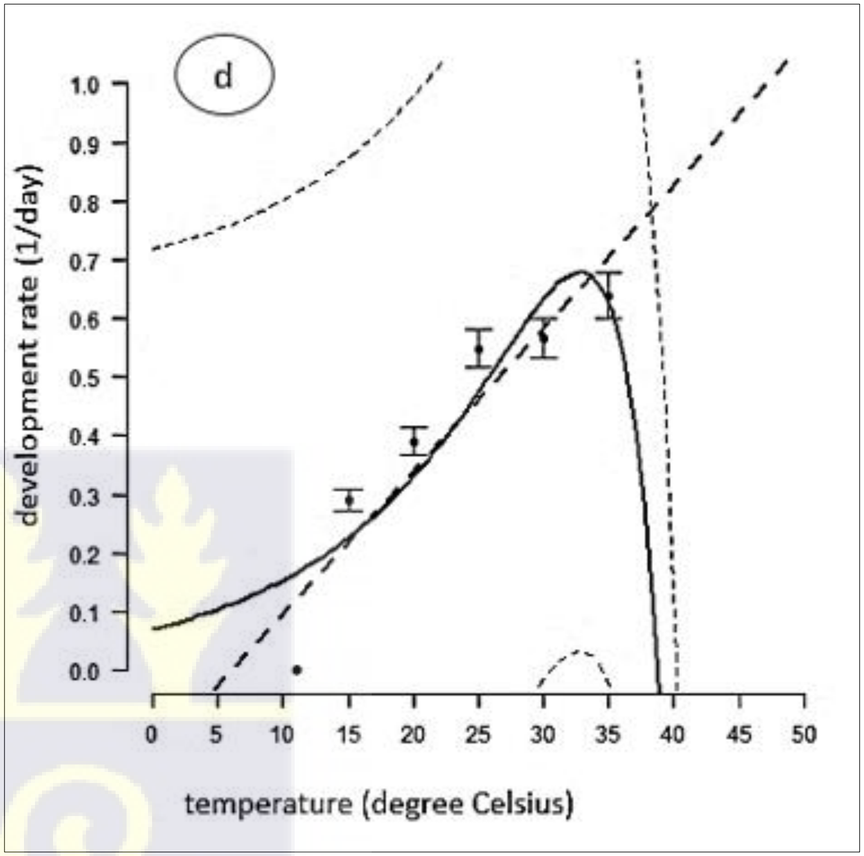
The relationship between temperature and development rate was well described by the linear models (R^2 between 0.82-0.96, AIC between -9.54-15.18). Apart from the egg stage, the thermal constant (k) increased with the age, with 33.33DD for the first instar and 45.54DD for the pupa stage. The estimated lower development threshold temperatures from the linear regressions were 10.19, 8.00, 12.83, 5.04 and, 9.36 ºC for the egg, first instar, second instar, propupal and pupal stages, respectively (Table 5.2).

The non-linear Logan, Sharpe and DeMichele and Hilbert and Logan models allowed precise estimation of the predicted drop-in development rates at higher temperatures (Table 5.3, Figure 5.2). The temperature for the shortest development time was estimated from the non-linear model curve peaks for egg, first instar, second instar, propupa and pupa to be 35.5, 33, 36, 36.5 and 34.5°C, respectively.


a
development rate (1/day)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
5
10
15
20
25
30
35
40
45
50
temperature (degree Celsius)


b
development rate (1/day)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
5
10
15
20
25
30
35
40
45
50
55
temperature (degree Celsius)


c
development rate (1/day)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
5
10
15
20
25
30
35
40
45
50
55
temperature (degree Celsius)


d
development rate (1/day)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
5
10
15
20
25
30
35
40
45
50
temperature (degree Celsius)

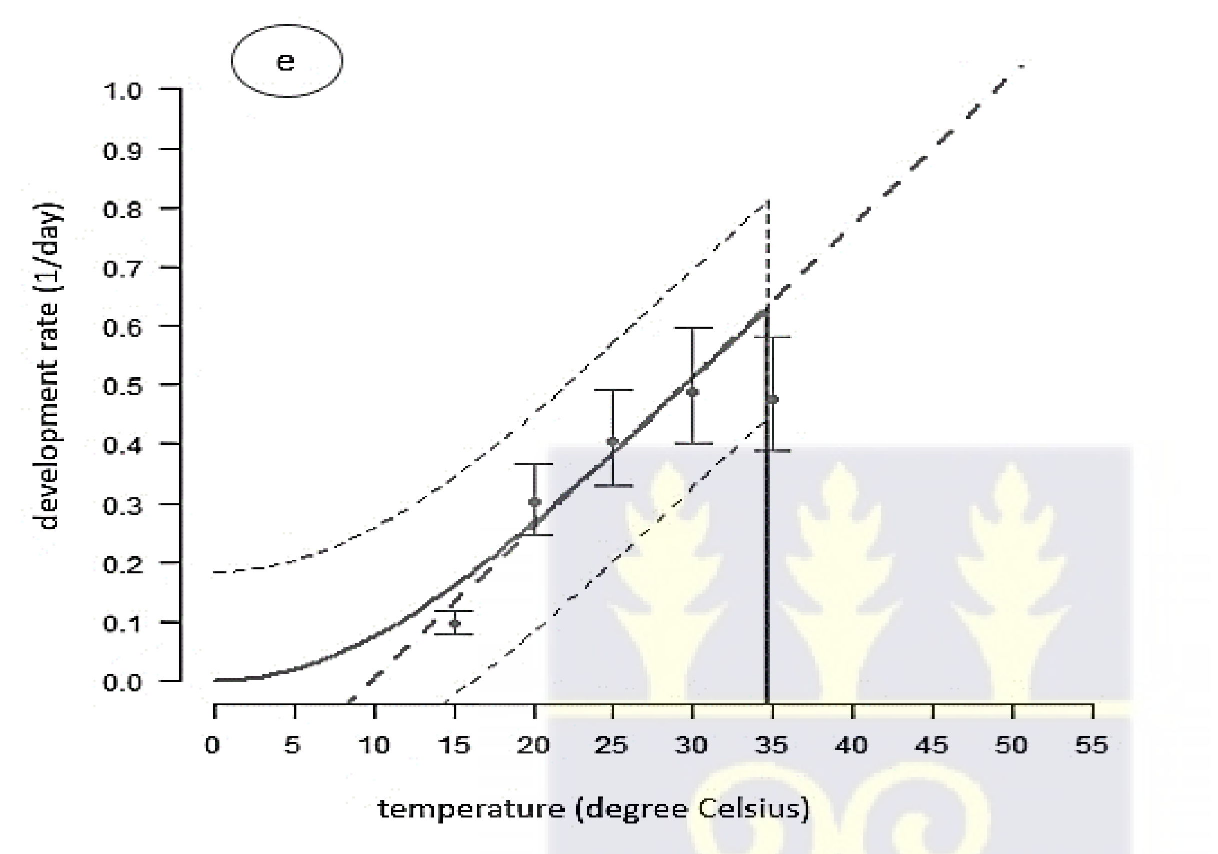


Figure 5.2. Temperature-dependent development rate (1/development time) of *T. parvispinus* immature stages, (a) egg, (b) first instar, (c) second instar, (d) propupa, and (e) pupa. The bold solid line is the selected model output and dashed lines above and below represents the upper and lower 95% confidence bands. Bars represent standard deviation of the mean.

Table 11. Parameters of the linear regressions and non-linear functions fitted for temperature effect on *T. parvisipinus* immature stage development rate (1/day).

Life stage	Linear regression model						Non-linear models								
	a	b	R^2	AIC	T_{min} °C	K (DD)	Logan 1 model parameters								
							Y	Tmax		p		v		R^2	AIC
Egg	-0.214	0.021	0.96	15.18	10.19	47.62	0.01 (0.01)	40.94 (0.01)		0.14 (0.01)		4.77 (0.39)		088	0.25
							Sharpe and DeMichele model parameters								
							p	To	H1	T1	Hh	Th	Ha	R^2	AIC
1st instar	-0.24 0	0.030	0.83	6.29	8.00	33.33	0.52 (0.00)	302.22 (2.60)	-631879.97 (0.00)	287.99 (0.17)	1020533.04 (0.00)	317.74 (0.00)	4006.49 (0.00)	0.89	6.16
							Allahyari model parameters								
							P	Tmax	Tmin	m	n			R^2	AIC
2nd instar	-0.372	0.029	0.94	-9.54	12.83	34.48	2.04 (0.64)	37.30 (1.22)	-692.90 (7.89)	164.70 (4.20)	105.27 (43.20)			0.99	-8.65
							Logan 1 model parameters								
							Y	Tmax		P		v		R^2	AIC
Propupa	-0.121	0.024	0.90	-8.10	5.04	41.66	0 (0.00)	38.76 (0.01)		0.31 (0.00)		12.81		0.84	-2.28
							Hilbert and Logan model parameters								
							Ψ	D		Tmax		Dt		R^2	AIC
Pupa	-0.206	0.022	0.90	-10.89	9.36	45.45	220920.77 (0.01)	30440750.73 (0.00)		100.377 (16.80)		4.95 (1.26)		0.81	3.06

Standard errors are indicated in parenthesis.

5.3.3 Mortality of immature stages

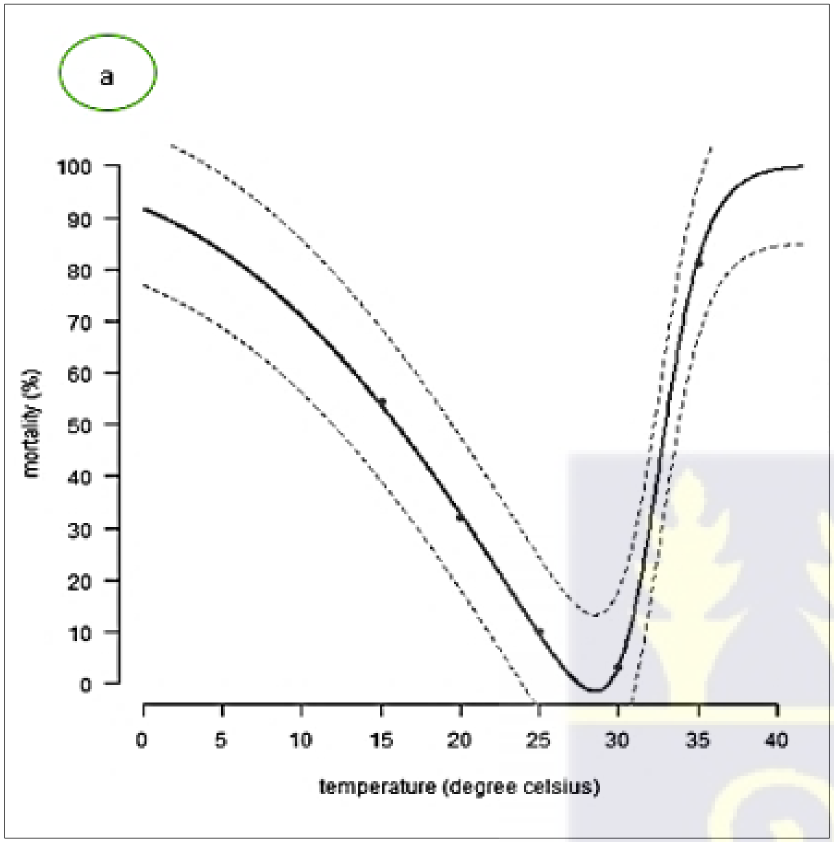
Temperature significantly contributed to the mortality of different life-stages of *T. parvispinus* eggs ($F_{2, 4} = 1027.56$, $P = 0.02$), first instar ($F_{2, 4} = 5.27$, $P = 0.159$), second instar ($F_{2, 4} = 11.39$, $P = 0.050$), propupa ($F_{2, 4} = 7943.60$, $P < 0.0001$) and pupa ($F_{2, 4} = 177.00$, $P = 0.050$). Egg mortality was highest at 35 ºC with 81%, followed by 54% mortality at 15 ºC, with the lowest egg mortality at 30 ºC being 3.2%. Mortality of the first instar was highest at 35 ºC with 81% and lowest at 30 ºC with 2.8%. The second instar had the highest mortality at 15 ºC and 20 ºC with 77% and 75% mortalities, respectively, whilst 30 ºC and 25 ºC had the lowest mortalities of 36% and 37%, respectively. The propupal mortality was highest at 15 ºC (82%) and lowest at 25 ºC (7.4%). Compared to other stages, propupal mortality was not so high at 35 ºC (Figure 5.3). For the pupa stage, mortality was extremely high at 15 ºC with 99%. 20 ºC saw a higher pupal mortality (71%) than 35 ºC (67%) whereas the lowest was observed at 30 ºC (11%). The relationship between temperature and mortality was perfectly described by the Wang 7 model for the egg stage (AIC = -28.42, $R^2 = 0.99$), the fourth order polynomial equation for the first instar (AIC = 0.66, $R^2 = 0.84$), the Weibull equation for the second instar (AIC = -7.76, $R^2 = 0.92$), the Wang 5 model for the propupa (AIC = -36.36, $R^2 = 0.99$) and the Marc model for the pupa stage (AIC = -19.12, $R^2 = 0.99$) (Table 5.4). The models predicted the optimum temperature for development between 25 ºC to 30 ºC, with less than 10% mortality for the egg stage, 30 ºC for the first and second instars, 25 ºC for the propupa and 30 ºC for the pupal stages (Figure 5.3).

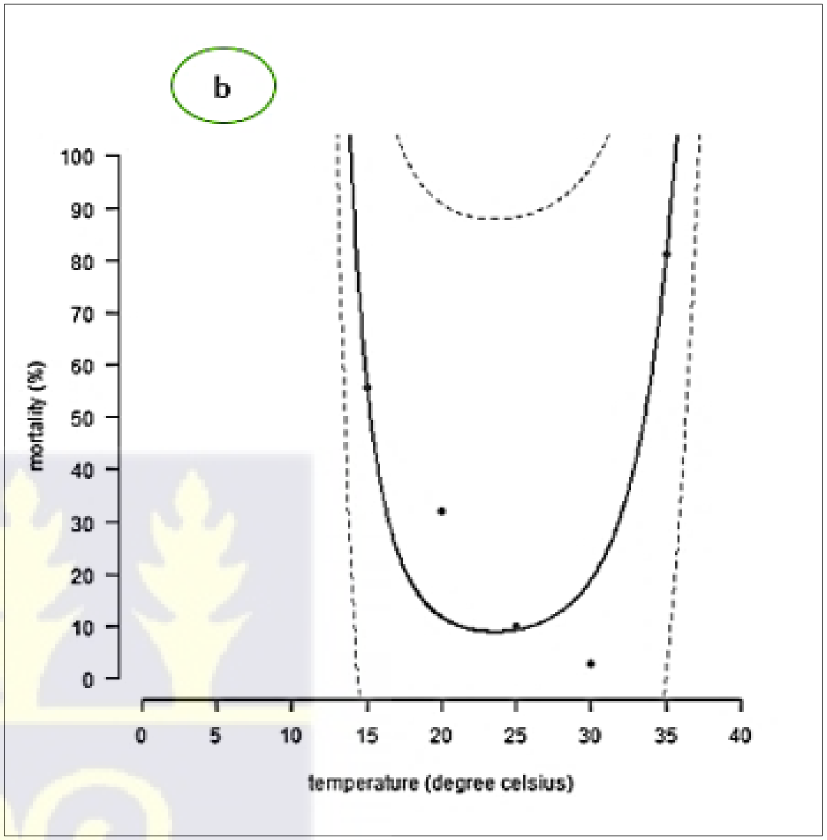
Table 12. Estimated parameters of the non-linear functions fitted to describe the mortality rate for *T. parvispinus* immature life stages.

Life stage	Wang 7 model parameters: $m(T) = 1 - H/(exp(1 + exp(-(T - Topt)/Bl)) * (1 + exp(-(Topt - T)/Bh)))$								
Egg	Topt	Bl	Bh	H	AIC	R^2	F	df	P
	32.27 (0.13)	24.48 (0.74)	1.44 (0.06)	9.51 (0.17)	-28.41	0.99	1027.56	(3,4)	0.023
1st instar	Polynomial 4 model parameters: $m(T) = Exp (b1 + b2 * T + b3\sqrt{T}$								
	b1	b2	b3	AIC	R^2	F	df	P	
	43.32 (20.56)	1.94 (0.98)	-18.84 (9.61)	0.66	0.84	5.27	(2,4)	0.159	
2nd instar	Weibull model parameters: $m(T) = a * (abs(T - b))^n$								
	a	b	n	AIC	R^2	F	df	P	
	0.27 (0.06)	27.68 (0.69)	0.45 (0.11)	-7.76	0.92	11.39	(2, 4)	0.050	
Propupa	Wang 5 model parameters: $m(T) = 1 - H/(exp(1 + exp(-(T - T_{opt})/B)) * (1 + exp(-(T_{opt} - T)/B)))$								
	Topt	B	H	AIC	R^2	F	df	P	

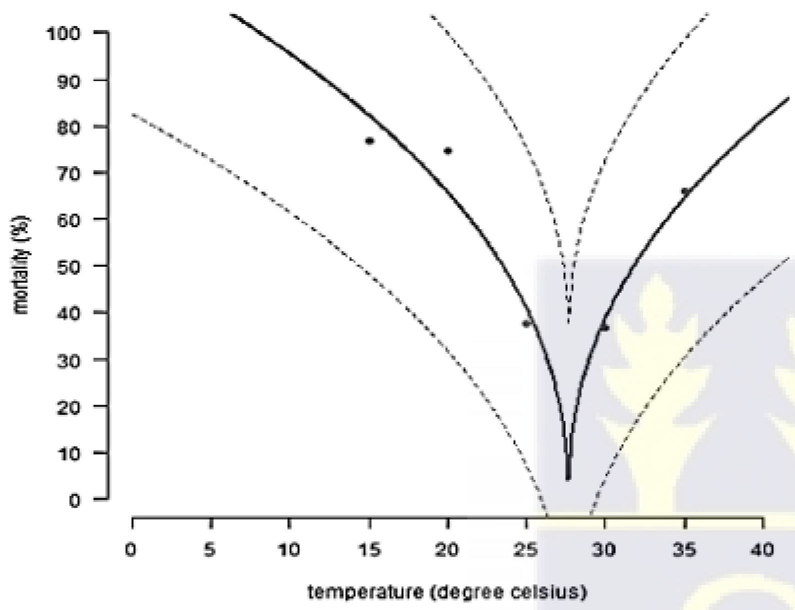
	22.281 (0.03)	6.78 (0.04)	12.217 (0.05)	-36.36	0.99	79.6	(2,4)	< 0.001	
Pupa	Marc model parameters: *m(T)* = (1 – exp (-(exp(a1 + b1 * T)))) + (1 - exp(-(exp(a2 + b2 * T))))								
	a1	b1	a2	b2	AIC	R2	df	P	
	4.70 (0.43)	-0.22 (0.02)	-173.78 (0.00)	4.96 (0.00)	-19.12	0.99	(3,4)	0.050	

Standard errors are indicated in parenthesis.

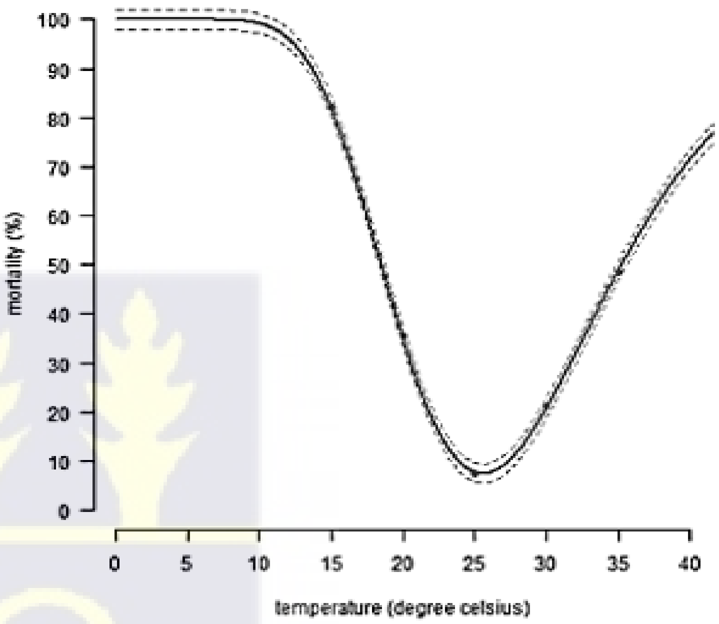

a
mortality (%)
100
90
80
70
60
50
40
30
20
10
0
0
5
10
15
20
25
30
35
40
temperature (degree celsius)


b
mortality (%)
100
90
80
70
60
50
40
30
20
10
0
0
5
10
15
20
25
30
35
40
temperature (degree celsius)

c


mortality (%)
100
90
80
70
60
50
40
30
20
10
0
0
5
10
15
20
25
30
35
40
temperature (degree celsius)

d


mortality (%)
100
90
80
70
60
50
40
30
20
10
0
0
5
10
15
20
25
30
35
40
temperature (degree celsius)

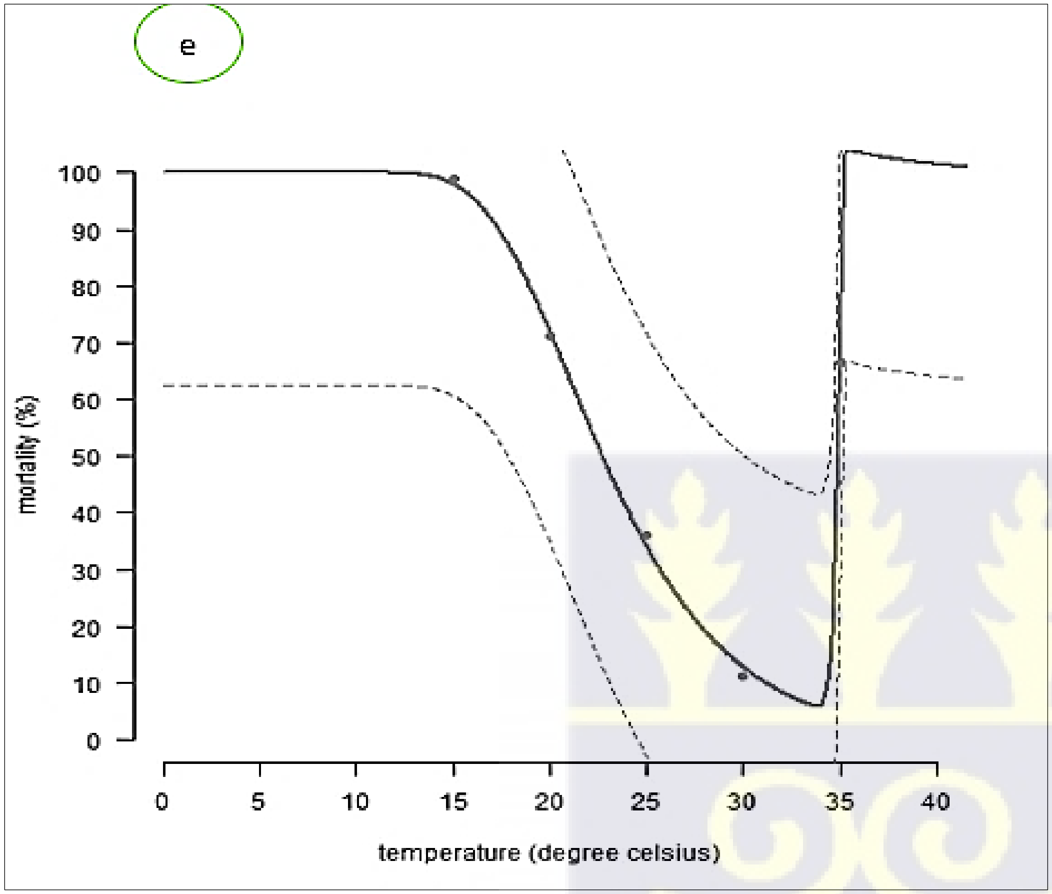


Figure 5.3. Temperature-dependent mortality of *T. parvispinus* fitted to several functions. (a) egg, (b) 1st instar (c) 2nd instar; (d) propupa and, (e) pupa. The black points are observed values, and the black solid curves are the selected model's output. The dotted lines represent the upper and lower 95% confidence bands of the model.

5.3.4 Longevity and oviposition of adult

The life span of both the male and female adults of *T. parvispinus* was significantly affected by temperature ($F_{3,14} = 214.18$, $P = 0.000$ and $F_{3,14} = 85.13$, $P = 0.000$, respectively) (Table 5.5). The Tanigoshi equation perfectly described the effect of temperature on the female longevity rate (AIC = -21.37, $R^2 = 0.98$) and the longevity rate of the male fitted perfectly with the Wang-Lan-Ding equation (AIC = -8.99, $R^2 = 0.98$) (Figure 5.4).

Table 13. Parameters of the non-linear functions fitted to the mean senescence rates estimated for *T. parvispinus* adult life stages.

Life-stage	Tanigoshi model parameters: $r(T) = a_0 + a_1T + a_2 T^2 + a_3T^3$									
Female	a_0	a_1	a_2	a_3	AIC	R^2	F	df	P	
	-0.631	0.094	-0.004	0.000	-21.37	0.98	214.18	3,14	0.000	
Male	Wang-Lan-Ding model: $r(T) = k(1 - \exp((-a) * (T - T_{min}))) * (1 - \exp(b * (T - T_{max})))/(1 + \exp((-r) * (T - c)))$									
	k	a	b	c	T_{min}	T_{max}	r	AIC	R^2	P
	0.430	0.039	0.002	-1.219	-22.329	-20.074	11.772	-8.99	0.99	0.000

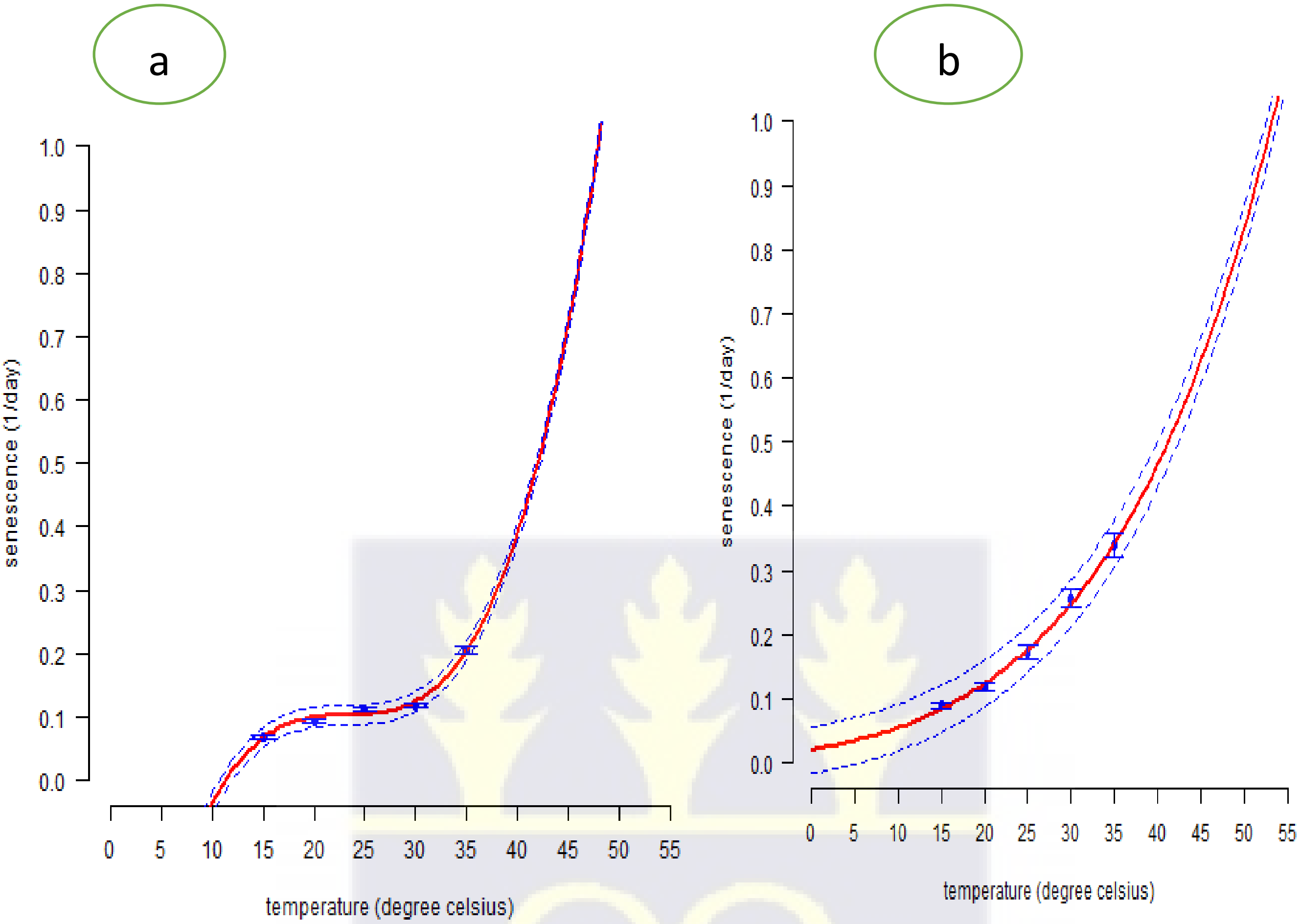


Figure 5.4. Temperature-dependent senescence rates (1/day) for *T. parvispinus* adults fitted to the Tanigoshi and Wang-Lan-Ding functions. (a) female and (b) male. Dotted lines represent the lower and upper 95% confidence intervals of the models. Red lines are the model output, and the standard errors are represented with bars.

Temperature had an influence on the reproductive cycle of *T. parvispinus*. The length of reproduction shortened as the temperature increased. The temperature-dependence of *T. parvispinus* oviposition was described by the Gaussian denominator function ($F_{3,4} = 23.28$, $P = 0.151$) (Table 5.6). The model predicted 25 ºC to 30 ºC as favourable temperatures for reproduction of *T. parvispinus*, with maximum eggs of 54.83 at 30 ºC. Total oviposition was higher at 35 ºC (38.33) than at 20 ºC (35.50) (Figure 5.5). The relationship between female age and cumulative oviposition was described by the modified Exponential function ($F_{1,59} = 630.60$, $P = 0.000$). By the time the female reached a normalized age of 0.444, 50% oviposition was completed.

Table 14. Estimated parameters of the Gaussian denominator and exponential functions fitted to total fecundity and age-related oviposition rate of *T. parvispinus*.

Variable	Simple Gaussian function, $f(T) = y0 + a \exp(-0.5((T - T_0)/b)^2)$								
	yo	a	To	b	AIC	R^2	df	F	P
Fecundity/female	-7.69 (33.11)	61.52 (31.67)	9.30 (3.90)	28.15 (0.63)	29.00	0.98	(3,4)	23.28	0.151
Relative oviposition rate	Exponential function, $l(T) = 1 - \exp(-a * T^b)$								
	a	b			AIC	R^2	df	F	P
	6.53 (1.50)	2.76 (0.31)			-85.61	0.92	(1,59)	630.60	0.000

Standard errors and degree of freedom (df) are indicated in brackets.

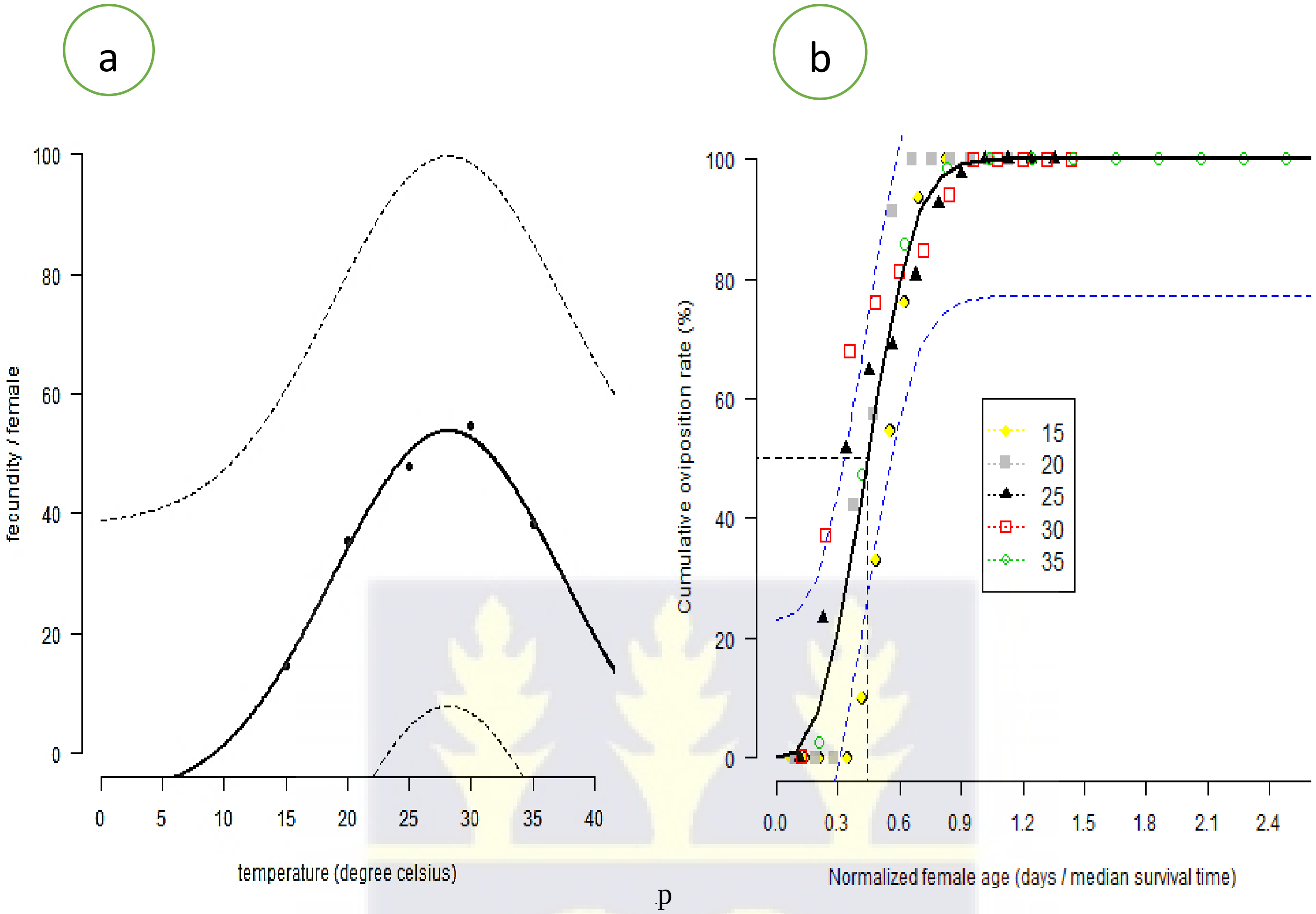


Figure 5.5. (a) Temperature-dependent total oviposition curve. (b) Cumulative proportion of egg production in relation to female age (longevity (days)/mean senescence time). The 50% oviposition age is indicated. The lower and upper 95% confidence intervals of the models are indicated with dotted lines.

5.3.5 Life-table parameters

The established sub-models were used to compile the overall phenology model for *T. parvispinus*. The phenology model estimated the life table parameters summarized on Table 5.7. The life-table parameters were significantly affected by temperature ($F_{4,\,25} = 32.27$, $P < 0.0001$, $F_{4,\,25} = 588.82$, P

< 0.0001, $F_{4, 25} = 68.36$, P < 0.0001, $F_{4, 25} = 2733.27$, P < 0.0001, $F_{4, 25} = 1527.81$, P < 0.0001, $F_{4, 25} = 20.59$, P < 0.0001), for gross reproductive rate, intrinsic rate of increase, net reproductive rate, mean generation time, finite rate of increase and doubling time, respectively). The net reproductive rate and the intrinsic rate of increase were maximum at temperatures between 25 ºC and 30 ºC. The gross reproductive rate was maximum at 35 ºC with 45 offspring per generation, compared to 33.42 and 9.80 at 25 ºC and 15 ºC, respectively. The GRR at 25 ºC was not significantly different from 30 ºC but differed significantly from all the other temperatures (P < 0.0001). The finite rate of increase at 15 ºC differed significantly from all the other tested temperatures (Table 5.7). The estimated values for 'T' indicate that the mean time of generation decreased with increasing temperature with 35.76, 26.00 and 13.67 days at 15 ºC, 20 ºC and 30 ºC, respectively.

Table 15. Simulated life table parameters of *T. parvispinus* at different constant temperatures.

Temperature	Life table parameters					
	GRR	r_m	R_o	T (days)	ƛ	Dt (days)
15	9.80 (0.200)a	-0.060 (0.00)a	0.24 (0.000)a	35.76 (0.000)a	0.70 (0.000)a	-66.57 (11.825)a
20	22.95 (4.674)b	-0.020 (0.006)b	0.63 (0.196)a	26.00 (0.915)b	0.99 (0.003)b	-50.31 (12.300)a
25	33.42 (2.929)c	0.12 (0.007)c	8.10 (0.686)b	17.61 (0.117)c	1.12 (0.008)c	5.94 (0.318)b
30	35.03 (2.736)cd	0.15 (0.005)d	8.19 (0.976)dc	13.67 (0.075)d	1.16 (0.007)d	4.59 (0.179)cb
35	45.00 (0.000)e	-0.11 (0.000)e	0.25 (0.000)a	12.75 (0.000)e	0.90 (0.000)e	-6.37 (0.000)db
F	32.27	588.82	68.36	2733.27	1527.81	20.59
df	4, 25	4, 25	4, 25	4, 25	4, 25	4, 25
P	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001

Standard errors are in parentheses. Means followed by different letters within columns are significantly different (P = 0.05, Tukey test). GRR = gross reproductive rate, r_m = intrinsic rate of increase, T = mean generation time, R_o = net reproduction rate and, Dt = doubling time, ƛ = finite rate of increase, df = degree of freedom, p = probability value.

5.4 Discussion

5.4.1 Modelling the impact of temperature on *T. parvispinus* development time

The development time of an insect depends on temperature (Bale *et al*., 2002; Skendžić *et al*., 2021). Differences existed in the development times of the different life stages of *T. parvispinus* in this study. The development time of *T. parvispinus* was shorter with increasing temperatures. This result is similar to the result of *T. parvispinus* and other thrips species reported by several authors (Park *et al*., 2010; Li *et al*., 2011; Yadav and Chang, 2014; Hutasoit *et al*., 2018). In this study, the longest egg to adult development period occurred at 15 ºC with 37.72 days and the shortest at 35 ºC with 8.84 days. This is similar to species like *Thrips palmi* with egg-to-adult development time of 35.7 days at 16 ºC and 9.6 days at 31 ºC (Yadav and Chang, 2014), but much shorter than the likes of *Frankliniella tritici* and *Frankliniella occidentalis* with 11 and 12 days development time at 29 ºC, respectively (Reitz, 2008, 2009). Hutasoit *et al*. (2018) earlier reported the egg-to-adult development time of 13.68 days at 27 ºC for *T. parvispinus* and this study reported 13.81 days at 25 ºC. However, though differences are minimal, the slight difference observed may be due to differences in temperatures and host plant effect as chilli was used as the rearing substrate in the stated study. Our findings have a direct link with observations under field conditions in Ghana, where *T. parvispinus* was shown to be more tolerant to increasing temperatures than other thrips species (Nkafu *et al*., 2024). This reason in addition to their short development times at high temperatures has contributed to its pest status on several vegetables, requiring immediate climate-adaptive emergency and management plans to curb its spread.

5.4.2 Impact of temperature on development rate

The most important environmental factor influencing development, survival, reproduction and distribution of insects have long been considered to be temperature (IPPC, 2001; Bale *et al*., 2002;

Skendžić *et al*., 2021). The results of this study showed that the development rate of *T. parvispinus* is significantly affected by temperature and therefore, agrees with this statement. The effect of temperature on the development rate of *T. parvispinus* was well fitted with linear functions especially for optimum temperatures between 20 ºC and 30 ºC. However, at higher temperatures, the Logan and Sharpe and DeMichele models allowed for the calculation of maximum threshold temperatures for the different life stages. In earlier studies, the Logan model was used to estimate the impact of temperature on the development rate of the coffee antestia bug, *Antestiopsis thunbergii* (Hemiptera: Pentatomidae) (Azrag *et al*., 2017) and the noctuid lepidopteran stem borers, *Busseola fusca* and *Sesamia calamistis* (Lepidoptera: Noctuidae) (Khadioli *et al*., 2014). The Sharpe and DeMichele models have been used in developing a temperature-based phenology model for predicting population growth potential, development, and survival of the mealybug, *Phenacoccus solenopsis* Tinsley (Hemiptera: Pseudococcidae) (Fand *et al*., 2014) and therefore, are considered of higher biological significance (Logan *et al*., 1976; Sharpe *et al*., 1977; Fand *et al*., 2014). The lower and upper threshold temperature for development and the thermal constant are useful indicators for an insect's potential distribution (Park *et al*., 2010). This study demonstrated that different life stages have different threshold temperatures with different thermal requirements, and this is important for thrips management purposes as this imply, a single heat treatment may not be effective for all the life stages. More so, with the lowest egg threshold temperature of 10.19 °C and the shortest egg development time temperature estimated at 35.5 °C, it implies this species can survive in wide geographical ranges of both cold and hot climates.

5.4.3 Impact of temperature on longevity and oviposition of adults

The lifespan and reproduction of adults were affected significantly by temperature. At higher temperatures of 35 ºC, adult longevity was three times lesser than that at 15 ºC leading to extensive shortening of reproductive phase, with females living longer than males at all temperatures. The cumulative oviposition rate was also dependent on temperature. A curvilinear response for oviposition reported 25-30 ºC as the optimum temperature for reproduction. This is consistent with the findings of Yadav and Chang (2014) who reported 25 ºC as the optimum temperature for reproduction for a similar thrips species. However, the total oviposition of *T. parvispinus* (52.4 eggs/female) appears lower than that of *T. palmi* (62.4 eggs/female). This can be attributed to differences in the reproductive characteristics of thrips species, rearing conditions, or host plant disparities. It is evident in this study that, after 30 ºC, the reproductive potential of *T. parvispinus* started declining, confirming the non-linear relationship that exist at temperature extremes. This non-linearity was perfectly described by the Gaussian denominator function which has been widely used on insects of different groups and different geographical origin (Fand *et al*., 2014).

Unfortunately, aside from the work of Hutasoit *et al*. (2018) conducted on *T. parvispinus* biology under room temperature, literature on the thermal requirement of *T. parvispinus* is scanty and makes it difficult for comparisons.

5.4.4 Impact of temperature on the life table parameters of *T. parvispinus*

The life table parameters observed in this study were influenced by temperature significantly. The gross reproductive rate increased linearly with increasing temperature with the highest at 35 ºC (45.00). *Thrips parvispinus* had an intrinsic growth rate of 0.12-0.15 individuals per female per day with a population which could double within 4.59-5.94 days between 25 ºC and 30 ºC. This suggest even if global warming continues and temperatures increase by 1.7 – 2.4 ºC by 2050 as predicted by Asante and Amuakwa-Mensah (2015) in Ghana, the different regions will still be suitable for *T. parvispinus* establishment, with even higher number of offsprings at high temperatures. This can increase their pest status leading to more damage on plants. By implication, pest management strategies that are better adapted to different climate change conditions will need to be developed to meet the thrips-free vegetable export standard. This results are in consonance with Hutasoit *et al*. (2018) who reported an intrinsic growth rate of 0.16 and a doubling time of 4.57 days at 27 ºC. For a closely related species, *T. palmi*, the intrinsic rates on cucumber leaves at 15, 20, 25, and 30 °C were 0.035, 0.080, 0.134, and 0.144 per day. The higher r_m of *T. parvispinus* is linked to differences in thrips species, varying female fecundity and survival rates of immature stages (Yadav and Chang, 2012b). However, the net reproductive rate of 5.71 observed by Hutasoit *et al*. (2018) was lower than that obtained at 25 ºC in this study. This can be due to differences in the rearing conditions, the quality and type of rearing host. The life table parameters can be used to determine the adaptability of insects to host plants (Gao *et al*., 2021). Host suitability is dependent on shorter development times and higher reproductive rates. The higher net reproductive rate in this study indicated that eggplant is a more suitable host for *T. parvisipinus* reproduction than the chilli used in the previous study. Plants in the Solanaceae family emit strong irritating volatiles or secondary metabolites that may affect the selection of this thrips for oviposition. In addition, host nutritional quality greatly influences the performance of thrips species (Gao *et al*., 2021. At extreme temperature, the intrinsic rate of natural increase was negative. This was because of the very low gross reproductive rate that was observed at 20 ºC and 15 ºC. On the other hand, the negative r_m observed at 35 ºC could be attributed to the high mortality rate especially at the pupal stage. In reality, since the first and second instars are particularly important damaging stages which pierce and suck out nutrients from economic crops, significant damage may occur when temperatures get as high as 35 ºC before the high pupal mortality become evident. In addition, the noticeably short lifecycle of 8.84 days observed in this study at 35 ºC can as well compensate for the high pupal mortality through rapid reproduction, making this species a looming threat to Ghanaian agriculture.

5.4.5 Conclusion

This study confirms the importance of temperature on the demographic and life table parameters of *T. parvispinus*. The fitted mathematical functions were compiled to develop the overall phenology model for this thrips species. This model provides for the first-time baseline optimal thermal requirements of this new species, *T. parvispinus* which will be useful for further study of the species thermal biology in Africa. The results provide evidence that the recent invasion and dominance of this new species is linked to the relatively shorter lifecycle in addition to the recent increase in temperatures which makes Ghanaian (tropical) climates more favourable for its establishment and reproduction. The developed model can be used to forecast thrips population increases, inform farmers when to implement control measures before thrips populations reach damaging levels, and prevent high pesticide residues, thus maintaining the quality of exports.

CHAPTER SIX

6.0 EFFICACY OF PEST MANAGEMENT OPTIONS ON THRIPS AND ASSOCIATED NATURAL ENEMIES ON EGGPLANT (*SOLANUM MELONGENA* VAR. PINK RAVAYA) ACROSS TWO DISTINCT AGROECOLOGICAL ZONES IN GHANA

6.1 Introduction

Alternative pest management options such as the search for new pesticides are currently recommended for the control of insect pests (Afreh-Nuamah, 1996; Owusu-ansah *et al*., 2001; Renukadev, 2018) such as thrips in vegetable production due to the harmful effects of broad-spectrum insecticides on non-target organisms, the environment and public health (Hata *et al*., 1993; Afreh-Nuamah, 2003; mo-Ikerodah *et al*., 2009). These alternatives referred to as selective or reduced-risk insecticides are defined as insecticides expected to accomplish one or more of the following objectives: reduce the potential for surface or groundwater contamination, or other valued environmental resources, reduce pesticide risk to non-target organisms and human health or broaden the adoption of integrated pest management strategies, or make such strategies more available or more effective (EPA, 1997). Therefore, a good insecticide should target the insect pests and have minimal effects on the natural enemies in the field (Varenhorst and O'Neal, 2012).

Pyrethroids and neonicotinoids are important groups of insecticides widely used to control many arthropod pests including thrips (Saeed *et al*., 2018; Fening *et al*., 2020). Pyrethroids, such as alpha-cypermethrin, have a rapid knockdown effect when in contact with the target pest. This group of insecticides prevent the closure of sodium-gated channels in insects (IRAC, 2022) which results in the repeated firing of nerve impulses, leading to paralysis as a result of the inability of the pest to detoxify this foreign particle. Neonicotinoids such as imidacloprid insecticides bind to the nicotine acetylcholine receptors in the insect's central nervous system which results in over stimulation of nerve cells, causing death by paralysis (Kundoo *et al*., 2018; IRAC, 2022). Botanicals have emerged as a better group of insecticides with higher selectivity and reduced toxicity to non-target organisms (Owusu-Ansah *et al*., 2001; Mochiah *et al*., 2011; Amoabeng *et al*., 2014; Ngosong *et al*., 2020), and they are being valued for their diverse mode of action including repellent, antifeedant or toxic effects on several pests (Ireri, 2015).

Determining the effectiveness of important less-risk insecticides such as Agroblaster® (Pyrethrum I and II, Equatorial Healthcare Services) and Agroclean® (Mint/coconut oil) is useful in optimising insecticide applications to prevent control failures and improving the choice of selection of the right pesticide for improved yields. This will also provide information on their compatibility with biocontrol agents, which is an essential component of IPM programmes, as well as their effect on plants. Natural enemies have gained significant attention in pest control programmes (Mandal and Patnaik, 2008) even though their use for effective thrips control is questioned by several authors (Tamò *et al*., 1993; Parrella and Lewis, 1997; Srinivasan, 2009). However, their populations are often affected by insecticides selected for use. Moreover, little is known about the efficacy of some of the recommended or newer insecticides or their effect on natural enemies in the study area. In addition, information on how the dynamics of thrips population vary with some pest management practices has not been documented. Therefore, field experiments were conducted during 2020 and 2021 to evaluate: (1) the effectiveness of novel insecticides for thrips control and their effect on plants and natural enemies, and (2) the effect of pest management modules on the dynamics of thrips pests. The information gathered will form part of the larger effort to ensure the quality of vegetables such as *S. melongena* produced for export meets the new EU Plant Health Implementing Directive (EU 2019/2072), issued in November 2019.

6.2 Material and methods

6.2.1 Study area

The two experiments were conducted in two agroecological zones, one in the Semi deciduous forest [AB farms, Dago (Eastern Region; Akuapim South Municipal district) (Latitude 5° 52' 39.66456", Longitude 0° 16' 29.82468")] and the other in the Coastal Savannah zone [(at the teaching and research farm of the University of Ghana (UG) (Latitude 5° 39' 54.00252", longitude 0° 11' 46.83588")] (Plate 6.1). The semi-deciduous forest agroecological zone has an annual rainfall between 900 and 1270 mm, an average annual temperature of 25 ºC, and relative humidity between 72%-95%, whilst the Coastal Savannah agroecological zone has an annual rainfall of between 700 and 1100 mm, an average annual temperature of 28 ºC and relative humidity between 59%-93%.

6.2.2 Experiment 1: To determine the effectiveness of novel insecticides for thrips control and their effects on natural enemies

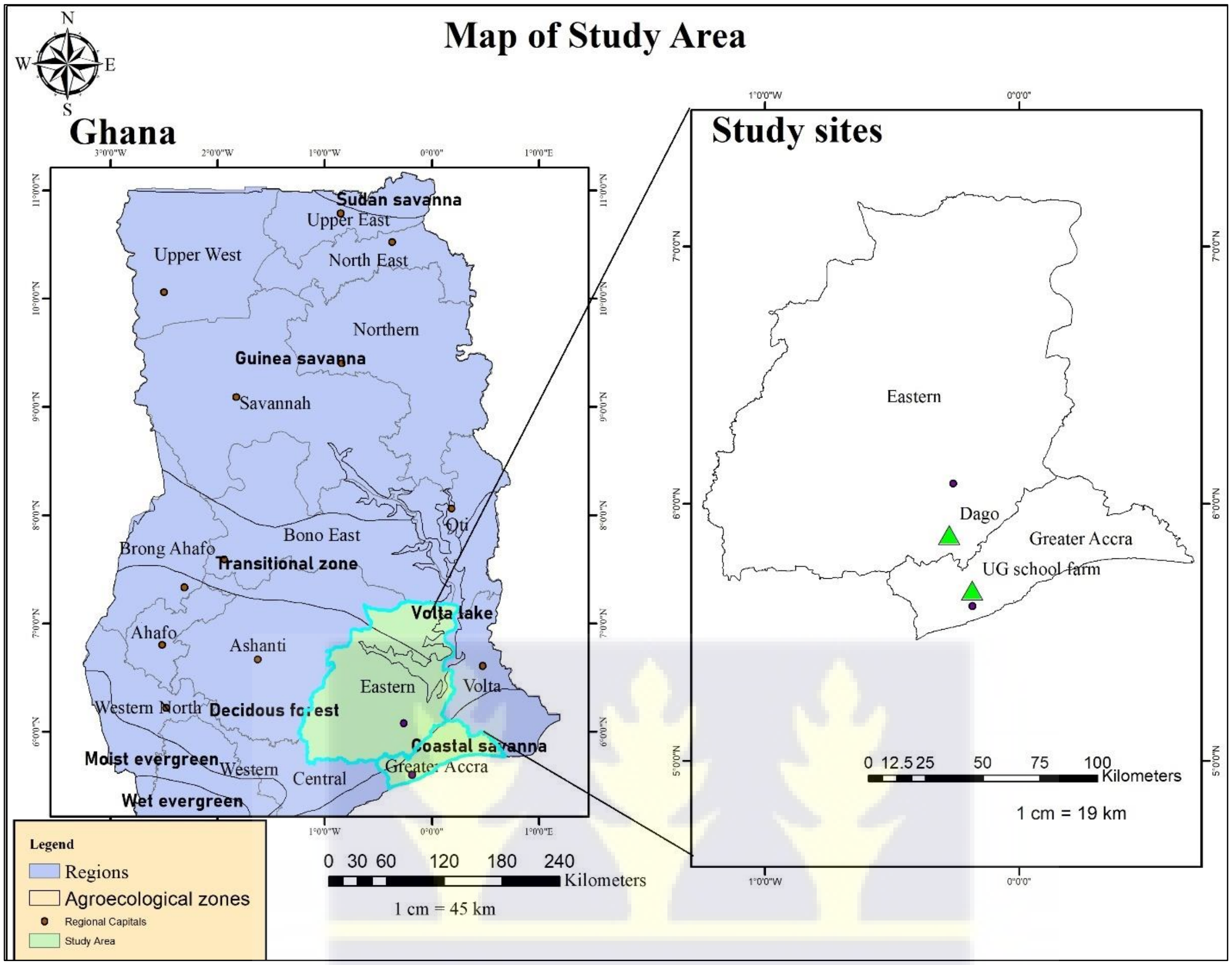


Plate 19. Map of study sites.

6.2.2.1 Selection of seeds

Certified healthy hybrid eggplant (*S. melongena* var. pink ravaya) seeds were purchased from Agriseed Company Limited, a licensed agro-based input shop in Accra, Ghana. The seeds were packaged in non-porous cans and stored in a well-ventilated room till the nursery was set up to ensure that seed viability was guaranteed at the time of planting. Eggplant (*S. melongena)* has recorded one of the highest number of thrips infestations among export vegetables in Ghana (EUROPHYT, 2010, 2013, 2014) and the variety “pink ravaya “ was selected because it is common in the export market (Infonet-Biovision, 2019).

6.2.2.2 Experimental design, nursey establishment, land preparation and transplanting

A nursery bed of 1 m x 7 m was set up at the teaching and research farm of the University of Ghana. Well-decomposed poultry manure (10t/ha) was incorporated into the soil and allowed for a week before planting the seeds in line, with inter-row distance of 10 cm. This was done to prevent the scorching of the seeds or seedlings by the heat that may be produced by further microbial decomposition of the manure. Weeds were hand-picked and watering was done daily to increase plant vigour and ensure the healthy growth of the seedlings. However, a week before transplanting, the seedlings were irrigated every three days, a process called hardening, to reduce transplanting shock and to allow them to adapt to field conditions. The experimental fields were cleared and ploughed with a tractor. The field layout was done using a measuring tape and 5.4 m x 5.4 m beds were made with hoes. The experimental field (Plate 6.2) was irrigated before transplanting was done to enable sufficient moisture in the soil which promotes good seedling establishment. The experiment was laid out in a randomized complete block design and replicated four times. Seven weeks old healthy seedlings were transplanted onto 2 cm deep holes on treatment plots labelled with whiteboards. Within and between plants distances were, 90 x 90 cm each, which gave a total of 25 plants per plot. Plots were labelled by assigning treatments randomly to them.

6.2.2.3 Farm maintenance (fertilization, weed control and watering)

Cultural practices were performed as and when needed. Weeds were manually removed with hoes at three weeks intervals in both sites. In the major season, the field was irrigated once weekly to complement the natural rainfall during this period, whilst in the minor season, watering was done every 3 days.

6.2.2.4 Treatment details and application of treatments

Six treatments which consisted of Equatorial Agroblaster®, Agroclean®, Viper 46EC® (Calli, Ghana Co. Ltd., Accra), Akape® (Agrimat Ltd., Madina, Accra), Alphacep 10EC® (Agrimat Ltd., Madina, Accra) and the control (no treatment applied) were evaluated for two seasons, major and minor rainy seasons of 2020/2021. Details of the treatments are presented in Table 6.1.

Table 16. Treatment description and application rates.

Treatments	Active Ingredient	Chemical class	Application Rate/15l
Equatorial Agroblaster®	Pyrethrum I and II (10g/l)	Pyrethrum	60ml
Agroclean®	Mint/coconut oil	Botanical	45ml
Viper®	Indoxacarb/Acetamiprid (30g/l) + (16g/l)	Oxadiazine/ Neonicotinoid	40ml
Akape®	Imidacloprid (200g/L)	Neonicotinoid	30ml
Alphacep®	Alpha-cypermethrin (100g/l)	Pyrethroid	100ml
Control (no treatment applied)	-	-	-

The insecticides were applied following the manufacturer's recommendation by diluting each insecticide in 15 litres of water. The mixtures were individually applied with a knapsack sprayer with a cone nozzle when the thrips populations reached the threshold level of 1.05-1.50 thrips per leaf/flower (Samler, 2012; Yadav and Chang, 2013), in the morning, before 10:00 am. Thrips activity is usually enhanced during this period, including increased movement from plant to plant, accompanied by increased consumption of sprayed plants. The first spray occurred at the University of Ghana farms (UG, Coastal Savanna zone) and Dago (Deciduous Forest zone) on 7/09/2020 and 3/09/2020, respectively. Upon re-infestation, the second and third sprays were made. This gave a total of three sprays that coincided with the eggplant physiological stages: vegetative, flowering and fruiting.

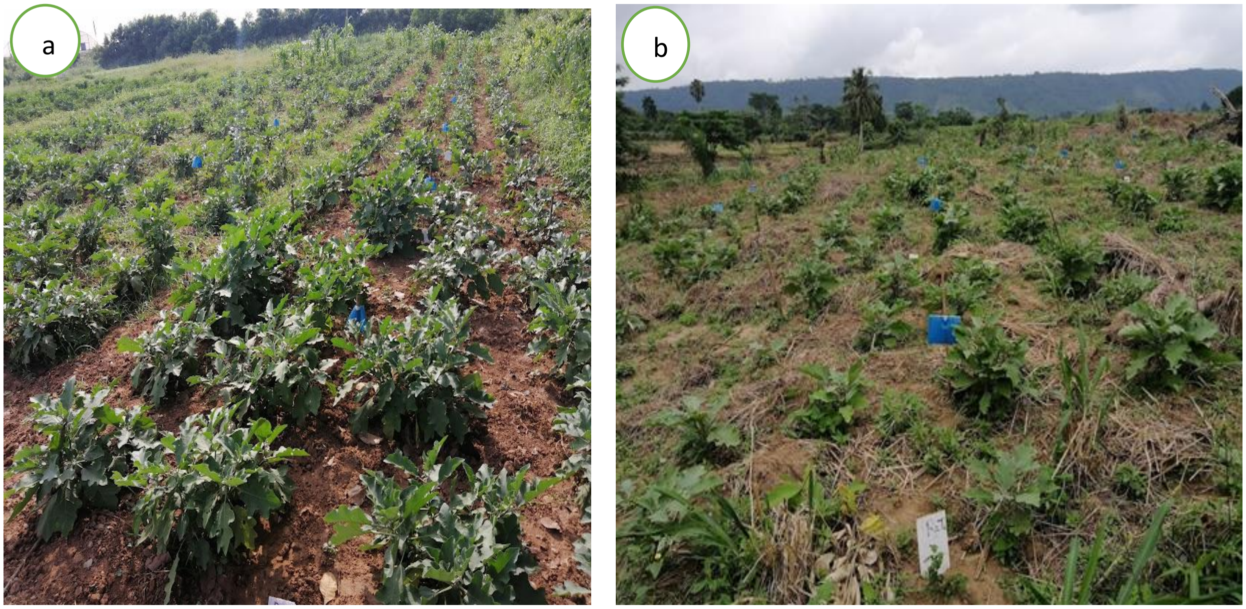


Plate 20. Experimental field, (a) Coastal Savannah (UG) and (b) Deciduous Forest (Dago).

6.2.2.5 Data collection

Data on thrips, other pests and natural enemies were recorded a day prior to each treatment application and at 3, 5 and 9 days (1DBS, 3DAS, 5DAS and 9DAS, respectively) after treatments application to determine the optimum time of application of each insecticide. Thrips damage and within-plant distribution was assessed 3 days after each treatment application. The data was collected between 6:00-8:00 am to avoid peak flight activity of thrips.

6.2.2.5.1 Sampling of thrips

The number of thrips-infested, and damaged plants were counted on 10 randomly selected plants per treatment. Observations on the number of thrips (larvae, pupae and adult stages) on two leaves each of 10 plants per treatment were counted visually by carefully inspecting both the upper and lower surfaces of leaves, since the visual estimation of thrips numbers is highly correlated with absolute thrips densities ($R^2 = 0.83$; $P < 0.001$) (Edelson, 1985). Thrips damage on flowers was scored from 1-5 as described by Cloyd and Sadof, 2003 (Plate 6.4). Thrips injury on leaves was accessed weekly with a score from 1-5 modified from Hawkins *et al*. (1966) and Kerns *et al*. (2018), where ‘1′ represents no feeding injury and ‘5′ indicates severe injury (numerous transparent whitish scars (scaring), leaf rolling or twisting, black varnish-like frass (excrement), etc.) (Plate 6.3). The effectiveness of the treatments was calculated according to Henderson and Tilton (1955) as;

$$\%\ \text{Treatment effectiveness} = 1 - \left[\frac{\text{Cb x Ta}}{\text{Tb x Ca}}\right] x\ 100$$

Where:

Cb = Number of thrips (larvae, pupae, and adults) on untreated control before treatment

Ta = Number of thrips (larvae, pupae, and adults) on treated plot after treatment

Tb = Number of thrips (larvae, pupae, and adults) on the treated plot before treatment

Ca = Number of thrips (larvae, pupae, and adults) on the untreated control after treatment

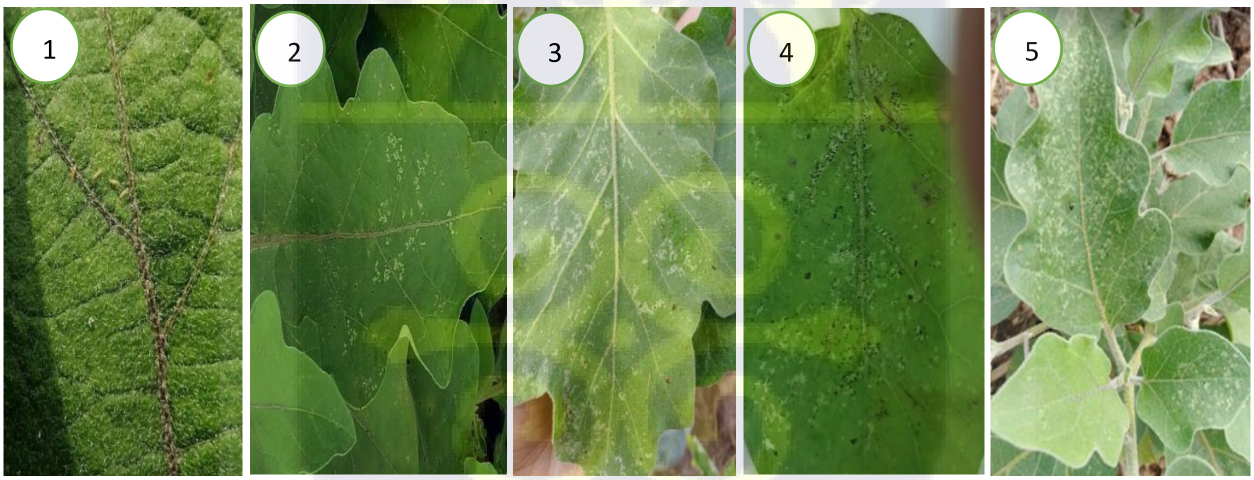


Plate 21. Damage assessment on leaves. The severity of injury indicated by score from 1-5.

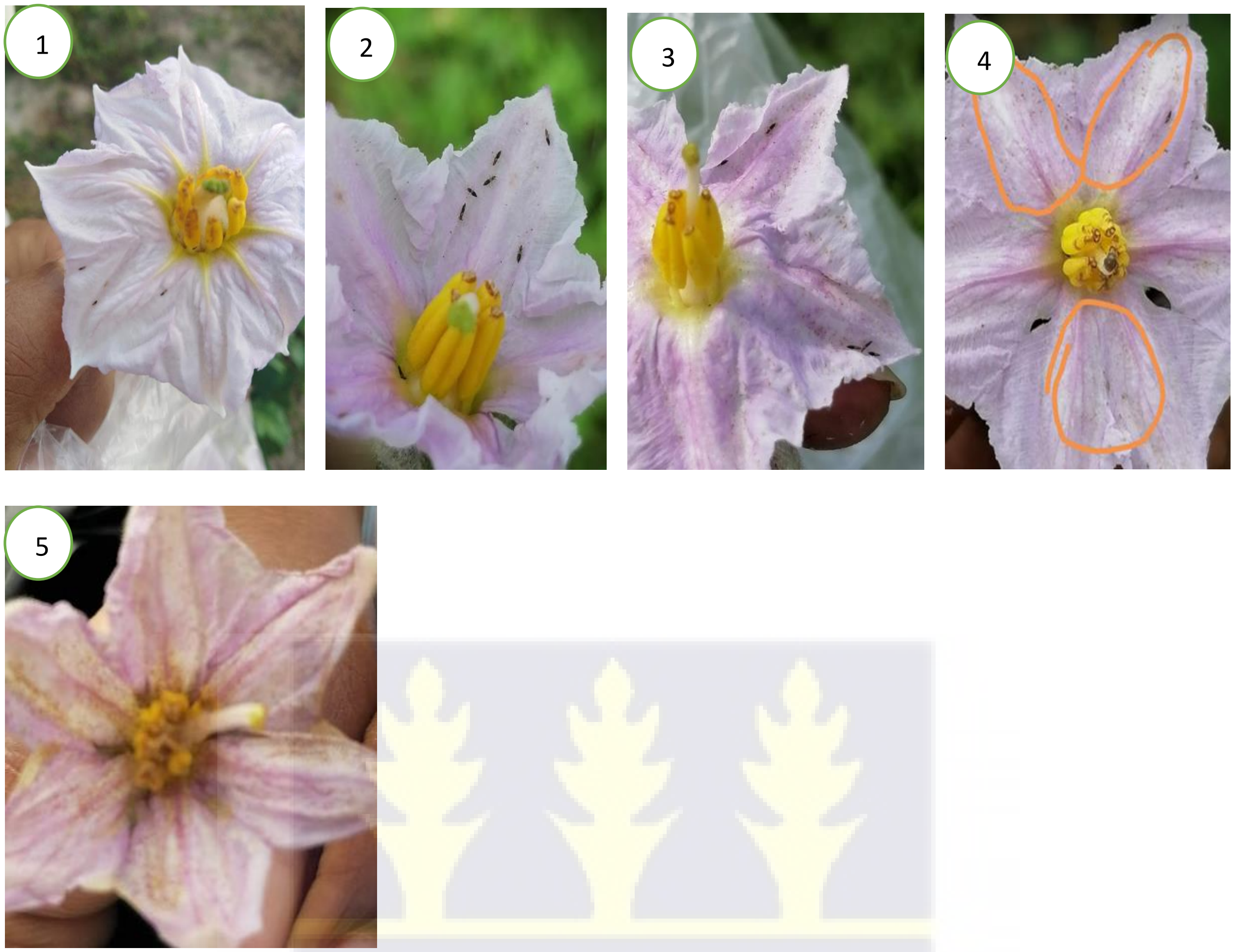


Plate 22. Damage assessment on flowers. The severity of damage indicated by score from 1-5.

6.2.2.5.2 Sampling of natural enemies

Ten plants were selected randomly per treatment and each plant was tilted from one end to the other to carefully count the population of natural enemies present on the whole plant. Both nymphs and adults of the minute pirate and big-eyed bugs were counted as well as larvae and adults of ladybird beetles. The immatures and the adults were counted for spiders. Plate 6.5 shows pictures of the natural enemies sampled during the experiment.

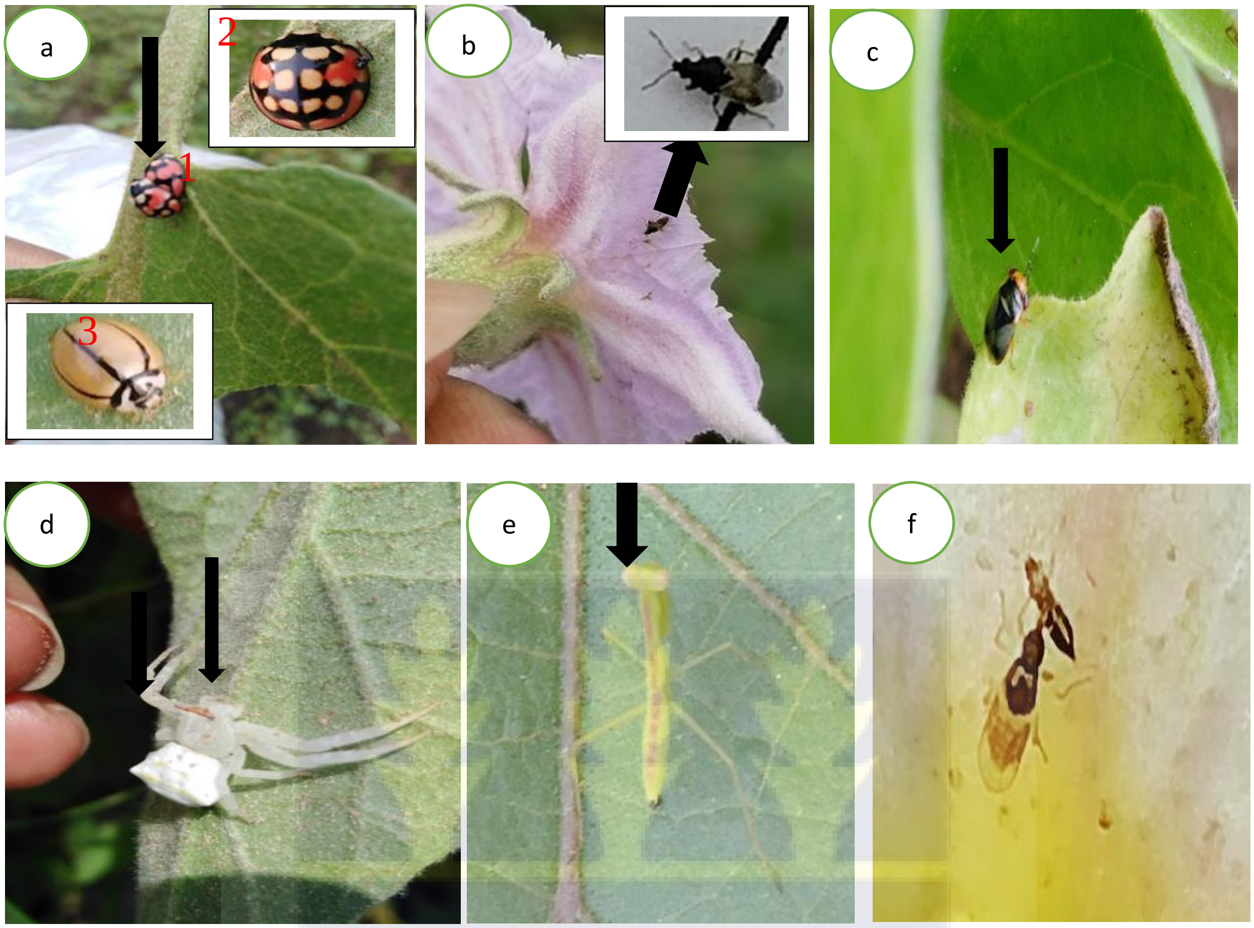


Plate 23. Natural enemies sampled in the field: (a) ladybird beetles, (1) *Cheilomenes lunata*, (2) *Cheilomenes sulphurea*, (3) *Cheilomenes propinqua*, (b) *Orius insidiosus*, (c) big-eyed bug, (d) spider and (e) praying mantis, and (f) *Orius* sp. preying on *T. parvispinus*.

6.2.2.5.3 Data on phytotoxicity

Phytotoxicity was assessed for each treatment, by visually observing any morphological changes such as leaf burn, discolouration, rolling and twisting after the application of the treatments. Therefore, it was categorized as none, slight, and strong (EPPO, 2014), where; none represent fully green plants with no changes after treatment application and strong represents severe changes on plants including severe burns, drying-out, yellowing, rolling and twisting after application.

6.2.2.5.4 Within-plant distribution of thrips

Within-plant distribution of thrips was accessed at 4, 7 and 10 weeks after transplanting by collecting three leaves each of the top, the middle and lower part of the plants into zip lock bags. Three flowers per plant were also collected and the samples were transported and counted with a hand lens in the laboratory. Additionally, a blue sticky trap (22.5 cm by 12.5 cm) was fixed at the centre of each plot at plant canopy height which was replaced weekly, transported to the laboratory and the thrips population counted.

6.2.2.5.5 Other pests

The population of other pest were recorded by examining five random plants per treatment plot. For this, the eggplant fruit and shoot borer infestation level and other pest were assessed. All pictures of encountered pests are found in Appendix 7.

6.2.2.5.6 Yield

The total weight of harvested fruits per treatment were recorded for the first and second harvest. The number of thrips infested fruits were counted and thrips damage on fruit (scaring) was scored from 1-5. Additionally, 10 fruits were cut open and the eggplant *Leucinodes Africensis* damage assessed (Appendix 8).

6.2.3 Experiment 2: Effect of pest management options on the population dynamics of thrips pests

This experiment was conducted in the same location as experiment 1 (Plate 6.1). The experimental design, field establishment and maintenance were as described in sections 6.2.2.2, and 6.2.2.3. However, four pest management modules representing four treatments were tested which included M1 (IPM module), M2 (less-risk pesticides module), M3 (Chemical Intensive Module (Farmer's method) and M4 (control module) with four replications. In M1, a row of maize was planted (50 x 50 cm) one week before eggplant transplants as a border crop (cultural control). White and yellow sticky traps were placed at the centre of the plot as mechanical control and when thrips population was above a threshold (60% infestation or 1.5 thrips/plant), chemical control was employed by applying a less-risk insecticide (Agroblaster®). In M2, two less-risk pesticides (Agroclean® and Agroblaster®) were applied in rotation if thrips pest population was above threshold. In M3, a commercial formulation of synthetic pesticides commonly used by farmers (K-Optimal EC, Solevo Ghana Limited., Tema) was applied following farmer's practice (insecticide applied on weekly basis, irrespective of thrips presence). Unlike in experiment 1, data was collected every other week to determine how the population dynamics of thrips varied throughout the eggplant production cycle. This included visual counts of thrips' numbers on two expanded upper leaves of 10 plants with a hand lens, starting three weeks after transplanting till the final harvest. Other pests were assessed and yield per plot was recorded for each harvest as in section 6.2.2.5.6. Finally, the cost of each pest management module was recorded, and the farm-gate price was used to calculate the gross monetary returns, net returns, and the incremental cost-benefit ratio to determine the economics of the treatment modules.

6.2.4 Data analysis

The collected data was checked for normality and homogeneity of variance using Shapiro-Wilk and Levene's tests, respectively. When the assumptions failed, count data on thrips, other pests and natural enemies were square root transformed and percentage data was arcsine square root transformed before analysis of variance (ANOVA) was conducted for experiment 1, after assumptions were met. To determine, the effect of treatments on within-plant distribution of thrips, a split-plot ANOVA was carried out using treatments as sub plots and plant parts as main plots. In experiment 2, repeated measures of ANOVA were conducted upon successful transformation using the GenStat software version 12. Where significant differences existed, Tukey multiple comparison test was used to separate means at 5% probability level. Data were analysed separately for each location and season. Back transformations are reported in tables. Descriptive statistics was used to determine the frequencies of plants with phytotoxic symptoms at different days after the treatments were applied.

The GenStat software is used in agricultural research and is particularly strong in handling repeated measures which accounts for autocorrelation within experimental units over time. GenStat has specialized features, advanced experimental design capabilities, and flexibility in handling complex datasets. It is adept in ensuring that all sources of variation, including between-plot and within-plot variations, are appropriately accounted for, enhancing the robustness of the findings. It offers comprehensive visualization tools to explore and present the population dynamics of thrips to understand the trends and provides meaningful insights that can inform effective pest management decisions.

6.2.4.1 Economic analysis of pest management modules

There was a total of two insecticide applications on M1, four on M2, six on M3 and no spray on M4 in the major and minor seasons of each location. At each application date, the labour cost of spraying the whole experiment (1 man day/spray) in each location was costed US$ 5.18. Therefore, the cost of the application of a single treatment was US$ 1.72. The cost of Agroblaster® was US$ 214.70/ha for two applications per season for M1. In M2, Agroblaster® and Agroclean® costed US$ 170.87/ha and US$ 214.70/ha, respectively for two applications each for the major and minor seasons, respectively. In M3, the cost of K-Optimal® for six applications was US$ 530.93/ha per season and location. The cost of the sticky trap and installation was US$ 88.87/ha and maize seeds for use as border rows in M1 were purchased at US$ 23.69/ha. Other costs such as land preparation, fertilization and weeding were held constant for all treatments and were not included in the analysis.

At each harvest, the total eggplant yield per plot was weighed and recorded. The fruits from each plot were graded as in section 6.3.2.3. The unmarketable yield was subtracted from the total yield/plot to give the marketable yield (expressed as kg/ha) which was sold in the local market. The Cedi (¢) which is the Ghanaian currency was converted to US$ using the prevailing exchange rate at the time (1Gh¢ = US$ 5.79 in the major season and US$ 5.83 in the minor season, respectively). A 5 kg basket was sold at US$ 4.32 and US$ 5.57 in both seasons, respectively, which represented US$ 0.864/kg and US$ 1.115/kg in the major and minor seasons, respectively. The costs of marketable yield and production were used to calculate the cost and benefit ratio for each season of the Coastal Savannah and Deciduous Forest zones, computed using the methods of Amoabeng *et al*. (2014) and Ereshrao (2018). All expenditures and incomes were expressed per hectare.

6.3 Results

6.3.1 Experiment 1

6.3.1.1 Effect of treatment on mean number of thrips at different days after application

A day before the different insecticides were applied, count of thrips population revealed no significant difference between the different treatments in the major and minor seasons of both agroecological zones (Deciduous Forest; $F_{5, 23} = 0.27$, $P = 0.926$ and $F_{5, 23} = 0.99$, $P = 0.451$, and Coastal Savannah; $F_{5, 23} = 0.91$, $P = 0.494$ and $F_{5, 23} = 0.18$, $P = 0.979$, respectively) (Appendix 5 and 6). However, at 3DAS, the effect of treatments on mean thrips' numbers were significant for both seasons and both zones (Deciduous Forest; $F_{5, 23} = 38.18$, $P < 0.001$ and $F_{5, 23} = 243.16$, $P < 0.001$, and Coastal Savannah; $F_{5, 23} = 43.03$, $P < 0.001$ and $F_{5, 23} = 88.99$, $P < 0.001$, respectively). During the major season in the Deciduous Forest zone, plots treated with Agroblaster® differed significantly from the control, but not among the other insecticide treatments, however, Alphacep® (Alpha-cypermethrin)-treated plots had the lowest abundance of thrips (Table 6.2). A similar trend was followed at 5DAS and 9DAS, where the treatment effect on thrips population were significant and all treatment differed significantly from the control in the major and minor seasons of the Deciduous Forest zone ($F_{5, 23} = 15.19$, $P < 0.001$, $F_{5, 23} = 5.19$, $P = 0.004$, 5DAS and 9DAS, respectively) with Agroclean® (4.75 $\pm$ 2.75) and Alphacep®-treated plots (26.5 $\pm$ 4.16) recording the lowest mean thrips population in the minor season and the control (112.43 $\pm$ 4.25) recording the highest, respectively (Table 6.3). In the Coastal Savannah, the thrips population was equally significantly affected by the insecticide treatments at 5DAS and 9DAS during the major ($F_{5, 23} = 21.37$, $P < 0.001$ and $F_{5, 23} = 12.36$, $P < 0.001$) and minor ($F_{5, 23} = 146.67$, $P < 0.001$ and $F_{5, 23} = 88.03$, $P < 0.001$) cropping seasons, respectively. Here, the control plots recorded significantly higher thrips population than all the other treatments at the different days after treatment application and the lowest population was counted on Agroclean®-treated plots at 3 and 9DAS and on Alphacep®-treated plots at 5DAS in the minor season.

Table 17. Effect of treatments on mean number (+ SE) of thrips at different days after application in the Deciduous Forest and Coastal Savannah Agroecological Zones in the major season. Data presented include pooled data of first, second and third sprays.

Treatment	Deciduous Forest (Dago)				Costal Savannah (UG)			
	1DBS	3DAS	5DAS	9DAS	1DBS	3DAS	5DAS	9DAS
Agroblaster®	30.25 (2.869)a	3.50 (0.841)a	8.25 (1.66)a	8.25 (2.77)a	18.00 (2.74)a	2.00 (0.41)a	3.25 (1.00)a	3.500 (1.30)a
Agroclean®	31.00 (2.887)a	5.25 (2.460)a	8.67 (2.92)a	8.50 (2.20)a	16.50 (3.52)a	1.5 (0.65)a	3.00 (0.41)a	3.5.00 (1.65)a
Viper®	31.75 (2.496)a	6.75 (1.481)a	18.58 (5.12)a	17.25 (6.21)a	20.50 (3.38)a	2.25 (0.85)a	15.5 (3.00)b	10.01 (4.00)b
Akape®	29.75 (2.869)a	2.83 (0.908)a	10.58 (3.06)a	7.33 (1.27)a	18.00 (2.12)a	2.25(0.90)a	4.25 (1.20)a	6.75 (2.36)a
Alphacep®	30.75 (3.224)a	1.83 (0.57)a	14.00 (3.37)a	11.50 (2.52)a	18.75 (2.90)a	1.25 (0.63)a	3.50 (0.29)a	9.25 (3.65)b
Control	34.50 (4.839)a	30.75 (3.010)b	41.00 (1.73)b	34.67 (3.58)b	24.50 (2.87)a	25.5 (3.12)b	27.75 (2.59)c	29.75 (2.63)c
F	0.27	38.18	15.19	9.031	0.91	43.03	21.37	12.363
P	0.926	< 0.001	< 0.001	< 0.001	0.494	< 0.001	< 0.001	< 0.001

Means with the same letters within rows are not significantly different from each other (Tukey test, 0.05). Standard errors are in parenthesis. 1DBS = one day before spray, 3DAS = 3 days after spray, 5DAS = 5 days after spray, 9DAS = 9 days after spray.

Table 18. Effect of treatments on mean number (± SE) of thrips at different days after application in the Deciduous Forest and Coastal Savannah Agroecological Zones in the minor season. Data presented include pooled data of first, second and third sprays.

Treatment	Deciduous Forest (Dago)				Costal Savannah (UG)			
	1DBS	3DAS	5DAS	9DAS	1DBS	3DAS	5DAS	9DAS
Agroblaster®	112.25 (11.60)a	14.08 (0.93)a	5.25 (0.25)a	12.15 (0.09)a	56.25 (3.54)a	3.50 (0.29)a	3.50 (1.44)a	18.00 (0.58)a
Agroclean®	97.25 (15.59)a	15.58 (0.63)a	4.75 (2.75)a	20.85 (3.55)a	58.75 (3.88)a	5.50 (2.59)a	1.50 (0.87)a	11.00 (0.00)a
Viper®	104.25 (15.59)a	21.08 (0.45)a	14.75 (6.47)a	42.35 (1.93)b	58.75 (4.29)a	3.50 (0.28)a	3.00 (0.58)a	19.00 (2.31)a
Akape®	101.75 (16.10)a	20.73 (3.53)a	5.75 (1.11)a	39.7 (1.73)cb	56.5 (4.09)a	2.50 (0.29)a	2.50 (0.29)a	6.00 (0.58)a
Alphacep®	133.5 (7.86)a	16.48 (3.18)a	9.75 (3.89)a	26.5 (4.16)a	57.50 (3.69)a	8.50 (2.02)a	1.50 (0.87)a	16.50 (2.02)a
Control	121.25 (13.59)a	108.75 (3.23)b	112.43 (4.25)b	114.5 (4.95)d	60.50 (4.09)a	62.50 (5.11)b	62.75 (4.57)b	75.75 (5.89)b
F	0.99	243.16	75.09	134.25	11.13	88.99	146.67	88.03
P	0.451	< 0.001	< 0.001	< 0.001	0.98	<0.001	< 0.001	< 0.001

Means with the same letters within rows are not significantly different from each other (Tukey test, 0.05). Standard errors are in parenthesis. 1DBS = one day before spray, 3DAS = 3 days after spray, 5DAS = 5 days after spray, 9DAS = 9 days after spray.

In the Deciduous Forest zone, the effect of the insecticide treatments on the percentage mean reduction of thrips was significant at 3DAS, 5DAS and 9DAS in the major ($F_{5, 23} = 58.82$, $P < 0.001$, $F_{5, 23} = 10.68$, $P < 0.001$, $F_{5, 23} = 10.59$, $P < 0.001$) and minor ($F_{5, 23} = 244.56$, $P < 0.001$, $F_{5, 23} = 56.06$, $P < 0.001$, $F_{5, 23} = 111.07$, $P < 0.001$) seasons, respectively. Plots treated with Alpha-cypermethrin reduced the abundance of thrips by 93.12%, 60.95% and 63.79% at 3DAS, 5DAS and 9DAS. The best treatment with the highest thrips reduction over the control included Alphacep®-treated plots at 3DAS (93.12%), Agroblaster®-treated plots at 5DAS (77.45%) and Akape®-treated plots at 9DAS (75.79%) during the major planting season. The most efficient treatment in reducing thrips population occurred 5DAS in the minor season on Agroblaster®-treated plots (94.96%) with the lowest percent thrips reduction at 9DAS on Akape® (57.88%) and Viper® plots (56.30%) (Figure 6.1). All treatments reduced thrips population and differed significantly from the control at all days after treatment application (Figure 6.1). In the Coastal Savannah zone, Alphacep®-treated plots had the highest percentage reduction in thrips population over the control at 3DAS (92.95%) and plots treated with Agroblaster® had the highest efficacy at 5DAS (85.81%) and 9DAS (83.00%). The lowest reduction occurred on Viper®-treated plots at 9DAS. The effect of treatment on percentage thrips population suppression was significant in the major season at 3DAS ($F_{5, 23} = 5.93$, $P = 0.002$), 5DAS ($F_{5, 23} = 19.93$, $P < 0.001$) and 9DAS ($F_{5, 23} = 6.78$, $P = 0.001$). Similarly, in the minor season, the treatment effect was significant at 3, 5 and 9DAS ($F_{5, 23} = 185.86$, $P < 0.001$, $F_{5, 23} = 673.89$, $P < 0.001$ and $F_{5, 23} = 194.48$, $P < 0.001$, respectively), where the treatments did not differ from each other but had significantly higher efficacies over the control.

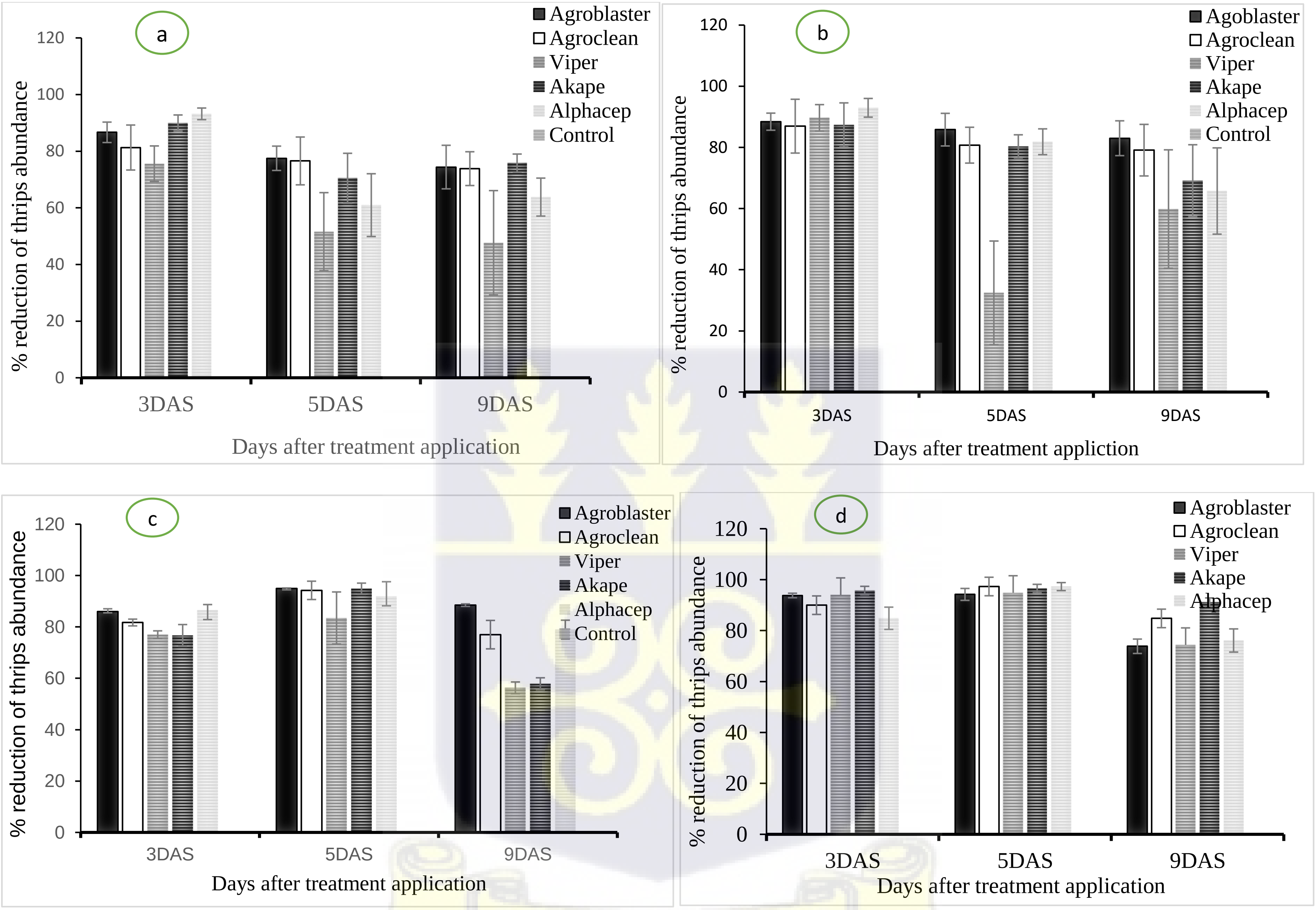

a
120
100
80
60
40
20
0
% reduction of thrips abundance
3DAS
5DAS
9DAS
Days after treatment application
■ Agroblaster
☐ Agroclean
▨ Viper
■ Akape
▨ Alphacep
▨ Control
b
120
100
80
60
40
20
0
% reduction of thrips abundance
3DAS
5DAS
9DAS
Days after treatment appliction
■ Agoblaster
☐ Agroclean
▨ Viper
■ Akape
▨ Alphacep
▨ Control
c
120
100
80
60
40
20
0
% reduction of thrips abundance
3DAS
5DAS
9DAS
Days after treatment application
■ Agroblaster
☐ Agroclean
▨ Viper
■ Akape
▨ Alphacep
▨ Control
d
120
100
80
60
40
20
0
% reduction of thrips abundance
3DAS
5DAS
9DAS
Days after treatment application
■ Agroblaster
☐ Agroclean
▨ Viper
■ Akape
▨ Alphacep

Figure 6.1. Efficacy of treatments in suppressing thrips population in the major and minor seasons in the Deciduous Forest and Coastal Savannah agroecological zones. (a) Deciduous Forest, major season, (b) Coastal Savannah, major season, (c) Deciduous Forest, minor season, and (d) Coastal Savannah, minor season. DAS = day after spray.

6.3.1.2 Effect of treatments on thrips damage

The colonization of the experimental eggplant with thrips resulted to damage or feeding injury on the leaves and flowers in both fields. However, more damage was observed on the flowers than the leaves at the two locations (Figure 6.2). The effect of the treatments on the mean flower damage and leaf injury were significant in the Deciduous Forest during the major ($F_{5, 23} = 10.53$, $P < 0.001$ and $F_{5, 23} = 50.01$, $P < 0.001$, respectively) and minor ($F_{5, 23} = 102.22$, $P < 0.001$ and $F_{5, 23} = 64.38$, $P < 0.001$) growing seasons, respectively. Plots treated with Agroclean® had the lowest mean feeding injury on leaves (1.18 ± 0.14) and flowers (1.68 ± 0.21), whilst control plots had consistently higher damage score on leaves and flowers (4.45 ± 0.27 and 4.70 ± 0.37, respectively). All treatments did not differ from each other with respect to the damage observed on both parts but differed significantly from the control for both the major and minor seasons ($P < 0.001$ and $P < 0.001$, respectively).

Similarly, in the Coastal Savannah zone, the major season saw a significant effect of the treatment on thrips injury on the leaves and flowers ($F_{5, 23} = 28.17$, $P < 0.001$ and $F_{5, 23} = 10.55$, $P < 0.001$) and the effect was likewise significant in the minor season ($F_{5, 23} = 22.19$, $P < 0.001$ and $F_{5, 23} = 110.35$, $P < 0.001$. Leaf injury score was lowest on Agroblaster®-treated plots (0.33 ± 0.10) and the highest was on the control plots (2.33 ± 0.33). The lowest flower damage score was recorded on plots treated with Agroblaster® (0.60 ± 0.12) and the highest was on the control plots (3.82 ± 1.26). All treatments differed significantly from the control ($P < 0.001$). A similar trend was observed in the minor season, except that the lowest damage was rather observed on Akape® plots (1.55 ± 0.13) (Figure 6.2).

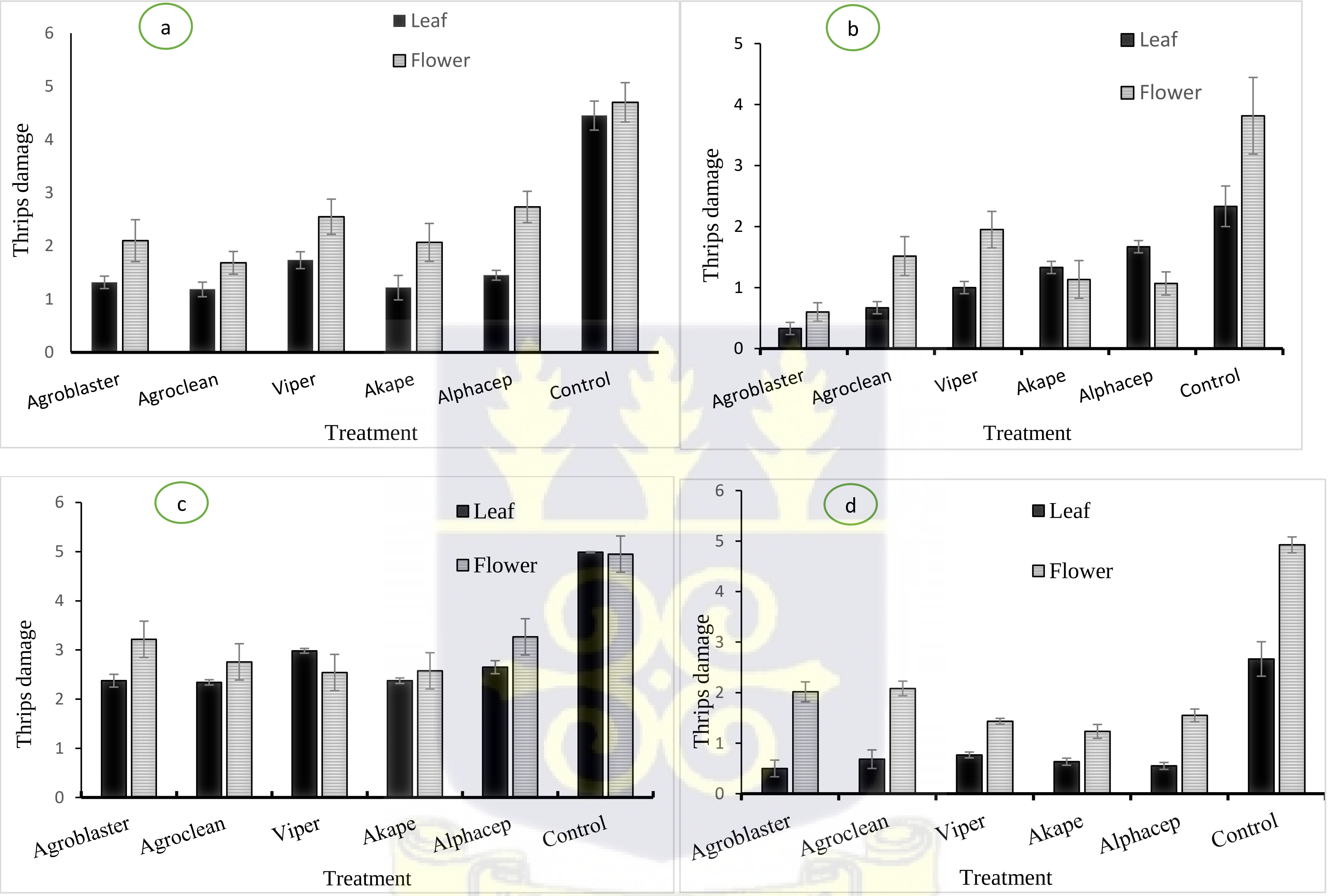

a
Leaf
Flower
Thrips damage
0
1
2
3
4
5
6
Agroblaster
Agroclean
Viper
Akape
Alphacep
Control
Treatment
b
Leaf
Flower
Thrips damage
0
1
2
3
4
5
Agroblaster
Agroclean
Viper
Akape
Alphacep
Control
Treatment
c
Leaf
Flower
Thrips damage
0
1
2
3
4
5
6
Agroblaster
Agroclean
Viper
Akape
Alphacep
Control
Treatment
d
Leaf
Flower
Thrips damage
0
1
2
3
4
5
6
Agroblaster
Agroclean
Viper
Akape
Alphacep
Control
Treatment

Figure 6.2. Effect of treatments on mean leaf and flower damage in the major and minor seasons in the Deciduous Forest and Coastal Savannah agroecological zones. (a) Deciduous Forest zone, major season, (b) Coastal Savannah zone, major season, (c) Deciduous Forest zone, minor season, and (d) Coastal Savannah zone, minor season.

6.3.1.3 Effect of treatments on thrips natural enemies

The effect of the insecticides on the mean number of Orius species was not significant at 1DBS, 3DAS, 5DAS and 9DAS in the major rainy season of the Deciduous Forest agroecological zone ($F_{5, 23} = 0.31$, $P = 0.901$, $F_{5, 23} = 0.41$, $P = 0.838$, $F_{5, 23} = 0.05$, $P = 0.998$, $F_{5, 23} = 0.55$, $P = 0.735$, respectively), but was significant at 9DAS in the minor rainy season ($F_{5, 23} = 5.80$, $P = 0.002$). During the major season in this location, plots treated with Agroblaster® recorded the highest mean pirate bug population at 1DBS, 3DAS and 9DAS (1.75 ± 0.63, 2.25 ± 1.45, 2.25 ± 0.63, respectively) and Akape®-treated plots recorded more population at 5DAS. In the minor season, Agroblaster®, Agroclean® and Viper®-treated plots had no initial record of the pirate bugs at one day before the insecticidal spray, but eventually recorded some population at 3DAS, 5DAS and 9DAS. Consistently, the control plot and Viper®-treated plots had the lowest *Orius* population at 1DBS and 3DAS, however, all the treatments did not differ significantly from the control, except at 9DAS in the minor season where Akape®-treated plots had significantly higher numbers (1.31 ± 0.09) than all the other treatments (Table 6.4). A similar trend was followed in the Coastal Savannah where, the lowest abundance was reported on Viper® plots at 3DAS and plots treated with Agroclean®, Viper® and Alphacep® did not record any *Orius* population at 9DAS for both seasons. The effect of effect treatment on mean *Orius* population was likewise not significant in the major and minor seasons as well as the different days after treatment application (Tables 28 and 29).

In the Deciduous Forest zone, the mean number of spiders was highest in the control and Agroblaster®-treated plots at 1DAS, Akape®-treated plots at 3DAS, Viper®-treated plots at 5DAS and 9DAS, however, differences between treatments were not significant in the major season ($F_{5, 23} = 0.95$, $P = 0.476$, $F_{5, 23} = 0.44$, $P = 0.814$, $F_{5, 23} = 0.78$, $P = 0.574$, and $F_{5, 23} = 1.38$, $P = 0.280$, respectively). The lowest spider population in the minor season was reported on Alphacep® plots at 3DAS and 9DAS which differed significantly from the other treatments at the respective days after treatment application. In the Coastal Savannah zone, Alpacep® plots recorded lower population of spiders which differed significantly from the higher population observed in other treatments in the minor season (Table 6.5). Just like the other zone, the effect of treatment was not significant at different days after spray ($F_{5, 23} = 2.35$, $P = 0.083$ and $F_{5, 23} = 0.75$, $P = 0.594$; 1DAS and 9DAS) in the Coastal Savannah except at 3DAS and 5DAS ($F_{5, 23} = 3.04$, $P = 0.037$ and $F_{5, 23} = 2.72$, $P = 0.045$) where Alphacep® had the lowest spider population which differed significantly from the other treatments including the control.

The coccinellids population was not significantly affected by the treatments in the major season in the Deciduous Forest agroecological zone ($F_{5, 23} = 0.36$, $P = 0.872$, $F_{5, 23} = 0.03$, $P = 0.999$, $F_{5, 23} = 0.04$, $P = 0.998$, and $F_{5, 23} = 0.4$, $P = 0.818$; 1DBS, 3DAS, 5DAS and 9DAS, respectively), even though, the abundance was more in plots treated with Akape® (2.00 ± 0.32) and Agroblaster® (1.00 ± 0.28) at 1DBS and 5DAS and lowest on all the other treatments at 5DAS. In the minor season, Agrobalaster® and Agroclean® had higher populations of ladybird beetles (1.50 ± 0.10 and 1.50 ± 0.10, respectively) throughout the sampling days which differed significantly from the other treatments at 3DAS ($F_{5, 23} = 13.00$, $P < 0.001$) and 9DAS ($F_{5, 23} = 31.80$, $P < 0.001$). Plots treated with Alphacep® consistently had no record of this natural enemy throughout the sampling days. The observed result on Alphacep®-treated plots was similar to the observation in the Coastal Savannah agroecological zone in the minor season, however, in the major season, ladybird beetles were recorded on Alphacep® plots with the highest population on Agroblaster®-treated plots (2.25 ± 0.26). The effect of treatment on the coccinellid population in the Coastal Savannah zone was not significant at 1DBS ($F_{5, 23}$ = 0.49, P = 0.780), 3DAS ($F_{5, 23}$ = 0.27, P = 0.923), 5DAS ($F_{5, 23}$ = 0.006, P = 0.997) and 9DAS ($F_{5, 23}$ = 0.42, P = 0.831).

The population of big-eyed bug was low in the major season with most treatments having low numbers and only Viper® and Akape® recorded big-eyed bug at 3DAS and Agroblaster® at 9DAS. The rest of the treatments did not record any population over the different sampling days. The treatments did not have any significant effect on the abundance of big-eyed in the Deciduous Forest zone in the major season ($F_{5, 23}$ = 0.22, P = 0.800, $F_{5, 23}$ = 0.80, P = 0.564, $F_{5, 23}$ = 0.91, P = 0.732, and $F_{5, 23}$ = 1.00, P = 0.446; 1DBS, 3DAS, 5DAS and 9DAS, respectively). Similarly, the treatments did not significantly affect the abundance of big-eyed bug in the Coastal Savannah zone ($F_{5, 23}$ = 1.73, P = 0.178, $F_{5, 23}$ = 0.64, P = 0.669, $F_{5, 23}$ = 0.72, P = 0.617, and $F_{5, 23}$ = 1.75, P = 0.177; 1DBS, 3DAS, 5DAS and 9DAS, respectively) although the control plots consistently recorded the highest numbers at different sampling days.

The abundance of praying mantis and the effect of treatment was not significant in both agroecological zones in the major and minor seasons (Tables 6.4 and 6.5).

Table 19. Effect of treatments on mean number (± SE) of natural enemies at different days after application in the Deciduous Forest and Coastal Savannah Agroecological Zones in the major season. Data presented include pooled data of first, second and third sprays.

Natural enemy	Treatment	Deciduous Forest (Dago)				Coastal Savannah (UG)			
		1DBS	3DAS	5DAS	9DAS	1DBS	3DAS	5DAS	9DAS
Pirate bugs	Agroblaster®	1.44 (0.25)	2.25 (0.46)	1.06 (0.35)	2.25 (0.18)	0.75 (0.21)	1.05 (0.28)	1.00 (0.27)	-
	Agroclean®	1.13 (0.28)	0.99 (0.29)	1.06 (0.35)	0.99 (0.29)	0.75 (0.29)	0.75 (0.29)	0.75 (0.29)	-
	Viper®	0.99 (0.29)	0.99 (0.29)	0.99 (0.29)	1.13 (0.27)	0.75 (0.29)	0.50 (0.21)	0.75 (0.29)	-
	Akape®	1.29 (0.33)	1.06 (0.35)	1.22 (0.30)	1.35 (0.38)	1.00 (0.28)	0.75 (0.28)	0.75 (0.28)	1.00 (0.55)
	Alphacep®	1.13 (0.27)	0.99 (0.29)	1.19 (0.33)	1.26 (0.24)	0.25 (0.13)	0.75(0.29)	0.50 (0.22)	-
	Control	0.99 (0.29)	0.98 (0.28)	1.13 (0.28)	1.13 (0.27)	0.75 (0.29)	0.75 (0.25)	0.75 (0.30)	-
	F	0.31	0.41	0.47	0.55	0.15	0.02	0.05	1.46
	P	0.901	0.838	0.998	0.735	0.979	1.000	0.997	0.042
Ladybird beetles	Agroblaster®	1.00 (0.35)	0.75 (0.07)	1.00 (0.28)	0.75 (0.27)	3.25 (0.19)	2.25 (0.26)	1.00 (0.27)	1.00 (0.35)
	Agroclean®	0.75 (0.29)	1.00 (0.25)	0.75 (0.29)	0.75 (0.27)	2.00 (0.29)	1.50 (0.16)	1.25 (0.40)	0.75 (0.21)
	Viper®	0.75 (0.29)	0.75 (0.07)	0.75 (0.29)	1.00 (0.29)	1.75 (o.25)	1.25 (0.24)	0.75 (0.29)	0.25 (0.13)
	Akape®	2.00 (0.32)	0.75 (0.06)	0.75 (0.29)	2.00 (0.29)	1.25 0.41)	1.00 (0.28)	0.75 (0.29)	0.75 (0.29)
	Alphacep®	1.00 (0.28)	0.74 (0.07)	0.75 (0.29)	0.75 (0.31)	1.750.39)	1.50 (0.39)	1.00 (0.28)	0.25 (0.12)
	Control	1.00 (0.27)	1.00 (0.06)	0.75 (0.29)	0.29 (0.10)	2.25(0.33)	1.50 (0.25)	0.75 (0.29)	1.25 (0.24)
	F	0.36	0.03	0.04	0.44	0.49	0.27	0.006	0.42
	P	0.872	0.999	0.998	0.818	0.780	0.923	0.997	0.831
Big-eyed bug	Agroblaster®	-	-	-	0.25 (0.13)	1.50 (0.30)	1.50 (0.35)	0.50 (0.22)	0.50 (0.22)
	Agroclean®	-	-	-	-	0.75 (0.21)	0.75 (0.21)	-	-
	Viper®	-	0.25 (0.12)	-	-	0.25 (0.26)	-	0.25 (0.13)	-
	Akape®	-	-	-	-	-	-	-	-
	Alphacep®	-	0.25 (0.13)	-	-	-	-	-	-
	Control	-	-	-	-	0.75 (0.43)	0.50 (0.22)	0.50 (o.22)	0.75 (0.29)
	F	0.22	0.80	0.91	1.00	1.39	1.55	0.64	0.82
	P	0.800	0.564	0.73	4.46	0.277	0.225	0.669	0.554

Spider	Agroblaster®	1.13 (0.28)	0.84 (0.13)	1.06 (0.21)	1.26 (0.24)	2.75 (0.28)	2.25 (0.48)	1.75 (0.38)	1.50 (0.25)
	Agroclean®	1.49 (0.09)	0.83 (0.13)	0.84 (0.13)	0.83 (0.12)	3.50 (0.21)	1.00 (0.28)	1.00 (0.28)	2.00 (0.32)
	Viper®	1.06 (0.38)	0.84 (0.12)	1.18 (0.18)	0.84 (0.13)	3.25 (0.57)	1.75 (0.35)	2.00 (0.32)	1.00 (0.28)
	Akape®	1.31 (0.08)	1.19 (0.33)	0.84 (0.12)	0.97 (0.15)	1.25 (0.30)	2.25 (0.23)	1.25 (0.33)	2.25 (0.36)
	Alphacep®	1.18 (0.18)	1.00 (0.29)	1.14 (0.25)	0.84 (0.24)	2.25 (0.48)	1.00 (0.35)	075 (0.29)	0.75 (0.29)
	Control	1.40 (0.10)	0.97 (0.15)	1.18 (0.17)	1.27 (0.23)	3.25 (0.23)	2.25 (0.18)	1.75 (0.30)	1.50 (0.25)
	F	0.95	0.44	0.78	1.38	0.424	0.35	0.32	0.49
	P	0.476	0.814	0.574	0.280	0.826	0.875	0.897	0.778
Praying mantis	Agroblaster®	-	-	-	-	-	1.50 (0.38)	1.00 (0.35)	1.25 (0.30)
	Agroclean®	-	-	-	-	-	0.75 (0.21)	-	0.75 (0.21)
	Viper®	-	-	-	-	-	-	0.50 (0.15)	0.75 (0.21)
	Akape®	-	-	-	-	-	-	0.50 (0.22)	-
	Alphacep®	-	-	-	-	-	-	-	-
	Control	-	-	-	-	0.75 (0.27)	0.50 (0.22)	0.50 (0.22)	0.78 (0.21)
	F				-	1.00	1.14	0.54	1.16
	P					0.446	0.375	0.75	0.366

Means with the same letters within rows are not significantly different (Tukey, 0.05). Standard errors are in parenthesis. 1DBS = one day before spray, 3DAS = 3 days after spray, 5DAS = 5 days after spray, 9DAS = 9 days after spray. – no recorded natural enemy.

Table 20. Effect of treatments on mean number (+ SE) of natural enemies at different days after application in the Deciduous Forest and Coastal Savannah Agroecological Zones in the minor season. Data presented include pooled data of first, second and third sprays.

Natural enemy	Treatment	Deciduous Forest (Dago)				Costal Savannah (UG)			
		1DBS	3DAS	5DAS	9DAS	1DBS	3DAS	5DAS	9DAS
Pirate bugs	Agroblaster®	-	0.70 (0.00)	0.70 (0.00)	1.09 (0.12)a	0.25 (0.12)	2.00 (0.13)a	0.75 (0.21)	1.00 (0.25)
	Agroclean®	-	0.837 (0.13)	0.71 (0.00)	1.10 (0.13)a	0.50 (0.22)	1.75 (0.09)a	0.25 (0.12)	-
	Viper®	-	0.84 (0.13)	0.70 (0.00)	0.71 (0.00)a	0.75 (0.21)	-	0.25 (0.13)	-
	Akape®	0.76 (0.21)	0.83 (0.12)	0.71 (0.00)	1.31 (0.09)ba	-	1.25 (0.18)ab	-	-
	Alphacep®	0.25 (0.13)	0.71 (0.00)	0.97 (0.15)	0.71 (0.00)a	-	1.25 (0.18)ab	-	-
	Control	0.73 (0.21)	0.707100	0.96 (0.15)	1.09 (0.13)a	0.50 (0.22)	1.75 (0.31)a	0.50 (0.220	0.25 (0.130
	F	1.56	0.60	2.40	5.80	0.70	5.31	0.85	2.43
	P	0.222	0.701	0.078	0.002	0.634	0.004	0.53	0.075
Ladybird beetles	Agroblaster®	0.25 (0.12)	1.50 (0.10)a	1.00 (0.18)	1.00 (0.00)a	0.50 (0.15)	1.50 (0.34)	2.75 (0.07)ab	2.00 (0.28)
	Agroclean®	-	1.50 (0.10)a	1.00 (0.25)	1.00 (0.00)a	0.75 (0.29)	1.75 (0.09)	1.50 (0.22)b	1.00 (0.25)
	Viper®	0.25 (0.12)	-	0.51 (0.22)	-	-	1.00 (0.18)	0.75 (0.13)abc	0.50 (0.140
	Akape®	-	0.50 (0.15)b	-	-	-	1.25 (0.20)	1.50 (0.21)b	1.00 (0.25)
	Alphacep®	-	-	-	-	-	-	-	-
	Control	-	-	0.25 (0.12)	1.50 (0.10)a	0.50 (0.22)	2.25 (0.29)	2.50 (0.16)ab	1.75 (0.28)
	F	0.80	13.00	1.55	31.80	0.74	1.98	7.37	1.86
	P	0.564	< 0.001	0.223	< 0.001	0.604	0.130	0.001	0.153
Big-eyed bug	Agroblaster®	0.96 (0.15)	-	1.00 (0.29)	0.93 (0.22)	1.00 (0.28)	0.50 (0.22)	1.00 (0.25)	0.75 (0.21)
	Agroclean®	0.71 (0.00)	-	0.93 (0.01)	0.84 (0.13)	0.75 (0.21)	-	0.75 (0.21)	-
	Viper®	0.97(0.14)	-	0.70 (0.00)	0.71 (0.00)	-	-	0.25 (0.13)	-
	Akape®	0.70 (0.00)	-	0.71 (0.00)	0.84 (0.13)	-	0.25 (0.13)	0.25 (0.13)	-
	Alphacep®	0.71 (0.00)	-	0.71 (0.00)	0.71 (0.00)	-	-	-	-
	Control	0.71 (0.00)	-	1.22 (0.30)	0.92 (0.22)	-	0.51 (0.22)	0.75 (0.29)	0.25 (0.13)
	F	2.40	-	1.16	0.48	1.73	0.64	0.72	1.75

	P	0.078	-	0.365	0.787	0.178	0.669	0.617	0.177
Spider	Agroblaster®	5.00 (0.82)	5.00 (0.00)a	8.00 (0.120)a	8.00 (1.73)a	5.00 (0.26	1.25 (0.47)a	3.00 (0.26)a	2.00 (0.15)
	Agroclean®	8.25 (1.11)	5.00 (0.71)a	11.00 ().19)b	4.00 (0.58)ab	3.25 (0.53)	3.50 (0.22)a	3.75 (0.07)ab	2.75 (0.48)
	Viper®	5.00 (1.47)	5.25 (0.85)a	2.00 (0.10)b	8.00 (0.00)a	4.00 (0.34)	1.00 (0.41)a	3.50 (0.15)a	2.00 (0.15)
	Akape®	5.50 (1.66)	5.50 (0.50)a	12.00 (0.23)d	6.00 (0.58)ab	3.25 (0.07)	1.00 (0.40)a	4.50 (0.13)a	2.00 (0.15)
	Alphacep®	5.00 (0.71)	2.00 (0.57)b	6.00e	1.50 (0.29)b	2.75 (0.14)	0.25 (0.10)b	1.75 (0.41)ac	2.00 (0.21)
	Control	4.75 (1.03)	4.75 (0.63)a	14.00 (0.25)f	5.50 (1.44)ab	7.25 (0.34)	1.75 (0.10)a	4.50 (0.12)ab	1.25 (0.10)
	F	1.27	4.53	5.377	6.38	2.35	3.04	2.72	0.75
	P	0.321	0.008	0.002	0.001	0.083	0.037	0.045	0.594
Praying mantis	Agroblaster®	-	0.24 (0.03)	1.00 (0.28)	0.25 (0.13)	1.00 (0.25)	0.25 (0.13)	1.00 (0.30)	1.25 (0.300
	Agroclean®	-	0.25 (0.02)	0.50 (0.21)	0.25 (0.13)	0.75 (0.29)	-	0.75 (0.29)	-
	Viper®	0.25 (0.12)	-	-	0.50 (0.22)	0.25 (0.13)	-	0.50 (0.21)	-
	Akape®	-	-	-	0.24 (0.13)	-	-	-	-
	Alphacep®	-	-	-	-	-	-	-	-
	Control	-	-	0.54 (0.22)	0.25 (0.12)	0.50 (0.22)	-	0.75 (0.29)	0.50 (0.22)
	F	1.00	0.80	1.00	0.30	0.83	1.00	0.44	1.92
	P	0.446	0.564	0.446	0.906	0.546	0.446	0.813	0.140

Means with the same letters within rows are not significantly different (Tukey, 0.05). Standard errors are in parenthesis. 1DBS = one day before spray, 3DAS = 3 days after spray, 5DAS = 5 days after spray, 9DAS = 9 days after spray. – no recorded natural enemy.

6.3.1.4 Phytotoxic effects of treatments on the crop

At one day before the treatments were applied, 100% of plants assessed in all treatments were fully green and healthy with no symptoms of phytotoxicity in both the major and minor rainy seasons of both agroecological zones (Figure 6.3). At 3DAS, whilst 100% of the sampled plants in all the other treatments showed no injury, the situation was different with Alphacep®-treated plots, where 90% were not injured, 9.08% were slightly injured and 0.92% were highly injured in the major season of the Deciduous Forest zone. At 5DAS, 99.25% of the Alphacep®-treated plots had no toxicity, 0.75% were slightly phytotoxic with no phytotoxicity at 9DAS just like the rest of the other treatments. In the major season, 30.03% of the plants were slightly phytotoxic at 3DAS but the plants had recovered by 9DAS where 96.68% showed no phytotoxic symptoms and only 0.83% still had slight injury. In the Coastal Savannah agroecological zone, whilst 100% of the sampled plants were not phytotoxic in all treatments before spray (1DBS), Alphacep®-treated plots had 29.19% (strong) injured plants at 3DAS, 26.65% (slight) at 5DAS and 2.5% (slight) at 9DAS, with no plant injury in other treatments in the minor season. The trend was similar in the major season where phytotoxicity was rather mild (3.25%) with 96.75% of the plants showing no deformation (Figure 6.3).

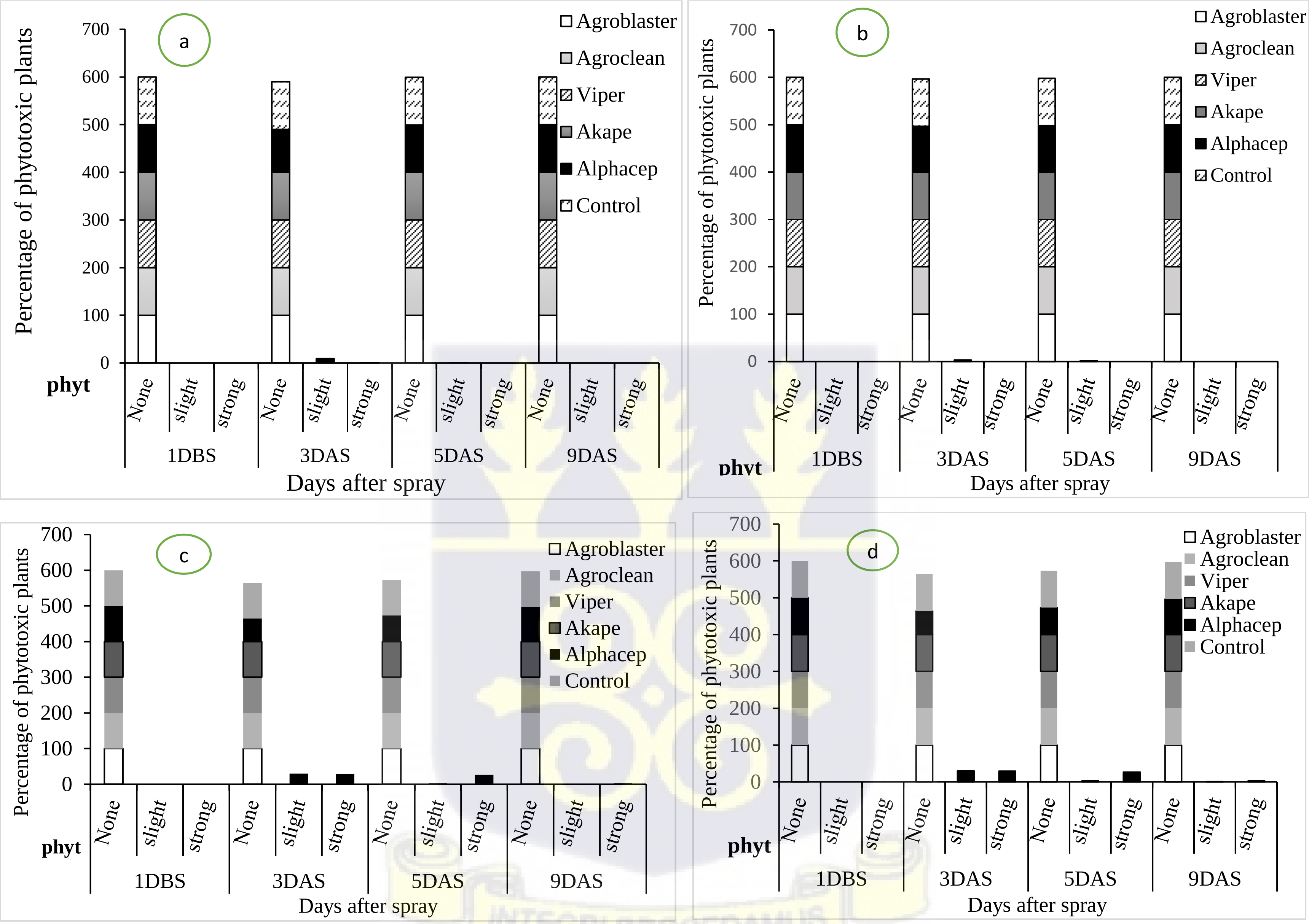
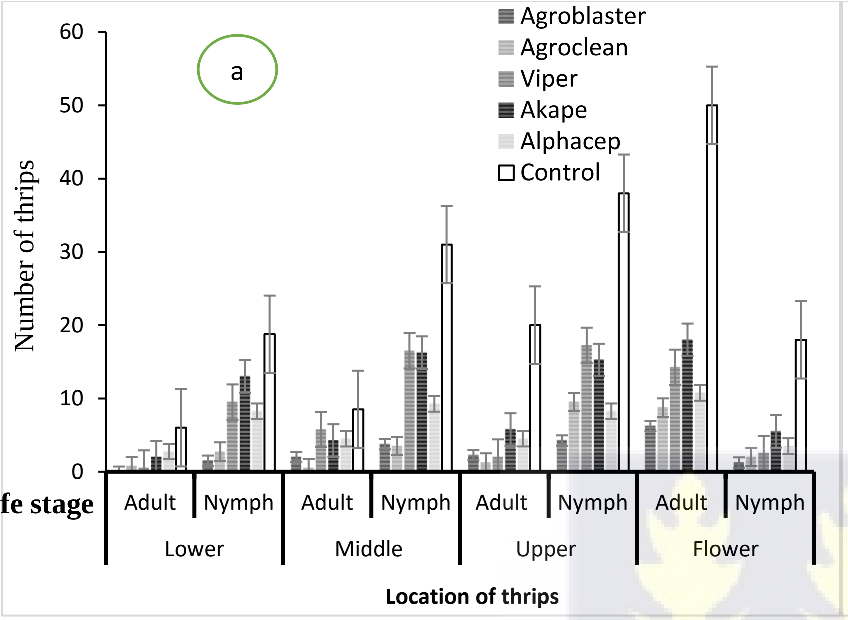

a
b
c
d
Percentage of phytotoxic plants
0
100
200
300
400
500
600
700
Agroblaster
Agroclean
Viper
Akape
Alphacep
Control
phyt
None
slight
strong
1DBS
3DAS
5DAS
9DAS
Days after spray

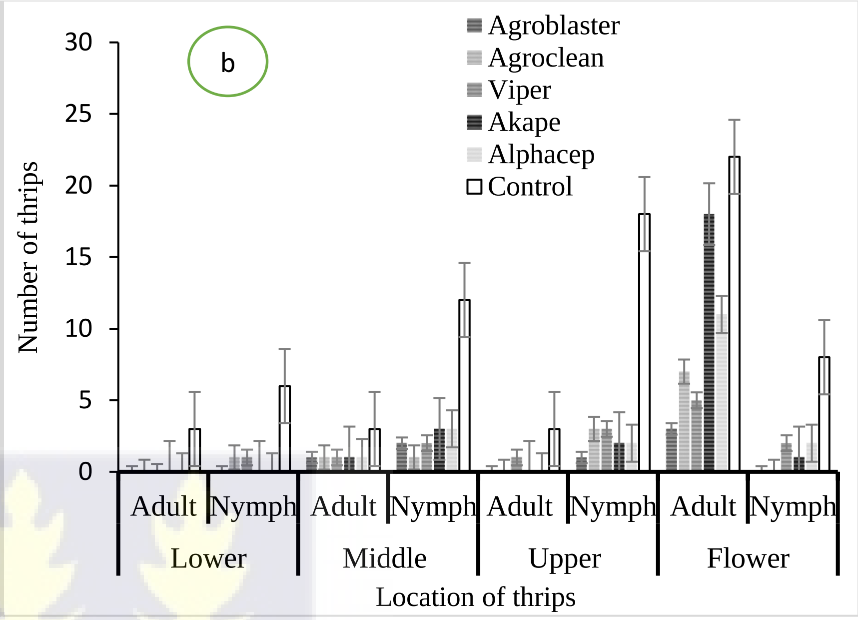
Figure 6.3. Phytotoxic effect of treatments at different days after application in the major and minor seasons in the Deciduous Forest and Coastal Savannah agroecological zones. (a) Deciduous Forest zone, major season, (b) Coastal Savannah zone, major season, (c) Deciduous Forest zone, minor season, and (d) Coastal Savannah zone, minor season. Phyt = phytotoxicity. DBS = day before spray, DAS = day after spray.

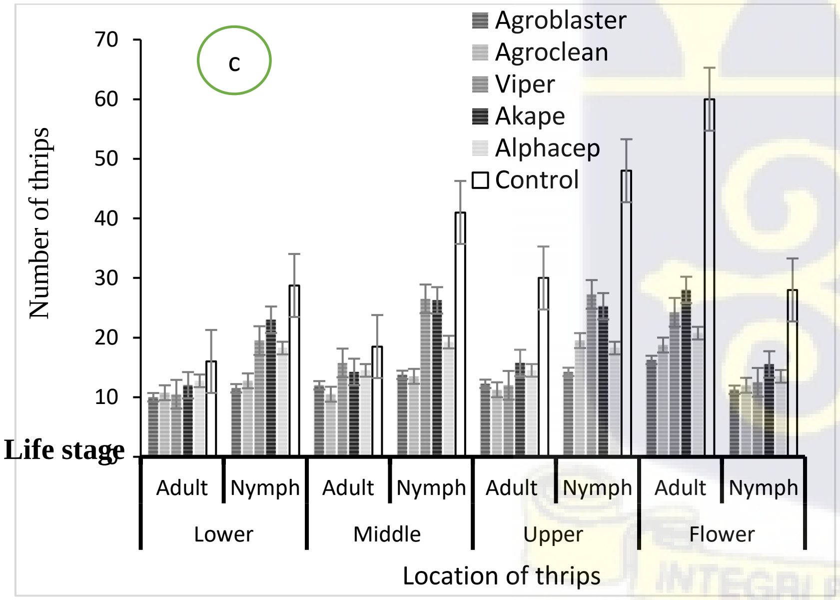
6.3.1.5 Within-plant distribution of thrips

Thrips were found on various parts of the plants sampled, including the leaves (lower, middle and upper leaves) and flowers. More thrips were sampled on flowers, followed by the upper leaves than the other parts of the plants across the different treatments (Figure 6.4). The population of thrips was lowest on the lower leaves which differed significantly from the rest of the sampled plant part in both seasons (0.92 ± 0.1 and 10.75 ± 1.00) in the Coastal Savannah ($F_{3, 9} = 26.53$, $P < 0.001$ and $F_{3, 9} = 5.20$, $P = 0\ 002$) and Deciduous Forest ($F_{3, 9} = 7.87$, $P < 0.001$ and $F_{3, 9} = 17.87$, $P < 0.001$) zones. The effect of insecticide treatments significantly affected the location of thrips on the plant in the major and minor seasons of the Coastal Savannah agroecological zone ($F_{5, 60} = 23.60$, $P < 0.001$ and $F_{5, 60} = 91.01$, $P < 0.001$), where the effect of the insecticides differed significantly from that of the control ($P < 0.001$). In the Deciduous Forest zone, the treatments likewise had a significant influence on the location of thrips on the plant in the Major ($F_{5, 60} = 95.43$, $P < 0.001$) and minor ($F_{5, 60} = 90.25$, $P < 0.001$) cropping seasons. Here, the flowers had significantly higher mean number of thrips (11.73 ± 0.91 and 21.73 ± 2.1) compared to that found on the lower leaves (5.48 ± 0.12 and 12.66 ± 2.11) and plots treated with Agroblaster® recorded lower thrips population compared to the control for all the sampled plant parts (Figure 6.4).

Throughout both seasons and in all locations, adult thrips showed high preference for flowers whilst nymphs preferred the leaves.


a
Agroblaster
Agroclean
Viper
Akape
Alphacep
☐ Control
Number of thrips
0
10
20
30
40
50
60
Life stage
Adult
Nymph
Adult
Nymph
Adult
Nymph
Adult
Nymph
Lower
Middle
Upper
Flower
Location of thrips


b
Agroblaster
Agroclean
Viper
Akape
Alphacep
☐ Control
Number of thrips
0
5
10
15
20
25
30
Adult
Nymph
Adult
Nymph
Adult
Nymph
Adult
Nymph
Lower
Middle
Upper
Flower
Location of thrips


c
Agroblaster
Agroclean
Viper
Akape
Alphacep
☐ Control
Number of thrips
0
10
20
30
40
50
60
70
Life stage
Adult
Nymph
Adult
Nymph
Adult
Nymph
Adult
Nymph
Lower
Middle
Upper
Flower
Location of thrips

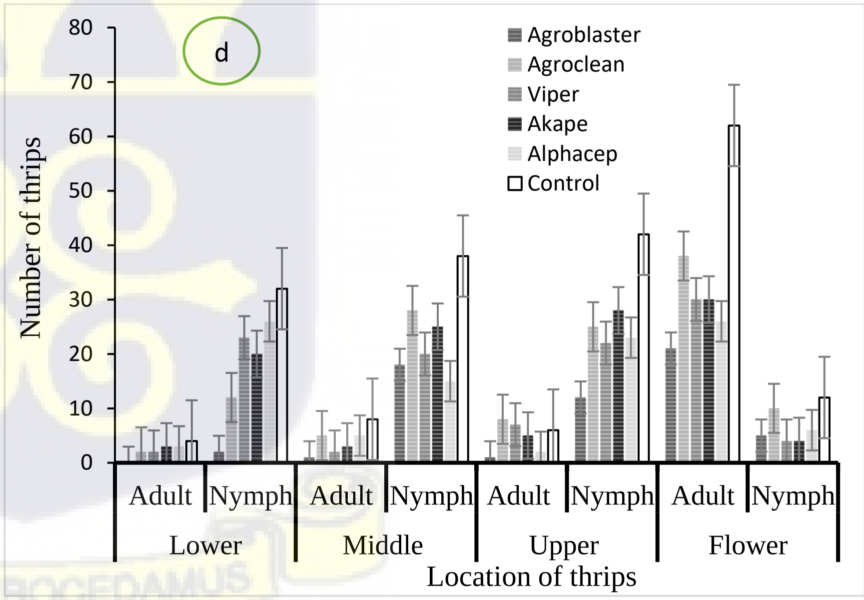

d
Agroblaster
Agroclean
Viper
Akape
Alphacep
☐ Control
Number of thrips
0
10
20
30
40
50
60
70
80
Adult
Nymph
Adult
Nymph
Adult
Nymph
Adult
Nymph
Lower
Middle
Upper
Flower
Location of thrips

Figure 6.4. Effect of treatments on within-plant distribution of thrips in the major and minor seasons in the Deciduous Forest and Coastal Savannah agroecological zones. (a) Deciduous Forest zone, major season, (b) Coastal Savannah zone, major season, (c) Deciduous Forest zone, minor season and (d) Coastal Savannah zone, minor season.

6.3.1.6 Effect of treatments on other pests

6.3.1.6.1 Whiteflies

The initial *B. tabaci* population was not significantly different before the treatments were applied in the different seasons in the two agroecological zones (Deciduous Forest; $F_{5, 23} = 0.03$, $P = 0.997$ and $F_{5, 23} = 0.05$, $P = 0.999$ and Coastal Savannah; $F_{5, 23} = 0.09$, $P = 0.9993$. and $F_{5, 23} = 0.16$, $P = 0.976$, respectively), however, at 3, 5 and 9DAS, the treatments contributed significantly to the whitefly's abundance in the different zones (Figure 6.5). In the major season, the lowest abundance was found on Alphacep®-treated plots whilst in the minor season, plots treated with Agroblaster® and Agroclean® had lower populations of this pest at 3, 5 and 9DAS which differed significantly from the highest population recorded in the control plots (53 ± 3.11, 42.75 ± 10.96, 56 ± 9.79; 1DBS, 3DAS and 5DAS, respectively) in the Deciduous Forest zone (Figure 6.5).

In the Coastal Savannah agroecological zone, Akape® and Viper®-treated plots recorded the lowest whiteflies and the treatments significantly contributed to the *B. tabaci* population at different days after application in the major cropping season ($F_{5, 23} = 3.49$, $P = 0.022$, $F_{5, 23} = 7.59$, $P = 0.001$ and $F_{5, 23} = 12.34$, $P < 0.001$; 3DAS, 5DAS and 9DAS, respectively). In the minor season, Akape®-treated plots had the lowest *B. tabaci* population at 3DAS (0.75 ± 0.25) and 5DAS (1.00 ± 0.58) and Alphacep® plots had the least population at 9DAS (3.75 ± 1.50) which differed significantly from the control (37.25 ± 7.91) but not among the others ($P < 0.001$). Overall, the population was lowest at 3DAS and started increasing by 9DAS (Fig 15).

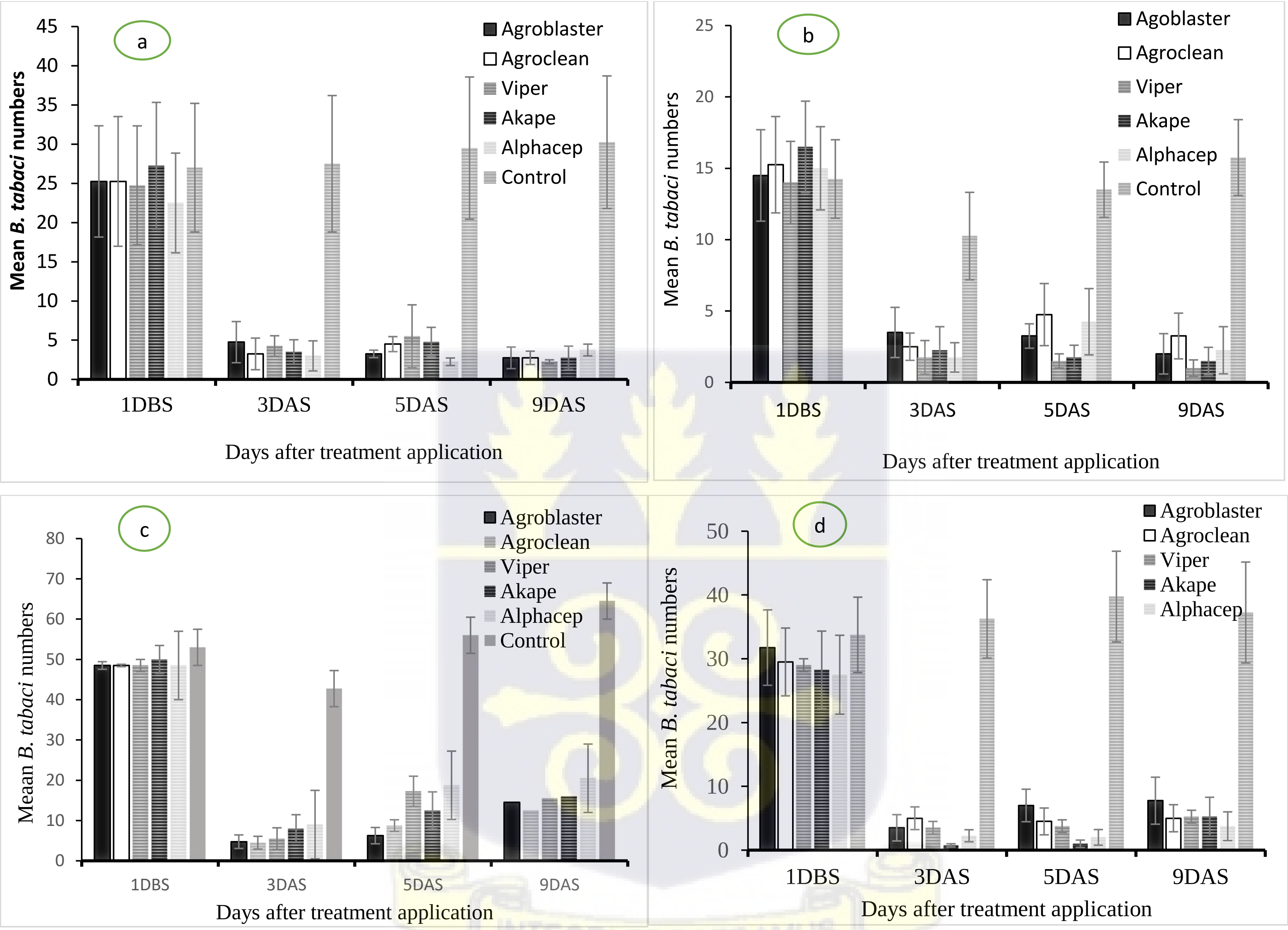

a
Mean B. tabaci numbers
45
40
35
30
25
20
15
10
5
0
Agroblaster
Agroclean
Viper
Akape
Alphacep
Control
1DBS
3DAS
5DAS
9DAS
Days after treatment application
b
Mean B. tabaci numbers
25
20
15
10
5
0
Agoblaster
Agroclean
Viper
Akape
Alphacep
Control
1DBS
3DAS
5DAS
9DAS
Days after treatment application
c
Meaan B. tabaci numbers
80
70
60
50
40
30
20
10
0
Agroblaster
Agroclean
Viper
Akape
Alphacep
Control
1DBS
3DAS
5DAS
9DAS
Days after treatment application
d
Mean B. tabaci numbers
50
40
30
20
10
0
Agroblaster
Agroclean
Viper
Akape
Alphacep
1DBS
3DAS
5DAS
9DAS
Days after treatment application

Figure 7. Effect of treatment on *B. tabaci* mean population (± SE) in the major and minor seasons in the Deciduous Forest and Coastal Savannah agroecological zones. (a) Deciduous Forest zone, major season, (b) Coastal Savannah zone, major season, (c) Deciduous Forest zone, minor season and (d) Coastal Savannah zone, minor season. DBS = day before spray, DAS = day after spray.

6.3.1.6.2 Aphids

Similar to whiteflies, the aphids population (*Myzus persicae* and *Aphis craccivora*) was significantly affected by the treatments at 3, 5 and 9DAS but not before spray (1DBS) during the major and minor cropping seasons in both locations (Deciduous Forest, minor season; $F_{5, 23} = 0.02$, $P = 1.000$, $F_{5, 23} = 14.14$, $P < 0.001$, $F_{5, 23} = 14.84$, $P < 0.001$, $F_{5, 23} = 5.13$, $P = 0.004$ and Coastal Savannah, minor season; $F_{5, 23} = 0.08$, $P = 1.000$, $F_{5, 23} = 5.00$, $P < 0.001$, $F_{5, 23} = 9.54$, $P < 0.001$, $F_{5, 23} = 10.07$, $P < 0.001$; 1DBS, 3DAS, 5DAS and 9DAS, respectively). In the major season of the Deciduous Forest zone, experimental plots treated with Agroblaster® and Agroclean® did not record any aphids at 3DAS, where all plots generally had low aphids after treatments were applied, but the population started increasing 9DAS in the different treatments. Alphacep® plots recorded the lowest mean number of aphids than the other treatments at 3 and 9DAS, with the highest abundance on control plots during the minor season (Figure 6.6). In the Coastal Savannah, Viper®, Akape® and Alphacep® had little or no aphid population at the different days after spray, whilst the highest was found on the control. In the minor season, plots sprayed with Viper® had the lowest number of aphids at 3 and 5DAS and the control had the highest abundance at all days after application. Additionally, the aphids' population on the control at 1DBS increased through 5DAS to 9DAS for all seasons.

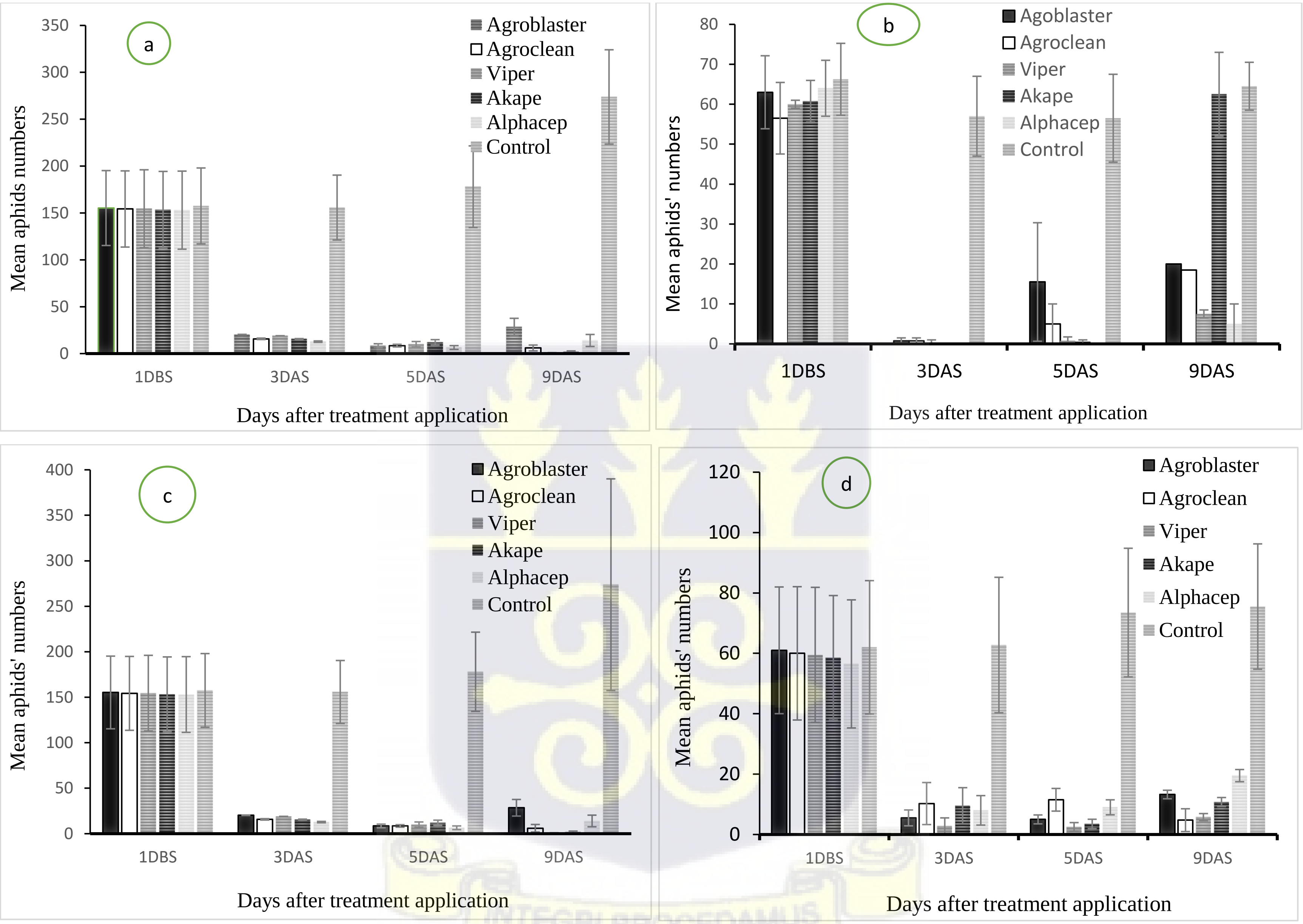

a
Mean aphids numbers
350
300
250
200
150
100
50
0
1DBS
3DAS
5DAS
9DAS
Days after treatment application
■ Agroblaster
☐ Agroclean
▨ Viper
■ Akape
▨ Alphacep
▨ Control
b
Mean aphids' numbers
80
70
60
50
40
30
20
10
0
1DBS
3DAS
5DAS
9DAS
Days after treatment application
■ Agoblaster
☐ Agroclean
▨ Viper
■ Akape
▨ Alphacep
▨ Control
c
Mean aphids' numbers
400
350
300
250
200
150
100
50
0
1DBS
3DAS
5DAS
9DAS
Days after treatment application
■ Agroblaster
☐ Agroclean
▨ Viper
■ Akape
▨ Alphacep
▨ Control
d
Mean aphids' numbers
120
100
80
60
40
20
0
1DBS
3DAS
5DAS
9DAS
Days after treatment application
■ Agroblaster
☐ Agroclean
▨ Viper
■ Akape
▨ Alphacep
▨ Control

Figure 8. Effect of treatment on aphids' mean population (± SE) in the major and minor seasons in the Deciduous Forest and Coastal Savannah agroecological zones. (a) Deciduous Forest zone, major season, (b) Coastal Savannah zone, major season, (c) Deciduous Forest zone, minor season and (d) Coastal Savannah zone, minor season. DBS = day before spray, DAS = day after spray.

6.3.1.6.3 Grasshoppers

At one day before the different insecticides were applied, count of *Z. variegatus* population revealed no significant difference between the treatments in the major and minor seasons of both agroecological zones (Deciduous Forest; $F_{5, 23} = 0.06$, $P = 0.997$ and $F_{5, 23} = 1.17$, $P = 0.361$, respectively and Coastal Savannah; $F_{5, 23} = 0.37$, $P = 0.859$ and $F_{5, 23} = 307$, $P = 0.361$). However, at 3, 5 and 9DAS, the effect of treatments on mean numbers of *Z. variegatus* were significant for both seasons and zones (Deciduous Forest; $F_{5, 23} = 9.45$, $P < 0.001$, $F_{5, 23} = 4.59$, $P = 0.007$ and $F_{5, 23} = 1.17$, $P < 0.001$ and $F_{5, 23} = 17.23$, $P < 0.001$, $F_{5, 23} = 211.64$, $P < 0.001$ and, $F_{5, 23} = 537.44$, $P < 0.001$ and Coastal Savannah; $F_{5, 23} = 11.82$, $P < 0.001$, $F_{5, 23} = 30.57$, $P < 0.001$ and $F_{5, 23} = 39.40$, $P < 0.001$ and $F_{5, 23} = 44.66$, $P < 0.001$, $F_{5, 23} = 28.41$, $P < 0.001$ and, $F_{5, 23} = 23.72$, $P < 0.001$; 3DAS, 5DAS and 9DAS, respectively) (Figure 6.7). Plots treated with Alphacep® had consistently lowest number of grasshoppers at 5 and 9DAS, followed by Akape®-treated plots, with the highest in the control plots in the Deciduous Forest agroecological zone. The lowest *Z. variegatus* population occurred 3DAS on Alphacep® plots (0.25 ± 0.01), followed by 5DAS on Viper® and Akape® plots (0.75 ± 0.12 and 0.76 ± 0.13) in the major season of the Coastal Savannah zone.

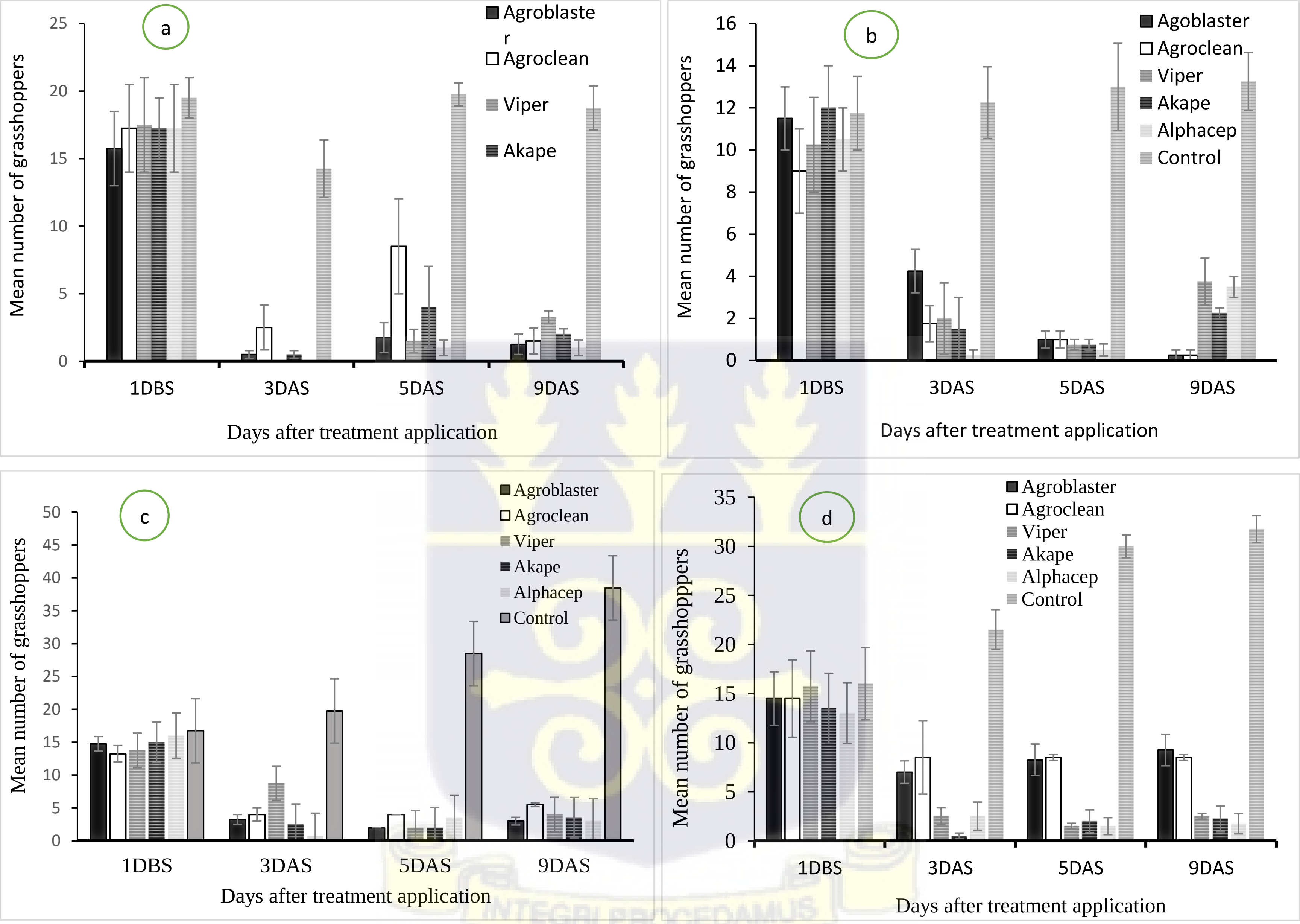

a
Mean number of grasshoppers
0
5
10
15
20
25
1DBS
3DAS
5DAS
9DAS
Days after treatment application
■ Agroblaste r
☐ Agroclean
▨ Viper
■ Akape
b
Mean number of grasshoppers
0
2
4
6
8
10
12
14
16
1DBS
3DAS
5DAS
9DAS
Days after treatment application
■ Agoblaster
☐ Agroclean
▨ Viper
■ Akape
▨ Alphacep
▨ Control
c
Mean number of grasshoppers
0
5
10
15
20
25
30
35
40
45
50
1DBS
3DAS
5DAS
9DAS
Days after treatment application
■ Agroblaster
☐ Agroclean
▨ Viper
■ Akape
▨ Alphacep
▨ Control
d
Mean number of grasshopppers
0
5
10
15
20
25
30
35
1DBS
3DAS
5DAS
9DAS
Days after treatment application
■ Agroblaster
☐ Agroclean
▨ Viper
■ Akape
▨ Alphacep
▨ Control

Figure 9. Effect of treatments on *Z. variegatus* mean population ($\pm$ SE) in the major and minor seasons in the Deciduous Forest and Coastal Savannah agroecological zones. (a) Deciduous Forest zone, major season, (b) Coastal Savannah zone, major season, (c) Deciduous Forest zone, minor season and (d) Coastal Savannah zone, minor season. DBS = day before spray, DAS = day after spray.

6.3.1.6.4 Leaf hoppers

Apart from 1DBS, *Empoasca* species recorded at 3, 5 and 9DAS were significantly affected by the treatments in the major and minor seasons in both locations (Deciduous Forest; $F_{5, 23} = 69.37$, $P < 0.001$, $F_{5, 23} = 98.81$, $P < 0.001$ and $F_{5, 23} = 164.56$, $P < 0.001$ and $F_{5, 23} = 29.20$, $P < 0.001$, $F_{5, 23} = 175.85$, $P < 0.001$ and $F_{5, 23} = 132.45$, $P < 0.001$, Coastal Savannah; $F_{5, 23} = 4.79$, $P = 0.006$, $F_{5, 23} = 6.47$, $P = 0.001$, $F_{5, 23} = 5.61$, $P = 0.003$ and $F_{5, 23} = 15.80$, $P < 0.001$, $F_{5, 23} = 117.64$, $P < 0.001$ and $F_{5, 23} = 106.40$, $P < 0.001$; 3DAS, 5DAS and 9DAS, respectively). In the Deciduous Forest, the lowest population of leaf hoppers was recorded 3DAS on Viper® plots in the major season with increasing numbers observed at 9DAS. In the minor season, Alphacep®-plots recorded the lowest *Empoasca* numbers (2.25 $\pm$ 0.49) at 3DAS, and Viper® and Akape®-treated plots had lower populations at 5DAS and 9DAS (Figure 6.8). During the minor season in the Coastal Savannah, Alphacep® plots had lower populations at 5 and 9DAS, whilst Viper® had lower numbers at 3DAS, and Akape® did not differ from Agroclean® but differed significantly from other treatments ($P = 0.042$).

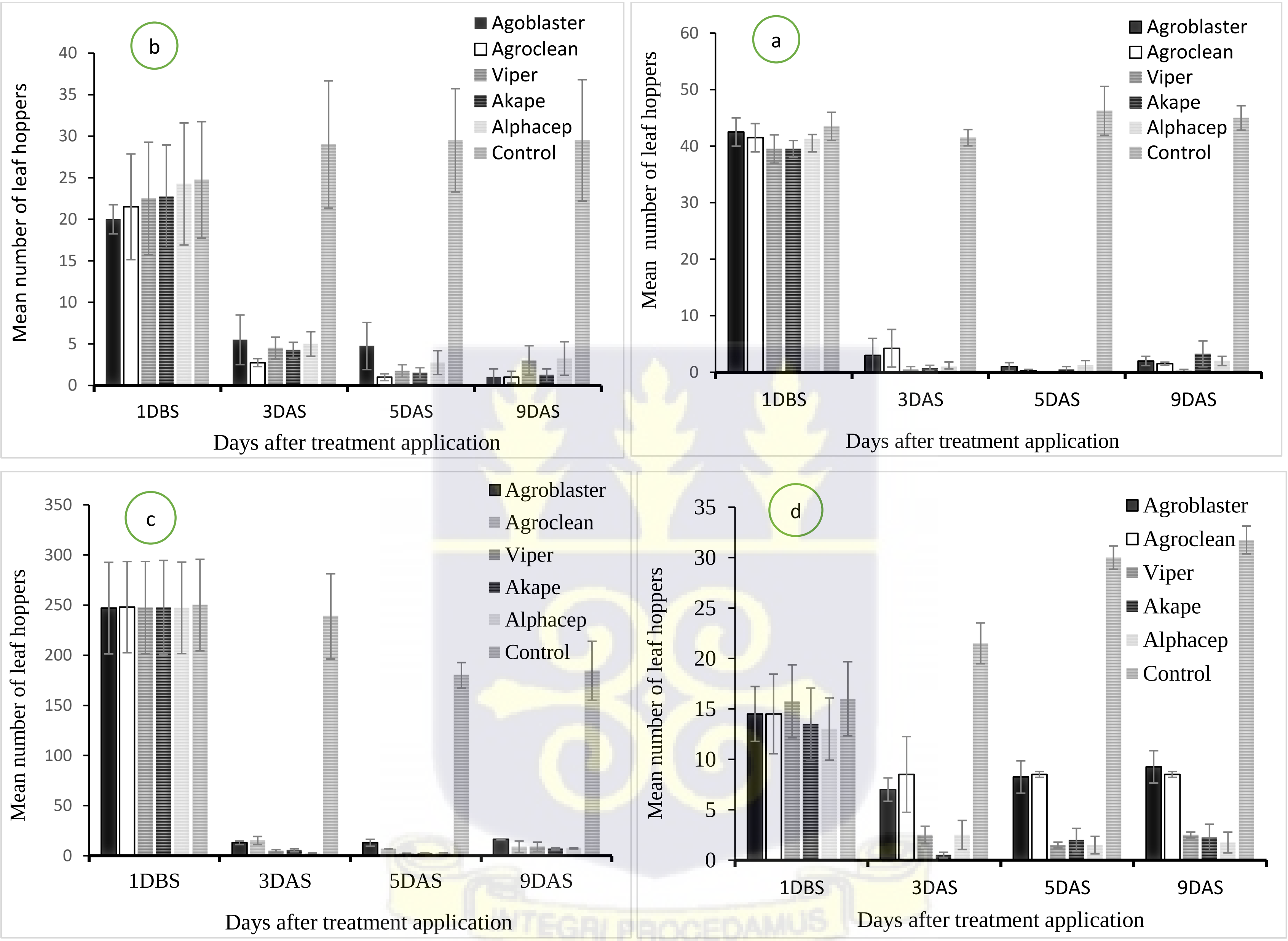

b
Mean number of leaf hoppers
0
5
10
15
20
25
30
35
40
Agoblaster
Agroclean
Viper
Akape
Alphacep
Control
1DBS
3DAS
5DAS
9DAS
Days after treatment application
a
Mean number of leaf hoppers
0
10
20
30
40
50
60
Agroblaster
Agroclean
Viper
Akape
Alphacep
Control
1DBS
3DAS
5DAS
9DAS
Days after treatment application
c
Mean number of leaf hoppers
0
50
100
150
200
250
300
350
Agroblaster
Agroclean
Viper
Akape
Alphacep
Control
1DBS
3DAS
5DAS
9DAS
Days after treatment application
d
Mean number of leaf hoppers
0
5
10
15
20
25
30
35
Agroblaster
Agroclean
Viper
Akape
Alphacep
Control
1DBS
3DAS
5DAS
9DAS
Days after treatment application

Figure 10. Effect of treatments on mean leaf hoppers (± SE) in the major and minor seasons in the Deciduous Forest and Coastal Savannah agroecological zones. (a) Deciduous Forest zone, major season, (b) Coastal Savannah zone, major season, (c) Deciduous Forest zone, minor season and (d) Coastal Savannah zone, minor season. DBS = day before spray, DAS = day after spray.

6.3.1.6.5 Eggplant fruit and shoot borers

In the Deciduous zone, the least *Leucinodes Africensis* damage score occurred on plots treated with Akape® in the major and minor seasons (0.75 ± 0.48 and 0.90 ± 0.100, respectively) with the highest damage in the control plots (4.00 ± 0.41 and 4.80 ± 0.88, respectively) (Figure 6.9). In the Coastal Savannah, Akape® and Agroblaster®-treated plots had the lowest damage scores in the major and minor seasons (0.63 ± 0.22 and 1.00 ± 0.00, respectively) with the highest in the control plots. The effect of insecticide treatments on *L. Africensis* damage score was significant in the major and minor cropping seasons of both agroecological zones (Deciduous Forest, $F_{5, 23} = 6.41$, $P = 0.001$ and $F_{5, 23} = 15.04$, $P < 0.001$ and Coastal Savannah; $F_{5, 23} = 11.62$, $P < 0.001$ and $F_{5, 23} = 26.60$, $P < 0.001$, respectively). All the treatments did not differ from each other, but their effect differed significantly from the control in the major and minor seasons of the Deciduous Forest ($P = 0.010$ and $P < 0.001$) and Coastal Savannah agroecological zones ($P < 0.001$).

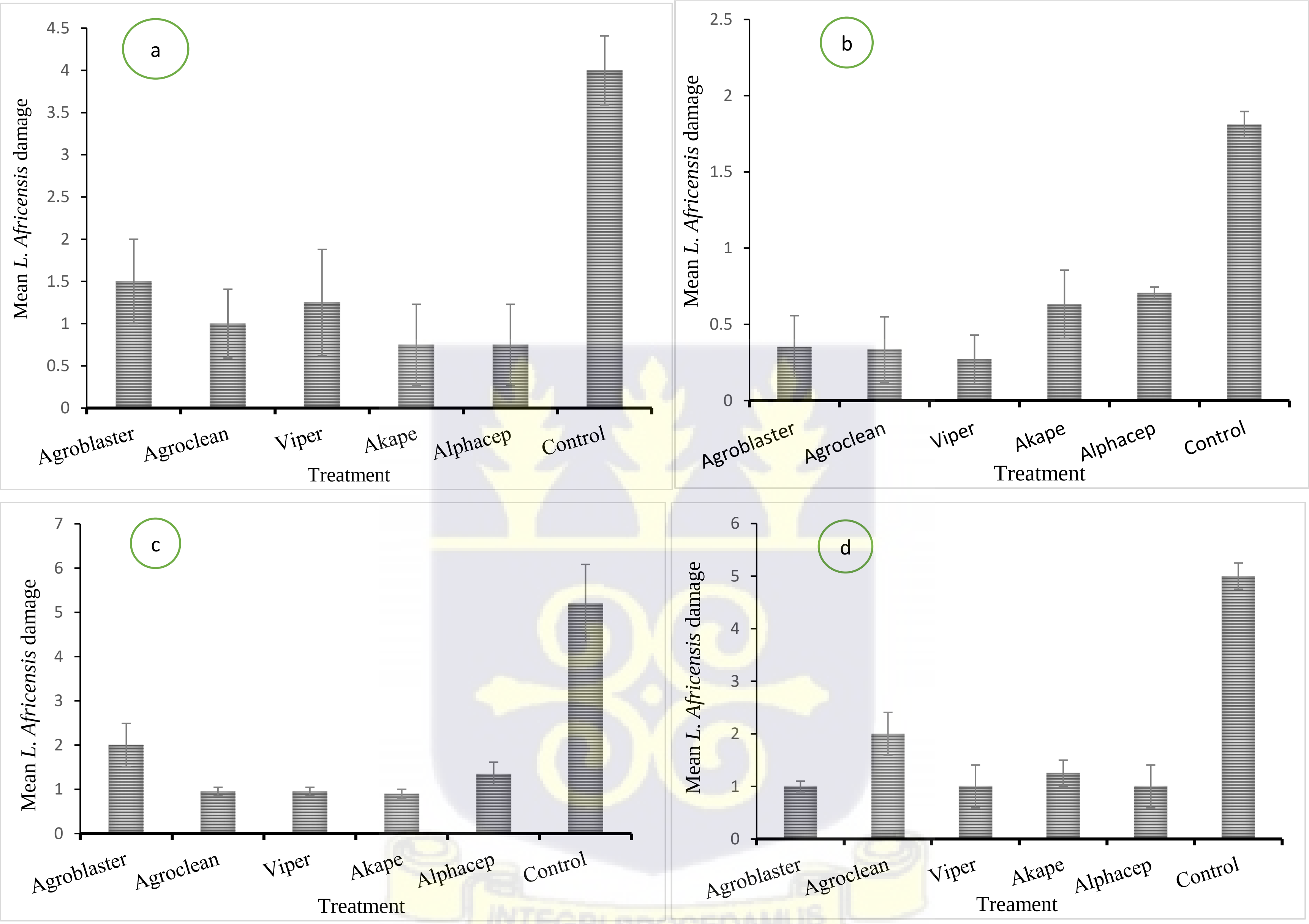

a
Mean *L. Africensis* damage
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Agroblaster
Agroclean
Viper
Akape
Alphacep
Control
Treatment
b
Mean *L. Africensis* damage
2.5
2
1.5
1
0.5
0
Agroblaster
Agroclean
Viper
Akape
Alphacep
Control
Treatment
c
Mean *L. Africensis* damage
7
6
5
4
3
2
1
0
Agroblaster
Agroclean
Viper
Akape
Alphacep
Control
Treatment
d
Mean *L. Africensis* damage
6
5
4
3
2
1
0
Agroblaster
Agroclean
Viper
Akape
Alphacep
Control
Treament

Figure 11. Effect of treatments on mean score (± SE) for *L. Africensis* damage in the major and minor seasons of the Deciduous Forest and Coastal Savannah agroecological zones. (a) Deciduous Forest zone, major season, (b) Coastal Savannah zone, major season, (c) Deciduous Forest zone, minor season and (d) Coastal Savannah zone, minor season.

6.3.1.6 Effect of treatments on eggplant yield

The kilogram/hectare yield of the harvested eggplant fruits is presented in Table 6.6. In the major season, the eggplant yield was higher in the Coastal than the Deciduous Forest zone. The control had lower weights (kg) than all treatments in the major and minor seasons of the Deciduous (218 ± 23.61 and 188.61 ± 53.75) and Coastal Savannah (304.36 ± 14.64 and 227.71 ± 49.39) agroecological zones, respectively. Whilst Viper® plots had the highest yield in the Deciduous Forest zone in the major and minor seasons (790.47 ± 130.36 and 729.60 ± 73.72, respectively), plots treated with Akape® produced heavier fruit weights in the Coastal Savannah zone (887 ± 200.86) in the minor season. During the major season, Agroblaster®-treated plots produced higher yield (1640.09 ± 180.01) than all the other treatments. The application of treatments significantly contributed to the observed yield in the major and minor seasons of the Deciduous Forest ($F_{5, 23} = 3.74$, P = 0.017 and $F_{5, 23} = 3.23$, P = 0.030) and Coastal Savannah agroecological zones ($F_{5, 23} = 5.44$, P = 0.003 and $F_{5, 23} = 3.26$, P = 0.029), respectively. All treatments differed significantly from the control plots, but not among the others, except during the major season in the Coastal Savannah where significant differences existed among the treatments (Table 6.6).

Table 21. Effect of treatments on eggplant yield (kg/ha) in the Deciduous Forest and Coastal Savannah Agroecological zones in the major and minor rainy seasons.

Treatment	Deciduous Forest yield (kg/ha)		Coastal Savannah yield (kg/ha)	
	Major	Minor	Major	Minor
Agroblaster®	522.12 (117.12)a	436.39 (150.59)a	1640.09 (180.01)a	702.16 (71.54)a
Agroclean®	624.14 (161.9)a	618.29 (139.29)a	1184.84 (160.64)abc	475.82 (30.10)a
Viper®	790.47 (130.36)a	729.60 (73.72)a	1358.88 (154.39)a	772.81 (162.64)a
Akape®	546.13 (38.25)a	603.57 (35.60)a	849.62 (110.27)bac	887.35 (200.86)a
Alphacep®	401.24 (42.51)a	400.24 (33.51)a	899.35 (154.69)c	858.11 (162.68)a
Control	218.62 (23.61)b	188.61 (53.75)b	304.36 (14.64)d	227.71 (49.39)b
F	3.74	3.23	5.44	3.26
P	0.017	0.030	0.003	0.029

Means with the same letters within columns are not significantly different. Numbers in brackets indicate standard errors.

6.3.2 Experiment 2

6.3.2.1 Effect of pest management options on the population dynamics of thrips pests

By the third and fourth week after transplanting of the eggplant seedlings which coincided with the first and second samplings (weeks 1 and 2), no thrips was found in all treatments in the major season (Figure 6.10). However, thrips population started building up before the third week and peaks were recorded at the sixth sampling week in all treatments, except in M4 where the highest population was recorded at the eighth week of sampling (36.50 ± 11.0.8) in the major season of the Deciduous Forest agroecological zone. In the Coastal Savannah, thrips incidence began at the third sampling week and peaked by the seventh week on M1 and M2 with a decrease afterwards, but on plots M3 and M4, the population increased consistently to the eighth week in the major season. The overall pest population was lowest on M1 (1.31 ± 0.17) and M2 (1.34 ± 0.13) and highest on M4 and M3. However, in the minor season, thrips pest's incidence began at one and two weeks for both locations, respectively, which was quite earlier than what was observed in the major season (Figure 6.10). The effect of the management options on the population dynamics of thrips was significant in both seasons and agroecological zones (Deciduous Forest; $F_{3, 9} = 6.67$, $P = 0.012$ and $F_{3, 9} = 46.99$, $P < 0.001$ and Coastal Savannah; $F_{3, 9} = 18.25$, $P < 0.001$ and $F_{3, 9} = 13.39$, $P = 0.001$). The effect of sampling time was likewise significant in both seasons and zones (Deciduous Forest; $F_{7, 84} = 7.77$, $P = 0.010$ and $F_{7, 84} = 27.00$, $P < 0.001$; Coastal Savannah; $F_{7, 84} = 27.95$, $P < 0.001$ and $F_{7, 84} = 3.94$, $P = 0.05$). However, the interaction between the sampling weeks and treatments were not significant in the major season in the Deciduous Forest zone ($F_{21, 84} = 3.23$, $P = 0.236$) and minor season in the Coastal Savannah ($F_{21, 84} = 1.28$, $P = 0.325$), but was significant in the major season of the Coastal Savannah ($F_{21, 84} = 5.28$, $P = 0.003$) and minor season in the Deciduous zone ($F_{21, 84} = 5.40$, $P < 0.001$).

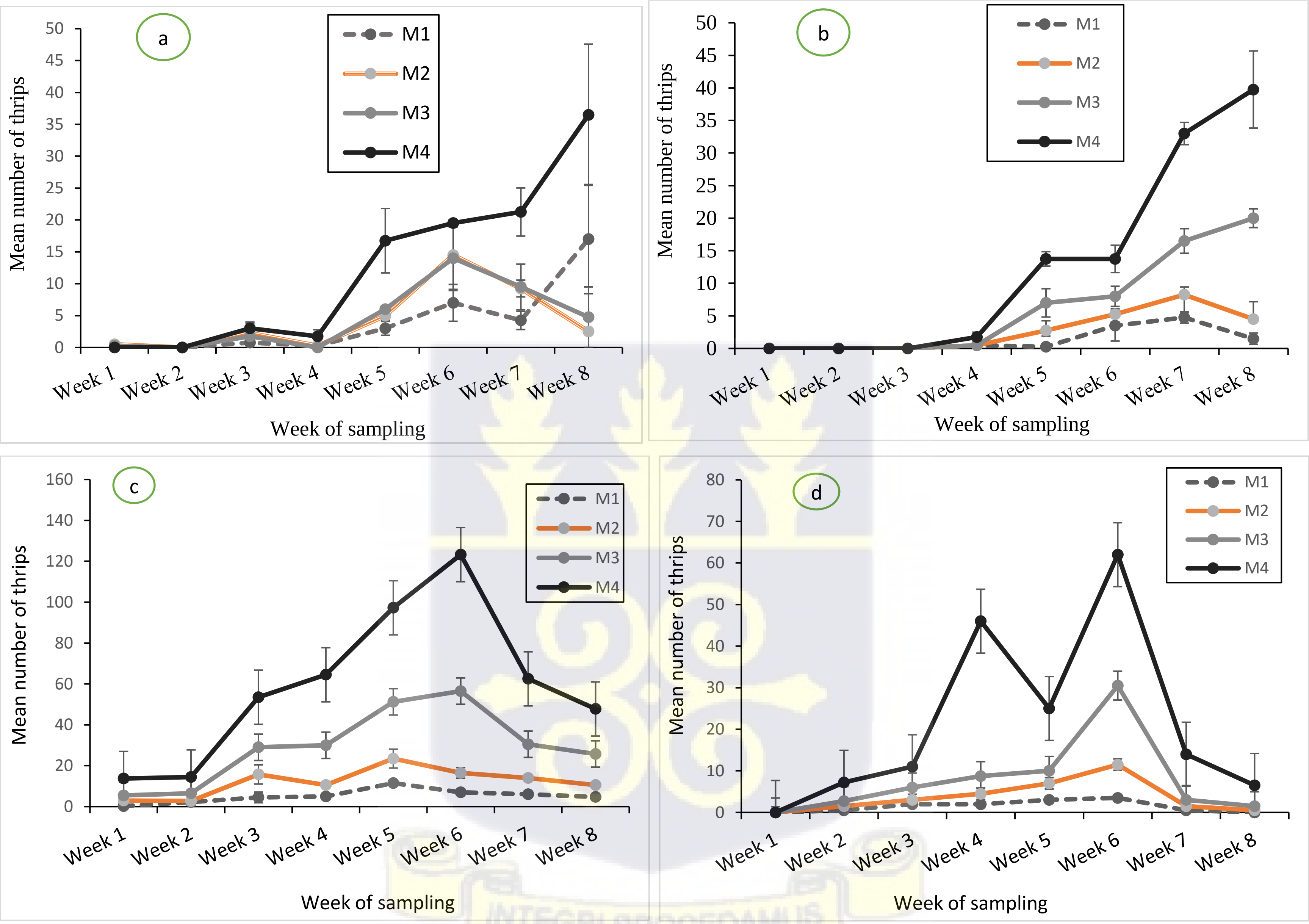

a
b
c
d
M1
M2
M3
M4
Mean number of thrips
Week of sampling
Week 1
Week 2
Week 3
Week 4
Week 5
Week 6
Week 7
Week 8
0
5
10
15
20
25
30
35
40
45
50
0
20
40
60
80
100
120
140
160
0
10
20
30
40
50
60
70
80

Figure 12. Effect of pest management modules on thrips population dynamics in the major and minor seasons in the Deciduous Forest and Coastal Savannah agroecological zones. (a) Deciduous Forest zone, major season, (b) Coastal Savannah zone, major season, (c) Deciduous Forest zone, minor season and (d) Coastal Savannah zone, minor season. M1 = IPM module, M2 = less risk pesticides module, M3 = Chemical intensive module (Farmer's method) and M4 = control module.

6.3.2.2 Effect of pest management options on the abundance of other insect pests

Several insect pests were recorded during the study in both locations. The most abundant pests were the leaf hoppers, *Empoasca* species, directly followed by whiteflies, *B. tabaci* or EFSB in both seasons (Figure 6.11). Apart from the eggplant fruit and shoot borer (EFSB) and leaf hoppers which were lowest on M3, the abundance of all the other insect pests was lowest on M1 and M2 plots compared to that on the M4 plots. During the major season, the pest management modules significantly contributed to managing the abundance of most insect pests in the Coastal Savannah (EFSB ($F_{3, 15} = 24.33$, $P < 0.001$), mites ($F_{3, 15} = 4.08$, $P = 0.033$), aphids ($F_{3, 15} = 4.01$, $P = 0.034$), leaf hoppers ($F_{3, 15} = 5.35$, $P = 0.014$), grasshoppers ($F_{3, 15} = 5.68$, $P = 0.012$), but not whiteflies ($F_{3, 15} = 1.96$, $P = 0.173$). Similarly, whilst the effect of pest management modules in the Deciduous Forest was not significant for aphids ($F_{3, 15} = 1.22$, $P = 0.345$) and whiteflies ($F_{3, 15} = 1.19$, $P = 0.353$, it was significant for EFSB ($F_{3, 15} = 17.34$, $P < 0.001$), mites ($F_{3, 15} = 3.25$, $P = 0.05$), leaf and grasshoppers ($F_{3, 15} = 2.43$, $P = 0.045$ and $F_{3, 15} = 6.50$, $P = 0.007$). The management modules significantly affected the abundance of all sampled pests, except leaf hoppers and grasshoppers in the minor season in the Deciduous Forest and Coastal Savannah zones ($F_{3, 15} = 2.62$, $P = 0.099$ and $F_{3, 15} = 0.88$, $P = 0.507$, respectively). However, M4 recorded the highest population of all sampled pests in the major and minor seasons in both locations

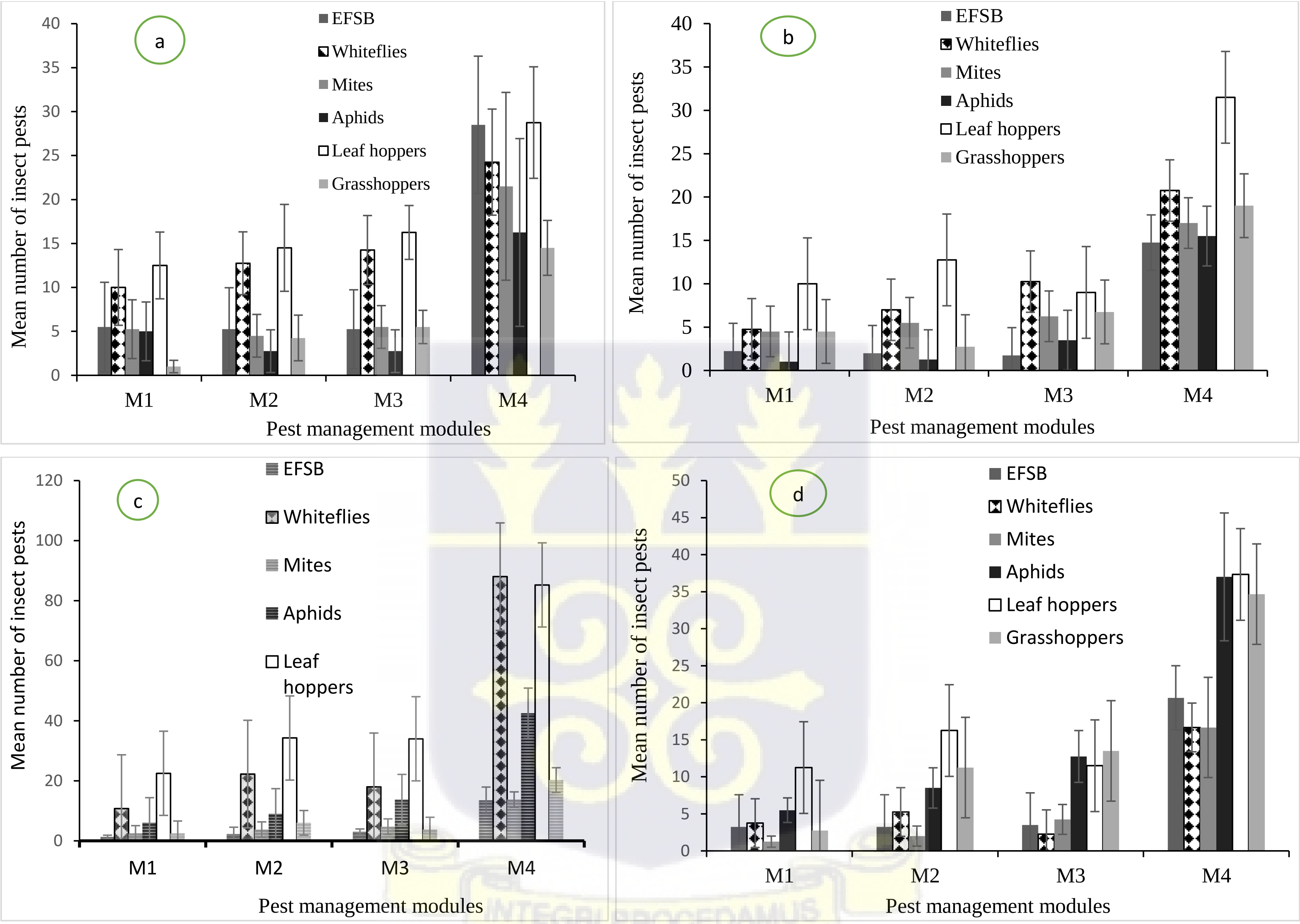

a
EFSB
Whiteflies
Mites
Aphids
Leaf hoppers
Grasshoppers
Mean number of insect pests
0
5
10
15
20
25
30
35
40
M1
M2
M3
M4
Pest management modules
b
EFSB
Whiteflies
Mites
Aphids
Leaf hoppers
Grasshoppers
Mean number of insect pests
0
5
10
15
20
25
30
35
40
M1
M2
M3
M4
Pest management modules
c
EFSB
Whiteflies
Mites
Aphids
Leaf hoppers
Mean number of insect pests
0
20
40
60
80
100
120
M1
M2
M3
M4
Pest management modules
d
EFSB
Whiteflies
Mites
Aphids
Leaf hoppers
Grasshoppers
Mean number of insect pests
0
5
10
15
20
25
30
35
40
45
50
M1
M2
M3
M4
Pest management modules

Figure 13. Effect of pest management modules on the abundance of other insect pests in the major and minor seasons in the Deciduous Forest and Coastal Savannah agroecological zones. (a) Deciduous Forest zone, major season, (b) Coastal Savannah zone, major season, (c) Deciduous Forest zone, minor season and (d) Coastal Savannah zone, minor season. M1 = IPM module, M2 = less risk pesticides module, M3 = Chemical intensive module (Farmer's method) and M4 = control module.

6.3.2.3 Effect of pest management options on the yield

The fruit weights from the first and second harvest were pooled for each plot and expressed in kilogram per hectare (kg/ha). Fruits were considered unmarketable based on the degree of insect pests damage observed by visual inspection. The unmarketable or damaged fruit weight was taken and compared across the modules. Generally, a higher yield was recorded in the major than the minor season for the two locations, and yield was higher in the Coastal Savannah than the Deciduous Forest. The total yield was highest on M1 (1524.35 $\pm$ 14.85), followed by M2 (1502.06 $\pm$ 3.96) for both seasons in the Deciduous Forest zone whilst the unmarketable yields was highest in M4. Very few damaged fruits were observed in M1-treated plots and consequently, the unmarketable yield was very low as opposed to M4 plots where, almost all the total harvested fruits were graded unmarketable, especially in the minor season (Figure 6.12). A similar result was observed in the Coastal Savannah zone, where the total yield was highest on M1 and M3 plots and lowest on M4.

The effect of pest management modules was significant in the major and minor seasons in both ecological zones (Deciduous Forest; $F_{3, 15} = 478.57$, $P < 0.001$ and $F_{3, 15} = 2.50$, $P = 0.048$ and Coastal Savannah; $F_{3, 15} = 41.13$, $P < 0.001$ and $F_{3, 15} = 0.059$, respectively), the yield from M1-treated plots were not significantly different from M2 plots, but differed significantly from M3 and

M4 plots. Whilst the unmarketable yield in M4 plots was significantly higher than all the other plots (P = 0.003).

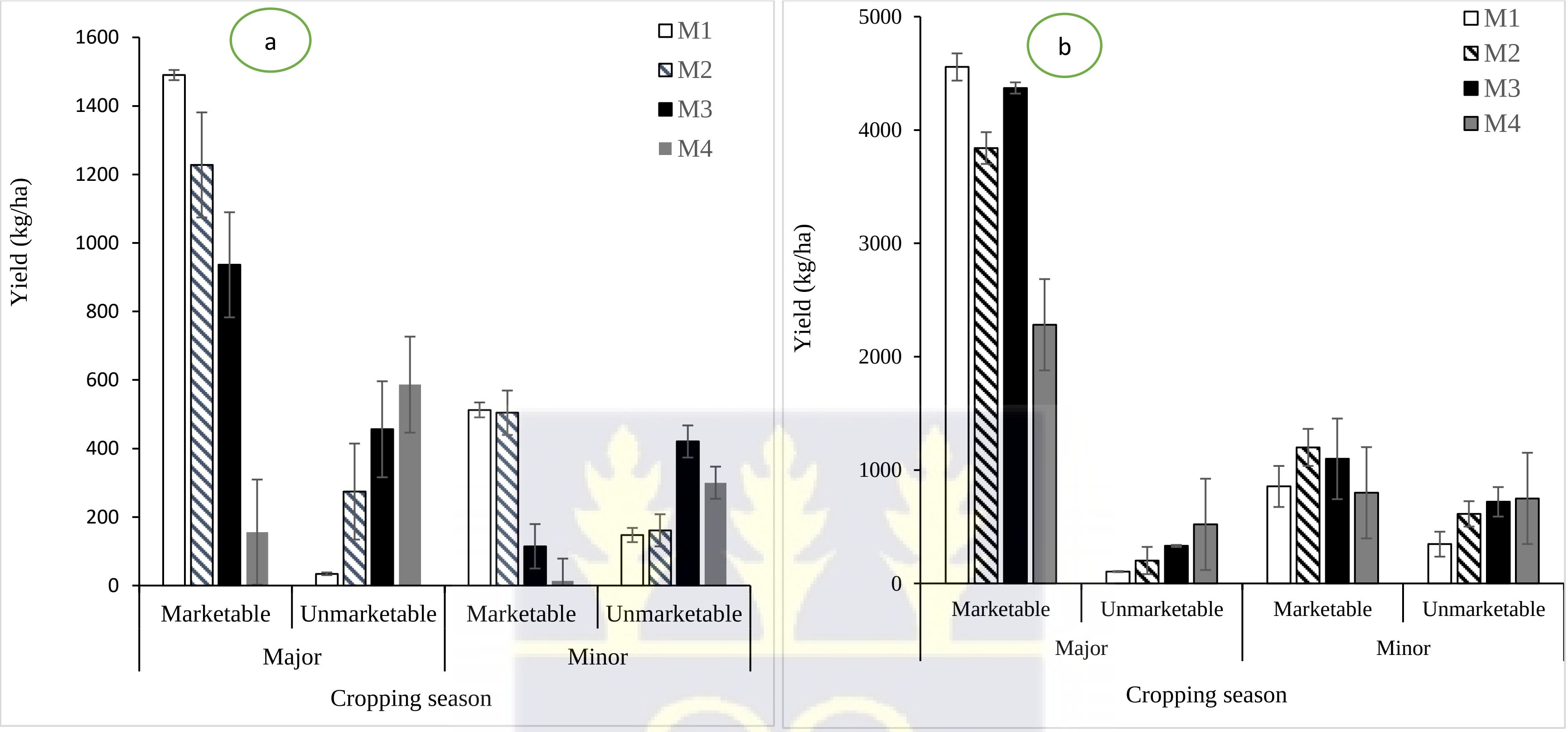


Figure 14. Effect of pest management modules on eggplant yield (kg/ha) in the major and minor seasons of the Deciduous Forest and Coastal Savannah agroecological zones. (a) Deciduous Forest zone and (b) Coastal Savannah zone. M1 = IPM module, M2 = less risk pesticides module, M3 = Chemical intensive module (Farmer's method) and M4 = control module.

6.3.2.4 Cost-benefit analysis of pest management modules

The results of the cost and benefit of controlling thrips and other pests of eggplant using the management modules indicated that the cost: benefit ratio was higher in the Coastal Savannah than the Deciduous Forest in the major raining season (Table 6.7). In the Deciduous Forest zone, the highest cost: benefit ratio was M1 (1: 3.08), followed by M3 (1: 1.66) and finally by M2-treated plots (1: 1.38). The highest net benefit was observed on M1 (3453.14 US$/ha) as opposed to M4 plots (1970.85 US$/ha). Likewise, M1 recorded the highest increase in yield over the control (2273.66 kg/ha) than all the other modules. The result was similar to that observed in the major season of the Deciduous Forest zone, however, the net benefit on M3-treated plots was negative (Table 6.8).

During the minor season, whilst the net benefit was highest on M2 in the Coastal Savannah zone, it was rather higher on M1 in the Deciduous Forest zone. The cost benefit ratio for M1 and M2 was negative for both agroecological zones, whilst the highest total plant protection cost was highest on M3 for all seasons (Tables 31 and 32). The total income earned on the marketable yield was higher on M1-treted plots for both the major and minor cropping seasons in the two locations (Deciduous Forest; 1286.744 US$/ha and 574.57 US$/ha and Coastal Savannah; 3934.29 US$/ha and 570.72 US$/ha; major and minor seasons, respectively).

Table 22. Evaluation of the cost and benefit of controlling pests with pest management modules in the major raining season of the Deciduous Forest and Coastal Savannah agroecological zones.

	Deciduous Forest agroecological zone (Dago)						Coastal Savannah agroecological zone (UG)					
	Marketable yield (kg/ha)	Increased yield over the control (kg/ha)	Cost of plant protection (US$/ha)	Net benefit (US$/ha)	Gross monetary returns (US$/ha)	Cost: benefit ratio	Marketable yield (kg/ha)	Increased yield over the control (kg/ha)	Cost of plant protection (US$/ha)	Net benefit (US$/ha)	Gross monetary returns (US$/ha)	Cost: benefit ratio
M1	1490.05	1334.01	623.4	663.344	1151.99	1: 1.85	4555.91	2273.66	481.14	3453.14	1963.44	1: 3.10
M2	1227.709	1071.67	977.86	82.35	925.44	1: 0.95	3840.88	1558.64	977.86	2338.96	1345.98	1: 1.38
M3	936.21	780.17	1419.36	-610.89	673.72	1: -0.47	4370.71	2088.47	1419.36	2355	1803.51	1: 1.66
M4	156.04	0	0	156.04	0	-	2282.24	0	0	1970.85	0	-

M1 = IPM module, M2 = less risk pesticides module, M3 = Chemical intensive module (Farmer's method) and M4 = control module.

Table 23. Evaluation of the cost and benefit of controlling pests with pest management modules in the minor season of the Deciduous Forest and Coastal Savannah agroecological zones.

	Deciduous Forest agroecological zone (Dago)						Coastal Savannah agroecological zone (UG)					
	Marketable yield (kg/ha)	Increased yield over the control (kg/ha)	Cost of plant protection (US$/ha)	Net benefit (US$/ha)	Gross monetary returns (US$/ha)	Cost: benefit ratio	Marketable yield (kg/ha)	Increased yield over the control (kg/ha)	Cost of plant protection (US$/ha)	Net benefit (US$/ha)	Gross monetary returns (US$/ha)	Cost: benefit ratio
M1	512.69	498.91	475.18	515.22 37.51	98.4 498.91	1: 1.17	509.26	459.44	475.18	514.85 34.08	95.54 459.44	1: 1.08
M2	504.37	490.58	977.86	506.62 - 473.49	-409.66 490.58	1: -0.57	587	537.18	977.86	602.01	-320.02 537.18	1: -0.38
M3	114.58	100.79	1419.36	104.09 - 1304.78	-1290.95 10 0.79	1: -0.08	378.94	329.12	1419.36	368.84	-994.69 329.12	1: -0.74
M4	13.79	0	0	15.45 13.79	0 0	-	49.82	0	0	56.18	- -	-

M1 = IPM module, M2 = less risk pesticides module, M3 = Chemical intensive module (Farmer's method) and M4 = control module.

6.4 Discussion

6.4.1 Experiment 1

6.4.1.1 Effect of treatments on thrips population and damage

The result of this study showed that thrips numbers were highest on all treatments and in both locations before the insecticides were applied. However, the population reduced at the different sampling days after the treatments were applied. Similar findings have been reported by Ereshrao (2018), who observed no significant differences in thrips population on plots before treatment applications. Seal *et al*. (2013) likewise found low numbers of thrips after application of various groups of insecticides such as pyrethroids and neonicotinoids on eggplant and snap beans. The generally low population recorded after treatment application in this study is indicative of the effectiveness of the various insecticides in reducing thrips population. Among the insecticides, Agroblaster® and Agroclean® recorded relatively higher thrips population at 3DAS, and thrips abundance was lowest at 9DAS on these two treatments compared to other treatments. It appears in the current study that the synthetic pyrethroid, Alphacep®, acted faster than the natural pyrethrins (Agroblaster®) which made Agroblaster® to be relatively more effective by 9DAS unlike Alphacep® where its rapid knockdown effect on thrips was more visible immediately after spray (3DAS). Additionally, differences in the doses of both products might have contributed to such differences. A high thrips population was found in the Deciduous Forest than the Costal Savannah zone, as well as the minor than the major season. In the Deciduous Forest, field experiments were conducted on an exporter field with previous history of cultivating export vegetables in a monocropping system. This might have provided favourable grounds for the initial build-up and further reproduction of thrips to get such high thrips numbers than what was observed in the Coastal Savannah where crop rotation was often done. These high numbers resulted to the more severe damage observed in that locality.

Eggplant flowers were more injured than the leaves. This observations agree with those of Todd *et al*. (1995) and Reitz (2002). Flowers contain the pollen with high nutritional values which enhance their growth and reproduction and consequently, the high numbers consume more plant tissues resulting in more damage than on the leaves.

6.4.1.2 Efficacy of insecticides on percentage reduction of thrips

The efficacy of the novel insecticides varied across the sampling days for the different treatments. The best treatment with the highest percentage of thrips reduction was Alphacep® at 3DAS, Agroblaster® at 5DAS and Akape® at 9DAS in Deciduous Forest zone and in the Coastal Savannah, the highest reduction was seen on Alphacep®-treated at 3DAS (92.95%) and Agroblaster® at 5DAS (85.81%) and 9DAS (83.00%). Similarly, Seal *et al*. (2003) reported differences in the efficacies of different groups of insecticides whilst Burubai *et al*. (2011) found insecticide combinations such as Kartodim 10EC (pyrethroid) and garlic extract to reduce thrips infestation at 5 and 10 days after spray. The efficacy of Viper® in suppression pests of eggplant and other export vegetables have been documented (Fening *et al*., 2020). The insecticides tested in this study have different active ingredients (a.i) and these a.i have different efficacies whose effectiveness reduces as the time after application increases. Therefore, it is important to have basic knowledge of the mode of action of any insecticide before selecting it for use in pest management. It is evident in this study that using a fast-acting group of insecticide such as pyrethroids can be useful in eliminating the first instars of thrips which are destructive and takes just one day to moult to the next stages. However, applying a botanical like Agroclean® will offer more protection at a later stage during which the adults might have emerged. This also gives information on the precise timing of the next application which is shorter for Alphaacep® than Agroblaster®. As such, the need for calendar application of insecticides, most often practiced by farmers becomes unnecessary.

6.4.1.3 Effect of treatments on natural enemy population

The population of natural enemy was higher in the Deciduous Forest than the Coastal Savannah. The abundance of the various natural enemies; spiders, minute pirate bugs and ladybird beetles were not different significantly in all treatments before and after the application of the insecticides for the different sampling days in all locations, with the exception of *Orius insidiosus* at 9DAS (Akape®) and ladybird beetles at 3 (Agroblaster®) and 9DAS (control) in the minor season of the Deciduous Forest agroecological zone. The existence of non-significant differences before treatment and at 3, 5 and 9DAS is indicative that the insecticides had no negative effect on the sampled natural enemies. Fening *et al*. (2011), Mochiah *et al*. (2011) and Ngosong *et al*. (2020) had earlier reported that plant-based insecticides had little effect on natural enemies. Agroblaster® is a natural pyrethrum made from pyrethrin I and II and Agroclean® is a botanical made with mint oil, respectively whilst Akape® and Viper are neonicotinoids. These groups of insecticides have been considered relatively safer to non-target organisms. However, Alphacep® had some effect on spiders with a significantly lower population than that on the control in the minor season of both locations. Similarly, Fening *et al*. (2013) had documented the highest reduction in the abundance of natural enemies on the pyrethroid, (lambda-cyhalothrin) plot.

6.4.1.4 Effect of treatments on phytotoxicity

Phytotoxicity refers to the toxicity effect of insecticides on plants. This effect can be in form of leaf, shoot and stem burns, scorching or any other morphological changes on plants after pesticides application. In this study, all treatments including the control but with exception of Alphacep® plots showed no phytotoxicity, with 100% of the plants showing no symptoms before and after application of the insecticides (3, 5 and 9DAS) in the major and minor seasons of the Deciduous Forest and Coastal Savannah agroecological zones. However, plots treated with Alphacep®

showed some percentage of phytotoxic plants in both locations and seasons. Similar to this study, Mochiah *et al*. (2019) did not observed phytotoxicity on control maize plots and Bypel®-plots infested with fall armyworm. He, however, found slight, medium and strong phytotoxicity with varying concentrations of the fall armyworm recommended insecticide Sauveur 62 EC, a neonicotinoid/pyrethroid. The phytotoxic effect reported in this study was also severe in the minor than the major season for all locations. It is possible that unfavourable climatic conditions during the dry season such as low rainfall might have aggravated and contributed to the effect being more pronounced in this period. Nevertheless, the percentage of phytotoxic plants in addition to the degree of phytotoxicity reduced with increasing time post insecticide application such that, by nine days after the insecticides were applied, the few plants with slight and strong phytotoxic symptoms had recovered.

6.4.1.5 Effect of treatment on within-plant distribution of thrips

Thrips have been shown to occupy different locations on their host plants such as leaves, buds and flowers. In this study, the thrips population was generally higher on the flowers, followed by the upper, the middle and the lower leaves which confirms earlier studies by Cho *et al*. (2000), Reitz (2002) and Hansen *et al*. (2003). The adults were shown to have high preference for flowers, whilst the nymphs were more on the leaves. What insects choose to feed on at different stages depends on their physiological needs. Thrips nymphs are younger, still developing which requires energy. As such, nymphs convert carbohydrates in plant sap taken from leaves into proteins and energy reserves. Adults need more protein for development of their gonards and for reproduction and they turn to frequent the flowers which contain pollen and nectar with richer source of nutrients needed for such activities. The nutritive value of the flowers have been documented (Tsai *et al*., 1996). Additionally, the higher nymph population on the upper than the middle and lower leaves can be attributed to the fact that, upper leaves are younger with softer tissues which allow the fast penetration and consumption of host tissues as opposed to older leaves with waxy coating which causes them to be tough and as such, hinder incision, and penetration of thrips stylets into plant tissues during feeding. This study further revealed that, even though thrips stages preferred different portions of plant, the location of thrips on the host plant can significantly be influenced by the management options used for their control. Here, the thrips population on the different plant parts were lower on Agroblaster® than the rest of the treatments in the two locations. This bit of the result contradicts that of Hansen *et al*. (2003) who attributed thrips location on the plant solely to behavioural attributes and not to insecticide application. Nonetheless, it is possible that when an insecticide is applied, thrips might try to escape the effect of this foreign particles by moving from place to place and in so doing, change their location/position to new areas which might not be their initial preferred locations.

6.4.1.6 Effect of treatments on other pests

In conformity to decrease in the abundance of other pests such as EFSB, aphids, whiteflies, leaf and grasshoppers on treated plots, a further increase in their populations stopped at the different days after application of the tested insecticides. On the other hand, the increase in the abundance of the various pests on untreated or control plots indicates the suppression of pest's population on the treated plots was due to the insecticides, as explained by Seal *et al*. (2013) and Ngakou *et al*. (2008). In addition, the higher abundance of aphids, EFSB, leaf hoppers and whiteflies observed in the Deciduous Forest than the Coastal Savannah can be attributed to differences in geographical characteristics of the ecological zones. These ecological differences have been shown to influence population dynamics of different thrips species (Reitz, 2002; Hansen *et al*., 2003).

6.4.1.7 Effect of treatments on yield

The highest yield in the Deciduous Forest was obtained on Agroclean® and Viper®-plots and Agroblaster® and Akape®-plots in the major and minor seasons in the Coastal Savannah zone, respectively. Attack by thrips led to flower abortion and fruits with scars, which reduces the yield and quality of the harvested fruits, thereby affecting marketability. The higher yield in the Coastal than the Deciduous Forest zone was due to the lower pest population during the production period, differences between the two seasons and possibly other confounding factors which were beyond the scope of the study such as soil quality parameters and agroecological differences.

6.4.2 Experiment 2: Effect of pest management modules on thrips population dynamics, yield, and cost-benefit ratio

The population dynamics of thrips were shown to vary with treatment, location, and season. Thrips incidence was fastest in the minor season of both agroecological zones than the major season. The observed variation in pest and natural enemy populations between seasons underscores the complex interplay between environmental conditions and pest behaviour, demonstrating the significant role of seasonal differences in population dynamics of the thrips pests (North and Shelton, 1986; Ibrahim and Adesiyun, 2010). The lowest thrips abundance on the IPM and less-risk modules than the control and chemical intensive modules confirmed the effectiveness of the treatment modules. In a similar manner, Bosco and Tavella (2010) observed a higher thrips population on the chemical than biological control treatment. Particularly on M1, in addition to the effect of two applications of Agroblaster®, the lower pests population observed could also be attributed to the border row of maize which may have acted as physical barrier which may have altered thrips host finding behaviour and prevented them from locating their host. Higher yields were then obtained on the treated plots with comparatively higher undamaged fruits since the insecticides were able to control the pests. Physical examination of the harvested fruits in the control plots showed damaged, scared, or malformed fruits which could not be sold.

Whilst the selected insecticides reduced the population of thrips and other pests in this study, it is important to preserve their effectiveness and prevent or delay development of resistance by rotating them with insecticides with different modes of action, such as in M2. According to Seal *et al*. 2013, whilst Spinosad offered 95% control of *T. palmi* adults in the first years, its effect became reduced in the later years due to frequent use. The cost: benefit ratio was highest in M1, since a combination of several other methods including supervised control were used to reduce pest population. The yield of all treatment was higher than the control, however, the hight cost of weekly application and the cost of insecticide on M3 plots increased the overall expenditure cost, resulting to negative net gross monetary returns in the minor season. The study highlights the effectiveness of integrated pest management (IPM) strategies in reducing pest populations and improving yields, advocating for the adoption of sustainable control measures that incorporate both chemical and non-chemical tactics.

6.4.3 Conclusion

This study demonstrated that thrips population, natural enemies, other pests and eggplant yield varied by season and geographical location. The tested insecticides effectively supressed thrips and the population of other pests in the two locations compared to the control. The highest efficacy occurred 5DAS, but this depended on the type (active ingredient) of the insecticides. However, whilst the Agroblaster®, Agroclean®, Viper® and Akape® had no effect on the population of natural enemies and the plant themselves, Alphacep® showed mild effect on spiders with slight and medium phytotoxicity to plants, whose symptoms were completely erased by 9DAS. The pest population was lower in the Coastal Savannah which led to higher yield than the Deciduous Forest zone. Thrips preference for flowers was higher than the other parts sampled but this was affected by insecticide treatments. In experiment 2 (pest management options), the population dynamics of thrips varied with the sampling weeks, season, and geographical location. The IPM module had the lowest pest population which led to the highest yield and consequently higher cost: benefit ratio, and thus recommended for the sustainable control of thrips and other pests in vegetable production. By evaluating the impact of these strategies not only on thrips but also on their natural enemies, you ensure that the management practices are sustainable and do not inadvertently harm the ecosystem. Implementing effective, environmentally friendly pest management options will improve the health and yield of eggplant crops, making them more suitable for export.

CHAPTER SEVEN

7.0 GENERAL DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

7.1 General discussion and conclusions

Studying the diversity and abundance of thrips species is useful in differentiating between pests and non-pest species, monitoring their populations (Samler, 2012; Bravo-Pérez *et al*., 2018; Ebratt-Ravelo *et al*., 2019), updating a country's pest list, and selecting pest management measures which can conserve local biodiversity and also meet the thrips-free requirements of international trade. This study has established that the export vegetables cultivated in Ghana are hosts to several species of thrips and thrips diversity is greater in the Central than any of the sampled regions. The identification of these species revealed several local (*F. schultzei* and *T. tabaci*) and invasive pests' species (*T. parvispinus* and *G. uzeli*) which must be controlled to ensure that vegetable exporters meet the stringent sanitary and phytosanitary measures. The New EU Plant Health Regulation (EU 2016/2031) and its Implementing Directive (EU 2019/2072) prohibits the introduction of new thrips pests from imports from third countries and requires countries to adopt enhanced provisions such as information campaigns to the public, implement annual surveys, simulation exercises, prepare contingency plans, and action plans for eradication of especially the priority pests (COLEACP, 2020). The generated diversity information directly supports sustainable management by enabling the deployment of specific control measures that are effective against the thrips species present, thereby enhancing the quality and export potential of vegetables.

The primary step in any thrips control programme is to monitor their levels to determine the population fluctuations and establish thresholds which can justify the need for the application of any control measure. (Kawai, 1986; Yadav and Chang, 2013). Among the different monitoring methods recommended so far, sticky traps provide a more reliable estimate of thrips population than estimate from plant samples (Waiganjo *et al*, 2008). The results of this study demonstrated that, thrips occurred in the chilli and eggplant fields in all seasons and infested all the developmental stages. A similar finding has been reported by Waiganjo *et al*. (2008). He found *T. tabaci* infesting all stages of the onion crop and in all the four tested cropping seasons. The higher thrips species and other arthropod population reported in the second than the first season in this study can be attributed to the effect of rainfall and exceedingly high relative humidity in the major season, which tended to wash down thrips which might have resulted to drowning and eventual death. This phenomenon has been demonstrated by several authors (North and Shelton, 1986; Ibrahim and Adesiyun, 2010), and excess soil moisture have been shown to expose the non-feeding thrips stages to attack by pathogens (Zhang and Young, 1998). In the second season, conditions were very dry with high temperatures and relatively low relative humidity. These conditions impacted the nutritional quality of host plants which increased their attractiveness to thrips invasion (Lewis, 1973). Additionally, dry or water-stress conditions triggers host plants to emit more volatile compounds which increases the ability of the observed arthropods to locate their host plants (Takabayashi *et al*., 1994; Paré and Tumlinson, 1999), thereby, justifying their increase during this period. It appears in this study that, natural enemies were more affected with the conditions in the dry season than the thrips themselves which led to their populations being extremely reduced compared to the first season. Whilst Waiganjo *et al*. (2008) found only minimum relative humidity to significantly predict onion thrips population among the other factors; temperature, wind, rainfall and maximum relative humidity, weather factors highly influenced thrips dynamics in this study. Climatic conditions within a species niche differs from those in the surrounding areas and therefore, the microclimate is a better predictor of a species behaviour and abundance. The non-significant relationship on weather factors reported in certain literature is because, the weather data, most often, is collected from weather stations. These stations are usually farther apart from the experimental sites and as such, fail to provide the microclimatic data which has better a relationship with species in the same environment.

Among the climatic factors regulating insect species incidence, abundance and distribution, temperature is the most important factor (Bale *et al*., 2002; Skendžić *et al*., 2021) and the development time, reproduction and lifetable parameters of the newly identified species, *Thrips parvispinus* in this study has been shown to be influenced by temperature significantly. The rate of development was fastest at high temperatures and both males and females of this species lived shorter at higher temperatures. An understanding of how this species behaves under different temperature scenarios is useful in developing temperature-dependent phenology models which can guide pest management decisions in integrated control programs. Such models can enhance the timing and precision of insecticide applications, reducing unnecessary pesticide use and production costs.

Extensive information has been generated in this study from the on-field thrips management trial which can be used to select the best location-specific insecticides for use on eggplant production as well as improve the timing and precision of pesticide applications. The end result is to eliminate unjustified pesticide application, reduce wastage and overall cost of production. In this study, the thrips' population was more in the flowers, followed by upper leaves and lowest on the lower leaves. Knowledge of within plant distribution of thrips is of particular relevance for understanding how crop damage occurs, designing and planning efficient sampling strategies, and implementing pest management measures (Reitz, 2002; Hansen *et al*., 2003). Agroblaster®, Agroclean®, Viper®

and the IPM module reduced thrips' pests effectively and will enhance the export of vegetables if adopted by farmers. The differential impact of insecticides on pests, natural enemies, and plant health emphasizes the need for careful selection and application of pesticides to minimize adverse effects and preserve ecosystem balance. However, maintaining the effectiveness of the tested novel insecticides in this study through rotations or combining with other non-chemical control options such as the IPM module will be ideal to ensure sustainable vegetable production. Since Alphacep® was effective in suppressing pest populations, but had phytotoxic effect, the manufacturer's recommended dosage of 100ml/15L of water was practically higher than the dosage of all the other insecticides. This concentration should be reviewed as lower doses might still be effective yet with no footprints on natural enemies and plants. The author envisions that if the extensive information (knowledge of the identified species, monitory thrips white sticky traps, use of integrated pest management module and information on thrips thermal requirements) generated form this study is used appropriately, thrips will be effectively managed in Ghana to allow the continuous export of vegetables.

7.2 General recommendations

These recommendations underscore the necessity for ongoing and comprehensive research to tackle the challenges posed by thrips and other pests in agricultural systems. By addressing these key areas, stakeholders can work towards developing effective, sustainable pest management strategies that safeguard crops and support the agricultural economy. The key commendations include:

1. **Periodic surveys and capacity building on thrips identification**: Periodic surveys should be conducted across vegetable export farms in Ghana to detect new thrips species on

consistent basis. PPRSD should engage with thrips experts to provide training for agricultural stakeholders, including farmers and extension officers, on accurate thrips identification techniques, incorporating both morphological and molecular methods, as demonstrated in the study, to improve species-level identification and enhance pest management decisions. Strict measures are needed at the KIA to detect and prevent further entry of new species on imported materials.

2. **Thrips species monitoring and management:** The IPM approach developed in this study is reliable, cost-effective, and recommended for sustainable vegetable production. There is need to include white sticky traps in the current monitoring plan and continue national-wide monitoring to keep abreast with fluctuations as climate change intensifies. There is need to further determine *T. parvispinus* effect on other thrips species, assess whether the local natural enemies can prey on them, assess its presence in other regions of Ghana as well as neighbouring countries to form collaborative efforts in developing a regional management plan.
3. **Variety of vegetative environment and host species confirmation:** It is important to consider different vegetative environments than those used in this study, as this may reveal even more thrips species present in Ghana, which can add up to our overall knowledge and understanding of these insects. Further studies are needed to confirm the predatory and pest status of *F. vespiformis* and *G. uzeli*, respectively.
4. There is need to employ the developed temperature-dependent phenology model in geographic information systems (GIS) for the spatial analysis of climate change impact on *T. parvispinus* future invasiveness, distribution and spread in different agroecologies regionally and globally.

5. The parasitoid, *Ceranisius femoratus* was identified in this study. It has been reported in Cameroon with great promise for thrips biological control. There is need to assess its presence, distribution and ability to control thrips species in Ghana.

REFERENCES

Abang, A. F., Kouamé, C. M., Abang, M., Hanna, R., and Fotso, A. K. (2014). Assessing vegetable farmer knowledge of diseases and insect pests of vegetable and management practices under tropical conditions. *International Journal of Vegetable Science*, *20*(3), 240–253. https://doi.org/10.1080/19315260.2013.800625.

Abass, K., Ganle, J. K., and Adaborna, E. (2016). Coliform Contamination of Peri-urban Grown Vegetables and Potential Public Health Risks: Evidence from Kumasi, Ghana. *Journal of Community Health*, *41*(2), 392–397. https://doi.org/10.1007/s10900-015-0109-y.

Abeeluck, D., Du nhawoor, C., and Unmole, L. (2009). Development and mplementation of integrated pest management in Mauritius: an overview. *University of Mauritius Research Journal*, *15*(1), 85–97. https://doi.org/10.4314/umrj.v15i1.

Abudulai, M., Salifu, A. B., and Haruna, M. (2006). Screening of cowpeas for resistance to the flower bud thrips, *Megalurothrips sjostedti* Trybom (Thysanoptera: Thripidae). *Journal of Applied Sciences*, *6*(7), 1621–1624. https://doi.org/10.3923/jas.2006.1621.1624.

Adom, M., Fening, K. O., Billah, M. K., Wilson, D. D., Hevi, W., Clottey, V. A., ... and Bruce, A. Y. (2020). Pest status, bio-ecology and management of the false codling moth, *Thaumatotibia leucotreta* (Meyrick) (Lepidoptera: Tortricidae) and its implication for international trade. *Bulletin of Entomological Research*, *111*(1), 17-30.

Afari-Sefa, V., Asare-Bediako, E., Kenyon, L., and Micah, J. A. (2015). Pesticide use practices and perceptions of vegetable farmers in the cocoa belts of the Ashanti and Western Regions of Ghana. *Advances in Crop Science and Technology*, *03*(03). http://dx.doi.org/10.4172/2329-8863.1000174.

Afreh-Nuamah, K. (1996). *People's participatory (bottom up) approach to integrated pest management in Africa*. *Prospects and Constraints.* Ghana Universities Press, Accra, pp. 15.

Afreh-Nuamah, K. (2003). Ghana national integrated pest management programme. *In:* K. M. Maredia, D. Dakouo, and D. Mota-Sanchez (Eds.), *Integrated Pest Management in the Global Arena*. CAB International, London, pp. 119-129.

Akella, S. V. S., Kirk, W. D. J., Lu, Y., Murai, T., Walters, K. F. A., and Hamilton, J. G. C. (2014). Identification of the aggregation pheromone of the melon thrips, *Thrips palmi*. *PLoS ONE*, *9*(8), e103315. https://doi.org/10.1371/journal.pone.0103315.

Aliakbarpour, H., and Rawi, C. S. M. (2011). Evaluation of yellow sticky traps for monitoring the population of thrips (Thysanoptera) in a mango orchard. *Environmental Entomology*, *40*(4), 873–879. https://doi.org/10.1603/EN10201.

Allan, S. A., and Gillett-Kaufman, J. L. (2018). Attraction of thrips (Thysanoptera) to colored sticky traps in a Florida Olive Grove. *Florida Entomologist*, *101*(1), 61–68. https://doi.org/10.1653/024.101.0112.

Allsopp, E. (2010). Investigation into the apparent failure of chemical control for management of western flower thrips, *Frankliniella occidentalis* (Pergande), on plums in the Western Cape Province of South Africa. *Crop Protection*, *29*(8), 824–831. https://doi.org/10.1016/J.CROPRO.2010.03.009.

Amoabeng, B. W., Gurr, G. M., Gitau, C. W., and Stevenson, P. C. (2014). Cost: Benefit analysis of botanical insecticide use in cabbage: Implications for smallholder farmers in developing countries. *Crop Protection*, *57*, 71–76. https://doi.org/10.1016/j.cropro.2013.11.019.

Amoah, P., Drechsel, P., Abaidoo, R. C., and Ntow, W. J. (2006). Pesticide and pathogen contamination of vegetables in Ghana’s urban markets. *Archives of Environmental Contamination and Toxicology*, *50*(1), 1–6. https://doi.org/10.1007/s00244-004-0054-8.

Amouzou, K., Fening, K.O., Hevi, W, Forchibe, E. E. and Billah, M. K. (2022). Efficacy of promising insecticides and lures for the management of insect pests of quarantine importance on ridged gourd *(Luffa acutangula* L.). *West African Journal of Applied Ecology*, *30*(1), 97-108.

Ananthakrishnan, T. N. (1970). *Indian Thysanoptera*. CSIR Zoological Monograph No. 1. Publications and Information Directorate, New Delhi. 194 pp.

Asante, F. A., and Amuakwa-Mensah, F. (2015). Climate change and variability in Ghana: Stocktaking. *Climate*, *3*, 78-99. https://doi:10.3390/cli3010078.

Azrag, A. G. A., Murungi, L. K., Tonnang, H. E. Z., Mwenda, D., and Babin, R. (2017). Temperature-dependent models of development and survival of an insect pest of African tropical highlands, the coffee antestia bug *Antestiopsis thunbergii* (Hemiptera: Pentatomidae). *Journal of Thermal Biology*, *70*, 27–36. https://doi.org/10.1016/J.JTHERBIO.2017.10.009.

Baah, F., Osekre, E., Mochiah, M., and Logah, V. (2015). Effect of different levels of nitrogen in liquid fertilizer on the population dynamics and within plant distribution of *Aphis gossypii* and *Thrips palmi* and yield of gggplant. *American Journal of Experimental Agriculture*, *9*(1), 1–10. https://doi.org/10.9734/ajea/2015/17715.

Bacci, L., Picanço, M. C., Moura, M. F., Semeão, A. A., Fernandes, F. L., and Morais, E. G. F. (2008). Sampling plan for thrips (Thysanoptera: Thripidae) on cucumber. *Neotropical Entomology*, *37*(5), 582–590. https://doi.org/10.1590/s1519-566x2008000500014.

Badii, K. B. (2014). *Knowledge Gaps, Training Needs and Bio-Ecological Studies on Fruit-Infesting Flies (Diptera: Tephritidae) in Northern Ghana*. PhD dissertation, University of Ghana, Legon.

Bale, J. S., Masters, G. J., Hodkinson, I. D., Awmack, C., Bezemer, T. M., Brown, V. K., Butterfield, J., Buse, A., Coulson, J. C., Farrar, J., Good, J. E. G., Harrington, R., Hartley, S., Jones, T. H., Lindroth, R. L., Press, M. C., Symrnioudis, I., Watt, A. D., and Whittaker, J. B. (2002). Herbivory in global climate change research: direct effects of rising temperature on insect herbivores. *Global Change Biology*, *8*(1), 1–16. https://doi.org/10.1046/J.1365-2486.2002.00451.X.

Banfo, M. (2009). *Thrips (Thysanoptera; Thripidae) host preference among horticultural crops in some parts of Ghana*. MPhil thesis, University of Ghana, Legon.

Beavers, J. B., Shaw, J. G., and Hampton, R. B. (1971). Color and Height Preference of the Citrus Thrips in a Navel Orange Grove12. *Journal of Economic Entomology*, *64*(5), 1112–1113. https://doi.org/10.1093/JEE/64.5.1112.

Bempah, C. K., Donkor, A., Yeboah, P. O., Dubey, B., and Osei-Fosu, P. (2011). A preliminary assessment of consumer's exposure to organochlorine pesticides in fruits and vegetables and the potential health risk in Accra Metropolis, Ghana. *Food Chemistry*, *128*(4), 1058–1065. https://doi.org/10.1016/j.foodchem.2011.04.013.

Bennett, F. D., Glenn, H., and Baranowski, R. M. (1993). *Goetheana Shakespearei* (Hymenoptera: Eulophidae) an immigrant parasitoid of thrips in Florida and Guadeloupe?. *The Florida Entomologist*, *76*(2), 395-397.

Bethke, J. A., San Diego Co., S. H., Dreistadt, U., Davis., and Varela, L. G. (2014). Thrips integrated pest management for home gardeners and landscape professionals. *In:* M. L. Flint and K. Beverlin (Eds.), *PEST NOTES Publication 7429.* http://ipm.ucanr.edu/PMG/PESTNOTES/pn7429.html.

Boonham, N., Smith, P., Walsh, K., Tame, J., Morris, J., Spence, N., Bennison, J., and Barker, I.

(2002). The detection of Tomato spotted wilt virus (TSWV) in individual thrips using real time fluorescent RT-PCR (TaqMan). *Journal of Virological Methods*, *101*(1–2), 37–48. https://doi.org/10.1016/S0166-0934(01)00418-9.

Bosco, L., and Tavella, L. (2010). Population dynamics and integrated pest management of *Thrips tabaci* on leek under field conditions in northwest Italy. *Entomologia Experimentalis et Applicata*, *135*(3), 276–287. https://doi.org/10.1111/j.1570-7458.2010.00991.x.

Bournier, A., Lacasa, A., and Pivot, Y. (1979). Régime alimentaire d'un thrips prédateur, *Aeolothrips intermedius* [Thys.: Aeolothripioas]. *Entomophaga*, *24*(4), 353–361. https://doi.org/10.1007/BF02374174.

Bragard, C., Dehnen-Schmutz, K., Di Serio, F., Gonthier, P., Jacques, M., Jaques Miret, J. A., Fejer Justesen, A., Magnusson, C. S., Milonas, P., Navas-Cortes, J. A., Parnell, S., Potting, R., Reignault, P. L., Thulke, H., Van der Werf, W., Vicent Civera, A., Yuen, J., Zappalà, L., Malumphy, C., … MacLeod, A. (2019). Pest categorisation of *Thrips palmi*. *EFSA Journal*, *17*(2). https://doi.org/10.2903/j.efsa.2019.5620.

Bravo-Pérez, D., Santillán-Galicia, M. T., Johansen-Naime, R. M., González-Hernández, H., Segura-León, O. L., Ochoa-Martínez, D. L., and Guzman-Valencia, S. (2018). Species diversity of thrips (Thysanoptera) in selected avocado orchards from Mexico based on morphology and molecular data. *Journal of integrative agriculture*, 17(11), 2509-2517.

Briere, J. F., Pracros, P., Le Roux, A. Y., and Pierre, J. S. (1999). A novel rate model of temperature-dependent development for arthropods. *Environmental Entomology*, *28*(1), 22–29. https://doi.org/10.1093/EE/28.1.22.

Broughton, S., Jones, R., and Coutts, B. (2004). Management of thrips and tomato spotted wilt virus. *Department of Agriculture and Food (Australia). Farmnote, 69.*

Broughton, Sonya, and Harrison, J. (2012). Evaluation of monitoring methods for thrips and the effect of trap colour and semiochemicals on sticky trap capture of thrips (Thysanoptera) and beneficial insects (Syrphidae, Hemerobiidae) in deciduous fruit trees in Western Australia. *Crop Protection*, *42*, 156–163. https://doi.org/10.1016/j.cropro.2012.05.004.

Brown, S. L., Todd, J. W., and Culbreath, A. K. (1996). Effect of selected cultural practices on incidence of tomato spotted wilt virus and populations of thrips vectors in peanuts. *Acta Horticulturae*, *431*, 491–498. https://doi.org/10.17660/ACTAHORTIC.1996.431.45.

Buckman, R. S., Mound, L. A., and Whiting, M. F. (2013). Phylogeny of thrips (Insecta:

Thysanoptera) based on five molecular loci. *Systematic Entomology*, *38*(1), 123–133. https://doi.org/10.1111/J.1365-3113.2012.00650.X.

Burubai, W., Etekpe, G. W., Ambah, B., and Angaye, P. E. (2011). Combination of garlic extract and some organophosphate insecticides in controlling thrips (*Thrips palmi*) pest in watermelon management. *International Journal of Applied Science and Engineering*, *9*(1), 19–23. https://pdfs.semanticscholar.org/d1e4/49dba91b60992be3f52a80104c526f2a3390.pdf.

CABI/EPPO. (2001). *Thrips palmi*. *EPPO Bulletin*, *31*(1), 53–60. https://doi.org/10.1111/j.1365-2338.2001.tb00968.x.

CABI. (2019). *Thrips palmi (melon thrips)*. Retrieved 5 July 2020 from https://www.cabi.org/isc/datasheet/53745#toDistributionMaps.

Callan, E. M. (1947). Technique for rearing thrips in the laboratory. *Nature*, *160*(4065), 432–432. https://doi.org/10.1038/160432a0.

Callan, E. M. C. (1943). Natural enemies of the cacao thrips. *Bulletin of Entomological Research*, *34*(4), 313–321. https://doi.org/10.1017/S0007485300023828.

Cannon, R. J. C., Matthews, L., and Collins, D. W. (2007). A review of the pest status and control options for *Thrips palmi*. *Crop Protection*, *26*(8), 1089–1098. https://doi.org/10.1016/j.cropro.2006.10.023.

Capinera, J. L. (2000). Melon thrips, *Thrips palmi* Karny (Insecta: Thysanoptera: Thripidae). *Electronic Data Information Source (EDIS), Publication EENY135. University of Florida, Gainesville, Florida, USA*. Retrieved 7 February 2020 from http://entomology.ifas.ufl.edu/.

Capinera, J. L. (2020). *Handbook of vegetable pests*. Academic press, London. 799 pp.

Carlson, E. C. (1964). Effect of flower thrips on onion seed plants and a study of their control. *Journal of Economic Entomology*, *57*(5), 735–741. https://doi.org/10.1093/JEE/57.5.735.

Cermeli, M., Montagne, A., and Castro, R. (2002). Control quìmico de *Thrips palmi* Karny (Thysanoptera, Thripidae) en caraota (*Phaseolus vulgaris* L.) II. Chemical control of *Thrips palmi* Karny (Thysanoptera, Thripidae) on field beans (*Phaseolus vulgaris* L.) II. *Revista de La Facultad de Agronomía*, *19*(1), 1–8.

Chellemi, D. O., Funderburk, J. E., and Hall, D. W. (1994). Seasonal abundance of flower-inhabiting *Frankliniella* Species (Thysanoptera: Thripidae) on wild plant species. *Environmental Entomology*, *23*(2), 337–342. https://doi.org/10.1093/EE/23.2.337.

Chen, A. T., Chu, C., Fitzgerald, G., Natwick, E. T., Henneberry, T. J., Chen, T., Chu, C., Fitzgerald, G., Natwick, E. T., and Henneberry, T. J. (2004). Trap evaluations for thrips (Thysanoptera : Thripidae) and hoverflies (Diptera : Syrphidae). *Environmental Entomology*, *33*(5), 1416–1420. https://doi.org/10.1603/0046-225X-33.5.1416.

Childers, C. C., and Achor, D. S. (1995). Thrips feeding and oviposition injuries to economic plants, subsequent damage and host responses to infestation. *In:* B. L. Parker, M. Skinner, and T. Lewis (Eds.), *Thrips Biology and Management*. Springer, Boston, MA, pp. 31–51. https://doi.org/10.1007/978-1-4899-1409-5_3.

Cho, K., Kang, S. H., and Lee, G. S. (2000a). Spatial distribution and sampling plans for *Thrips palmi* (Thysanoptera: Thripidae) infesting fall potato in Korea. *Journal of Economic Entomology*, *93*(2), 503–510. https://doi.org/10.1603/0022-0493-93.2.503.

Chu, C.-C., Ciomperlik, M. A., Chang, N.-T., Richards, M., and Henneberry, T. J. (2006). Developing and Evaluating Traps for Monitoring Scirtothrips Dorsalis (Thysanoptera: Thripidae). *Florida Entomologist*, *89*(1), 47–55. https://doi.org/10.1653/0015-4040(2006)89[47:daetfm]2.0.co;2.

Cloyd, R. A., and Sadof, C. S. (2003). Seasonal abundance and the use of an action threshold for western flower thrips, in a cut carnation greenhouse. *HortTechnology*, *13*(3), 497–500. https://doi.org/10.21273/HORTTECH.13.3.0497.

COLEACP. (2020). *Guidelines on exporting fresh eggplant and tomato*. Retrieved 7 February 2021 from https://eservices.coleacp.org/en/system/files/file_fields/2020/12/01/guideline-exportsoneggplantandtomato-nov2020.pdf.

Conti, B. (2009). Notes on the presence of *Aeolothrips intermedius* in North-Western Tuscany and on its development under laboratory conditions. *Bulletin of Insectology*, *62*(1), 107-112.

Culbreath, A. K., Tillman, B. L., Tubbs, R. S., Beasley Jr, J. P., Kemerait Jr, R. C., and Brenneman, T. B. (2010). Interactive effects of planting date and cultivar on tomato spotted wilt of peanut. *Plant disease*, *94*(7), 898-904. https://doi.org/10.1094/PDIS-94-7-0898.

Curry, G. L., Fieldman, R. M., and Smith, K. C. (1978). A stochastic model for a temperature-dependent population. *Theoretical Population Biology*, *13*(2), 197–213.

Daimei, G., Raina, H. S., Devi, P. P., Saurav, G. K., Renukadevi, P., Malathi, V. G., ...,and Rajagopal, R. (2017). Influence of Groundnut bud necrosis virus on the life history traits and feeding preference of its vector, *Thrips palmi*. *Phytopathology*, *107*(11), 1440–1445.

https://doi.org/10.1094/PHYTO-08-16-0296-R.

Davidson, J., and Andrewartha, H. G. (1948). The influence of rainfall, evaporation and atmospheric temperature on fluctuations in the size of a aatural population of *Thrips imaginis* (Thysanoptera). *The Journal of Animal Ecology*, *17*(2), 200. https://doi.org/10.2307/1485.

Deligeorgidis, P., Ipsilandis, C., Fotiadou, C., Kaltsoudas, G., Giakalis, L., and Garsen, A. (2005). Fluctuation and distribution of *Frankliniella occidentalis* (Pergande) and *Thrips tabaci* Lindeman (Thysanoptera: Thripidae) populations in greenhouse cucumber and tomato. *Pakistan Journal of Biological Sciences*, *8*(8), 1105-1111.

Dennill, G. B., and Erasmus, M. J. (1992). The insect pests of avocado fruits-increasing pest complex and changing pest status. *Journal of the Entomological Society of Southern Africa*, *55*(1), 51–57. https://doi.org/10.10520/AJA00128789_3196.

Dent, D. (2000). *Insect Pest Management* (2nd edition). CABI Bioscience, UK, pp. 425.

Diaz-Montano, J., Fuchs, M., Nault, B. A., Fail, J., and Shelton, A. M. (2011). Onion thrips (Thysanoptera: Thripidae): A Global Pest of Increasing Concern in Onion. *Journal of Economic Entomology*, *104*(1), 1–13. https://doi.org/10.1603/EC10269.

Diop, K. (1999). *The biology of Ceranisus menes (Walker) (Hym., Eulophidae), a parasitoid of the bean flower thrips Megalurothrips sjostedti (Trybom) (Thys., Thripidae): a comparison between African and Asian populations*, PhD dissertation, University of Ghana, pp. 190.

Dinham, B. (2003). Growing vegetables in developing countries for local urban populations and export markets: Problems confronting small-scale producers. *Pest Management Science*, *59*(5), 575–582. https://doi.org/10.1002/ps.654.

Ebratt-Ravelo, E. E., Castro-Avila, A. P., Vaca-Uribe, J. L., Corredor-Pardo, D., Hance, T., and Goldarazena, A. (2019). Composition and structure of Thripidae populations in crops of three geographical regions in Colombia. *Journal of Insect Science*, *19*(1), 27–28. https://doi.org/10.1093/jisesa/iez009.

Edelson, J. V. (1985). A sampling method for estimating absolute numbers of thrips on onions. *Southwestern Entomologist*, *10*(2), 103-106. https://www.cabdirect.org/cabdirect/abstract/19860532554.

Eliyahu, D., McCall, A. C., Lauck, M., Trakhtenbrot, A., and Bronstein, J. L. (2015). Minute pollinators: The role of thrips (Thysanoptera) as pollinators of pointleaf manzanita, *Arctostaphylos pungens* (Ericaceae). *Journal of Pollination Ecology*, *16*, 64.

https://doi.org/10.26786/1920-7603(2015)10.

Ellington, C. P. (1980). Wing mechanics and take-off preparation of thrips (Thysanoptera). *Journal of Experimental Bioliogy*, *85*, 129–136.

EPA. (1997). *Pesticide Registration (PR) Notice 97Ð3. United States Environmental Protection Agency, Washington, DC.*

EPPO. (2000). *Thrips parvispinus (THRIPV)[World distribution]. EPPO Global Database*. Retrieved 20 May 2020 from https://gd.eppo.int/taxon/THRIPV/distribution.

EPPO. (2004). *European Plant Protection Organization Global Database*. Retrieved 31 July 2020 from https://gd.eppo.int/reporting/article-1648.

EPPO. (2014). European and Mediterranean Plant Protection Organization. *Bulletin OEPP/EPPO Bulletin*, *44* (3), 265–273.

EPPO. (2019). *Thrips palmi (THRIPL)[World distribution]| EPPO Global Database*. Retrieved 31 July 2020 from https://gd.eppo.int/taxon/THRIPL/distribution.

Ereshrao, J. N. (2018). *Integrated pest management studies in chilli (Capsicum annuum l.)*. Masters thesis, Vasantrao Naik Marathwada Krishi Vidyapeeth, Parbhani, India, pp. 284.

EUROPHYT. (2010). *European Union Notification System for Plant Health Interceptions. Interceptions of harmful organisms in commodities imported into the EU Member States and Switzerland. Annual report 2010*. Retrieved 27 July 2020 from https://food.ec.europa.eu/system/files/2016-10/ph_biosec_europhyt-interceptions-2010_summary.pdf.

EUROPHYT. (2011). *European Union Notification System for Plant Health Interceptions. Interceptions of harmful organisms in commodities imported into the EU Member States and Switzerland. Annual report 2011*. Retrieved 27 July 2020 from https://food.ec.europa.eu/system/files/2016-10/ph_biosec_europhyt-interceptions-2011_summary.pdf.

EUROPHYT. (2012). *European Union Notification System for Plant Health Interceptions. Interceptions of harmful organisms in commodities imported into the EU Member States and Switzerland. Annual report 2012*. Retrieved 27 July 2020 from https://food.ec.europa.eu/system/files/2016-10/ph_biosec_europhyt-interceptions-2012_summary.pdf.

EUROPHYT. (2013). *European Union Notification System for Plant Health Interceptions.*

Interceptions of harmful organisms in commodities imported into the EU Member States and Switzerland. Annual report 2013. Retrieved 27 July 2020 from https://food.ec.europa.eu/system/files/2016-10/ph_biosec_europhyt-interceptions-2013_summary.pdf.

EUROPHYT. (2014). *European Union Notification System for Plant Health Interceptions. Interceptions of harmful organisms in commodities imported into the EU Member States and Switzerland. Annual report 2014*. Retrieved 27 July 2020 from https://food.ec.europa.eu/system/files/2016-10/ph_biosec_europhyt-interceptions-2014_summary.pdf.

EUROPHYT. (2015). *European Union Notification System for Plant Health Interceptions. Interceptions of harmful organisms in commodities imported into the EU Member States and Switzerland. Annual report 2015*. Retrieved 27 July 2020 from https://food.ec.europa.eu/system/files/2016-10/ph_biosec_europhyt-interceptions-2015_summary.pdf.

EUROPHYT. (2016). *European Union Notification System for Plant Health Interceptions. Interceptions of harmful organisms in commodities imported into the EU Member States and Switzerland. Annual report 2016.* Retrieved 28 July 2020 from https://food.ec.europa.eu/system/files/2017-01/ph_biosec_europhyt-interceptions-2016_summary.pdf.

EUROPHYT. (2017). *European Union Notification System for Plant Health Interceptions. Interceptions of harmful organisms in commodities imported into the EU Member States and Switzerland. Annual report 2017.* Retrieved 28 July 2020 from https://food.ec.europa.eu/system/files/2018-05/ph_biosec_europhyt-interceptions-2017_summary.pdf.

EUROPHYT. (2018). *European Union Notification System for Plant Health Interceptions. Interceptions of harmful organisms in commodities imported into the EU Member States and Switzerland. Annual report 2018.* Retrieved 28 July 2020 from https://food.ec.europa.eu/system/files/2019-01/ph_biosec_europhyt-interceptions-2018_summary.pdf.

EUROPHYT. (2019). *European Union Notification System for Plant Health Interceptions. Interceptions of harmful organisms in commodities imported into the EU Member States and*

Switzerland. Annual report 2019. Retrieved 28 July 2020 from https://food.ec.europa.eu/system/files/2020-01/ph_biosec_europhyt-interceptions-2019_summary.pdf.

EUROPHYT. (2020). *European Union Notification System for Plant Health Interceptions. Interceptions of harmful organisms in commodities imported into the EU Member States and Switzerland. Monthly reports 2020.* Retrieved 22 June 2020 from https://food.ec.europa.eu/system/files/2022-01/ph_biosec_europhyt-interceptions-2020_summary.pdf.

EUROPHYT. (2021). *European Union Notification System for Plant Health Interceptions. Interceptions of harmful organisms in commodities imported into the EU Member States and Switzerland. Monthly reports 2021.* Retrieved 18 December 2021 from https://food.ec.europa.eu/system/files/2021-10/ph_biosec_traces-interceptions-2021-09.pdf.

Fand, B. B., Tonnang, Z. E. H., Kumar, M., Kamble, A. L., and Bal, S. K. (2014). A temperature-based phenology model for predicting development, survival and population growth potential of the mealybug, *Phenacoccus solenopsis* Tinsley (Hemiptera: Pseudococcidae). *Crop Protection*, *55*, 98–108. http://dx.doi.org/10.1016/j.cropro.2013.10.020.

Fedor, P. J., Doričová, M., Prokop, P., and Mound, L. A. (2010). Heinrich Uzel, the father of Thysanoptera studies. *Zootaxa*, *2645*(1), 55–63.

Fening, K. O., Owusu-Akyaw, M., Mochiah, M. B., Amoabeng, B. W., Narveh, E., and Ekyem, S. O. (2011). Sustainable management of insect pests of green cabbage, *Brassica oleraceae* var. *capitata* L. (Brassicaceae), using homemade extracts from garlic and hot pepper. Third Scientific Conference of the International Society of Organic Agriculture Research (ISOFAR), Korea.

Fening, K. O., Amoabeng, B. W., Adama, I., Mochiah, M. B., Braimah, H., Owusu-Akyaw, M., Narveh, E., and Ekyem, S. O. (2013). Sustainable management of two key pests of cabbage, *Brassica oleracea* var. *capitata* L. (Brassicaceae), using homemade extracts from garlic and hot pepper. *Organic Agriculture*, *3*(3–4), 163–173. https://doi.org/10.1007/s13165-014-0058-2.

Fening, K. O., Billah, M. K and Kukiriza, C. N. (2016). *Protocol for evaluating the efficacy of six products against the False Codling moth, Fruit flies, Thrips and Whiteflies on Chillies, Garden egg and Ridged Gourd in Ghana. GhanaVeg, Accra, pp. 45.*

Fening, K.O. and Billah, M. K. (2017). *Guidelines to extend official export certification controls beyond the point of exit to include the fields of production and packhouses for vegetable exporters. Plant Protection and Regulatory Services Directorate (PPRSD) of MoFA, September 2017, Accra.*

Fening, K.O. and Billah, M. K. (2019). *Final Report. USAID Embedded Advisors for PPRSD.* Retrieved 20 December 2021 from https://govtribe.com/file/government-file/soo-annex-j-sps-embedded-advisor-for-pprsd-dot-pdf.

Fening, K. O., Billah, M. K., and Nankinga, C. M. K. (2020). Management of Pests of Quarantine Importance in Ghana's Export Vegetables (Chili, Eggplant and Ridged Gourds). *In:* S. Niassy, S. Ekesi, L. Migiro, and W. Otieno (Eds.), *Sustainable Management of Invasive Pests in Africa*. Springer, Cham, pp. 227–243. https://doi.org/10.1007/978-3-030-41083-4_18.

Fening, K. O., Amouzou, K., Hevi, W., Forchibe, E. E., Billah, M. K. and Wamonje, F.O (2022). First report and population dynamics of the Tobacco Thrips, *Thrips parvispinus* (Karny) (Thysanoptera: Thripidae) on ridged gourd, *Luffa acutangula* (L.) Roxy in selected export fields in Southern Ghana. *Journal of Agriculture and Rural Development in the Tropics and Subtropics 123* (2), 235–245. https://doi.org/10.17170/kobra-202212057193.

Fennah, R. G. (1965). The influence of environmental stress on the cacao tree in predetermining the feeding sites of cacao thrips, *Selenothrips rubrocinctus* (Giard) on leaves and pods. *Bulletin of Entomological Research*, *56*, 333–49 20.

Fitch, A. (1855). *Report on the noxious, beneficial and other insects of the state New-York. Transactions of the New York State Agricultural Society, C. Van Benthuysen, Albany, USA.*

Fournier, F., Boivin, G., and Stewart, R. K. (1995). Impact and economic threshold of *Thrips tabaci* on Onions. *In:* B. L. Parker, M. Skinner, and T. Lewis (Eds.), *Thrips Biology and Management*. Springer, Boston, MA, pp. 71–76. https://doi.org/10.1007/978-1-4899-1409-5_6.

Funderburk, J., Stavisky, J., and Olson, S. (2000). Predation of *Frankliniella occidentalis* (Thysanoptera: Thripidae) in field peppers by *Orius insidiosus* (Hemiptera: Anthocoridae). *Environmental Entomology*, *29*(2), 376–382. https://doi.org/10.1093/EE/29.2.376.

Funderburk, J. E. (2002). Ecology of thrips. *In:* R. Marullo and L. Mound (Eds.), *Thrips and Tospoviruses; Proceedings of the 7th International Symposium on Thysanoptera.* Australian National Insect Collection, Canberra, Australia, pp. 121-128.

Funderburk, J., Stavisky, J., Tipping, C., Gorbet, D., Momol, T., and Berger, R. (2002a). Infection of *Frankliniella fusca* (Thysanoptera: Thripidae) in Peanut by the Parasitic Nematode *Thripinema fuscum* (Tylenchidae: Allantonematidae). *Environmental Entomology*, *31*(3), 558-563. https://doi.org/10.1603/0046-225X-31.3.558.

Funderburk, J., Ripa, R., Espinoza, F., and Rodriguez, F. (2002b). Parasitism of *Frankliniella australis* (Thysanoptera: Thripidae) by *Thripinema khrustalevi* (Tylenchida: Allantonematidae) isolate Chile. *Florida Entomologist*, *85*(4), 645-649. https://bioone.org/journals/florida-entomologist/volume-85/issue-4/0015-4.

Funderburk, J., Reitz, S., Stansly, P., Olson, S., Sui, D., Mcavoy, G., Demirozer, O., Nuessly, G., and Leppla, N. (2011). Managing thrips in pepper and eggplant. *EDIS Document ENY-658, Florida Cooperative Extension Service, University of Florida, Gainesville.*, 1–11.

Gao, Y., Zhao, Y., Wang, D., Yang, J., Ding, N., and Shi, S. (2021). Effect of different plants on the growth and reproduction of *Thrips flavus* (Thysanoptera: Thripidae). Insects, 12(6), 502.

Ghana Talks Business. (2017). *Ghana loses $10m following ban on five vegetable exports*. Retrieved 7 July 2020 from https://ghanatalksbusiness.com/2017/07/ghana-loses-10m-following-ban-five-vegetable-exports/.

GhanaVeg Sector Reports. (2016). *Vegetable Business Opportunities in Ghana*. Accra, Ghana: Ghanaveg, pp. 1-88.

GhanaVeg Sector Reports. (2017). *Roadmap for Pest Reduction in Ghana's Export Vegetable Sector*. K. O. Fening and M. K. Billah (Eds.), Accra, Ghana: GhanaVeg, pp. 1-36.

Gharekhani, G. H., Ghorbansyahi, S., Saber, M., and Bagheri, M. (2014). Influence of the colour and height of sticky traps in attraction of *Thrips tabaci* (Lindeman) (Thysanoptera, Thripidae) and predatory thrips of family Aeolothripidae on garlic, onion and tomato crops. *Archives of Phytopathology and Plant Protection*, *47*(18), 2270–2275. https://doi.org/10.1080/03235408.2013.874100.

Ghosh, A., Basavaraj, Y. B., Jangra, S., and Das, A. (2019). Exposure to watermelon bud necrosis virus and groundnut bud necrosis virus alters the life history traits of their vector, *Thrips palmi* (Thysanoptera: Thripidae). *Archives of Virology*, *164*(11), 2799–2804. https://doi.org/10.1007/s00705-019-04381-z..

Gill, H. K., Garg, H., Gill, A. K., Gillett-Kaufman, J. L., and Nault, B. A. (2015). Onion thrips (Thysanoptera: Thripidae) biology, ecology, and management in onion production systems.

Journal of Integrated Pest Management, *6*(1), 1–9. https://doi.org/10.1093/jipm/pmv006

Grinfel'd, E. K. (1959). Feeding of thrips on the pollen of flowers and the origin of asymmetry in their mouthparts. *A Translation of Entomological Review, the American Institute of Biological Sciences*, *38*(4), 715-720.

Grout, T. G., and Richards, G. I. (1992). *Euseius addoensis addoensis*, an effective predator of citrus thrips, *Scirtothrips aurantii*, in the eastern Cape Province of South Africa. *Experimental and Applied Acarology*, *15*(1), 1–13. https://doi.org/10.1007/BF01193963.

Grove, T., Giliomee, J. H., and Pringle, K. L. (2001). Thrips (Thysanoptera) species associated with mango trees in South Africa. *African Entomology*, *9*(2), 153–162.

GNBCC. (2023). HBP Core Member, AB Farms Received The Presidents National Awards For Export Achievement. Retrieved 20 May 2024 from https://www.gnbcc.net/News/Item/7522.

Gutierrez, A. P., Ponti, L., d'Oultremont, T., and Ellis, C. K. (2007). Climate change effects on poikilotherm tritrophic interactions. *Climatic Change*, *87*(1), 167–192. https://doi.org/10.1007/S10584-007-9379-4

Gyau, A., and Spiller, A. (2007). The role of organizational culture in modeling buyer-seller relationships in the fresh fruit and vegetable trade between Ghana and Europe. *African Journal of Business Management*, *1*(8), 218–229.

Hansen, E. A., Funderburk, J. O. E. E., Reitz, S. R., Ramachandran, S., Eger, J. O. E. E., and Mcauslane, H. (2003). Within-plant distribution of *Frankliniella* species (Thysanoptera : Thripidae) and *Orius insidiosus* (Heteroptera : Anthocoridae) in field pepper. *Environmental Entomology*, *32*(5), 1035–1044. https://doi.org/10.1603/0046-225X-32.5.1035.

Hameed, A., Rosa, C., O'Donnell, C. A., and Rajotte, E. G. (2023). Ecological Interactions among Thrips, Soybean Plants, and Soybean Vein Necrosis Virus in Pennsylvania, USA. *Viruses*, 15(8), 1766.

Hata, T. Y., Hara, A. H., and Hansen, J. D. (1991). Feeding preference of melon thrips on orchids in Hawaii. *HortScience*, *26*(10), 1294–1295. https://doi.org/10.21273/hortsci.26.10.1294.

Hata, T. Y., Hara, A. H., Hu, B. K., Kaneko, R. T., and Tenbrink, V. L. (1993). Field sprays and insecticidal dips after harvest for pest management of *Frankliniella occidentalis* and *Thrips palmi* (Thysanoptera: Thripidae) on orchids. *Journal of economic entomology*, *86*(5), 1483-1489.

Hawkins, B. S., Peacock, H. A., and Steele, T. E. (1966). Thrips injury to upland cotton

(Gossypium hirsutum L.) varieties 1. *Crop Science*, *6*(3), 256-258.

Healey, M. (2016). *The Population dynamics of the thrips species assemblage in French bean , Lettuce, Tomato and Zucchini Agro-Ecosystems*. PhD dissertation, CQUniversity, Bundaberg, Australia.

Hector, A. A. (2006). *A Study of the behavior, ecology, and control of flower thrips in blueberries towards the development of an integrated pest management (IPM) program in Florida and Southern Georgia*. PhD dissertation, University of Florida.

Heming, B. S. (1978). Structure and function of the mouthparts in larvae of *Haplothrips verbasci* (Osborn) (Thysanoptera, Tubulilfera, Phlaeothripidae). *Journal of Morphology*, *156*, 1–38.

Henderson, C. F., and Tilton, E. W. (1995). Tests with Acaricides against the Brown Wheat Mite12. *Journal of Economic Entomology*, *48*(2), 157–161. https://doi.org/10.1093/jee/48.2.157.

Herring, J. L. (1966). The Genus Orius of the Western Hemisphere (Hemiptera: Anthocoridae). *Annals of the Entomological Society of America*, *59*(6), 1093–1109. https://doi.org/10.1093/AESA/59.6.1093.

Hirose, Y., Kajita, H., Takagi, M., Okajima, S., Napompeth, B., and Buranapanichpan, S. (1993). Natural enemies of *Thrips palmi* and their effectiveness in the native habitat, Thailand. *Biological Control*, *3*(1), pp. 1–5. https://doi.org/10.1006/bcon.1993.1001.

Hoddle, M. S. Mound, L. A. Paris, D. L. (2012). *Thrips of California 2012*. Identic Pty Ltd, Queensland Retrieved 21 November 2020 from https://doi.org/https://keys.lucidcentral.org/keys/v3/thrips_of_california_2019/the_key/california_thysanoptera_2019.html.

Hodges, A., Ludwig, S., Osborne, L., and Edwards, G. B. (2009). *Pest Thrips of the United States: Field Identification Guide*. USDA-CSREES Regional Integrated Pest Management Center, USA.

Hong, J., Lee, G. S., Park, J. J., Mo, H. ho, and Cho, K. (2019). Risk map for the range expansion of *Thrips palmi* in Korea under climate change: Combining species distribution models with land-use change. *Journal of Asia-Pacific Entomology*, *22*(3), 666–674. https://doi.org/10.1016/j.aspen.2019.04.013.

Hulshof, J., Ketoja, E., and Vänninen, I. (2003). Life history characteristics of *Frankliniella occidentalis* on cucumber leaves with and without supplemental food. *Entomologia*

Experimentalis et Applicata, *108*(1), 19–32. https://doi.org/10.1046/J.1570-7458.2003.00061.X.

Hunter, W. B., and Ullman, D. E. (1989). Analysis of mouthpart movements during feeding of *Frankliniella occidentalis* (Pergande) and *F. schultzei* (Trybom) (Thysanoptera: Thripidae). *International journal of insect morphology and embryology*, *18*, 161-171.

Hutasoit, R. T., Triwidodo, H., and Anwar, R. (2018). Biologi dan statistik demografi *Thrips parvispinus* Karny (Thysanoptera: Thripidae) pada tanaman cabai (*Capsicum annuum* Linnaeus). *Jurnal Entomologi Indonesia*, *14*(3), 107. https://doi.org/10.5994/JEI.14.3.107.

Ibrahim, N. D., and Adesiyun, A. A. (2010). Effect of rainfall in the control of onion thrips, *Thrips tabaci* Lindeman (Thysanoptera: Thripidae) in Sokoto, Nigeria. *Agriculture and Biology Journal of North America*, *1*(3), 377-386.

Iftikhar, R., Ashfaq, M., Rasool, A., A., and Hebert, P. D. (2016a). DNA barcode analysis of thrips (Thysanoptera) diversity in Pakistan reveals cryptic species complexes. *PLoS ONE*, *11*(1), e0146014. https://doi.org/10.1371/journal.pone.0146014.

Iftikhar, Romana., Ullah, I., Diffie, S., and Ashfaq, M. (2016b). Deciphering Thysanoptera : A comprehensive study on the distribution and diversity of thrips fauna in Pakistan. *Pakistan Journal of Zoology*, *48*(5), 1234-1240 (b).

Infonet-Biovision. (2019). *Eggplant-Infonet Biovision*. Retrieved 11 June 2019 from https://infonet-biovision.org/PlantHealth/Crops/Eggplant.

Infonet-Biovision. (2022). *Thrips*. Retrieved 11 December 2021 from https://infonet-biovision.org/PlantHealth/Pests/Thrips.

IPPC. (2001). *Climate change sunthesis report- contribution of working groups I, II, and III to the third assessment report of the Intergovernmental Panel on Climate Change*. Retrieved 10 November 2021 from https://www.ipcc.ch/site/assets/uploads/2018/05/SYR_TAR_full_report.pdf.

IRAC. (2022). *Mode of Action Classification Scheme. IRAC International MoA Working Group, version 10.4, pp. 1-40*.

Ireri, N. N. (2015). *Identity, abundance and management of banana Thrips In Embu County, Kenya Njue*. MSc thesis,University of Nairobi, pp. 106.

Jacobson, R. J. (1997). Integrated pest management (IPM) in glasshouses. *Integrated Pest Management (IPM) in Glasshouses.*, pp. 639-666.

Jayma L. Martin, and Mau, R. F. L. (2007). *Thrips palmi*. Crop Knowledge Master. Retrieved 10 July 2021 from http://www.extento.hawaii.edu/kbase/crop/Type/t_palmi.htm.

Johari, A., Herlinda, S., Pujiastuti, Y., Irsan, C., and Sartiami, D. (2014). Morphological and genetic variation of *Thrips parvispinus* (Thysanoptera: Thripidae) in chilli plantation (*Capsicum annuum* L.) in the lowland and highland of Jambi Province, Indonesia. *American Journal of BioScience*, *2*(1), 17–21.

Joseph, S. V., Braman, K., Hudson, W., and Nair, S. (2016). *Biology and Management of Thrips Affecting the Production Nursery and Landscape*. *UGA Cooperative Extension*. University of Georgia. https://extension.uga.edu/publications/detail.html?number=C1158andtitle=Biology

Karthik, S., Reddy, M. S. S., and Yashaswini, G. (2021). Climate change and its potential impacts on insect-plant interactions. *In: The Nature, Causes, Effects and Mitigation of Climate Change on the Environment*. *IntechOpen*, pp. 24. https://doi.org/10.5772/intechopen.98203.

Katayama, H. (1997). Effect of temperature on development and oviposition of western flower thrips *Frankliniella occidentalis* (Pergande). *Japanese Journal of Applied Entomology and Zoology*, *41*(4), 225–231. https://doi.org/10.1303/jjaez.41.225.

Kawai, A. (1986). Studies on population ecology of *Thrips palmi* Karny. XII. Analyses of damage to eggplant and sweet pepper. *Japanese Journal of Applied Entomology and Zoology*, *30*(3), 179-187. https://doi.org/10.1303/jjaez.30.179.

Kawai, Akira. (1988). Studies on population ecology of *Thrips palmi* Karny. 16. Distribution among leaf, flower and fruit on eggplant and sweet pepper. *Japanese Journal of Applied Entomology and Zoology*, *32*(4), 291–296. https://doi.org/10.1303/jjaez.32.291.

Kawai, Akira. (1990). Life cycle and population dynamics of *Thrips palmi* KARNY. *Japan Agricultural Research Quarterly*, *23*(4), 282–288.

Kendall, D. M., and Capinera, J. L. (1987). Susceptibility of onion growth stages to onion thrips (Thysanoptera: Thripidae) damage and mechanical defoliation. *Environmental Entomology*, *16*(4), 859–863. https://doi.org/10.1093/EE/16.4.859.

Kerns, C. D., Greene, J. K., Reay-Jones, F. P. F., and Bridges, W. C. (2018). Effects of planting date on thrips (Thysanoptera: Thripidae) in cotton. *Journal of Economic Entomology*, *112*(2), 699-707. https://doi.org/10.1093/jee/toy398.

Khadioli, N., Tonnang, Z. E. H., Ong'amo, G., Achia, T., Kipchirchir, I., Kroschel, J., and Le Ru, B. (2014). Effect of temperature on the life history parameters of noctuid lepidopteran stem borers, *Busseola fusca* and *Sesamia calamistis*. *Annals of Applied Biology*, *165*(3), 373–386. https://doi.org/10.1111/AAB.12157.

Kobayashi, K., and Hasegawa, E. (2012). Discrimination of reproductive forms of *Thrips tabaci* (Thysanoptera: Thripidae) by PCR with sequence specific primers. *Journal of Economic Entomology*, *105*(2), 555–559. https://doi.org/10.1603/EC11320.

Koyama, K., and Matsui, M. (1992). Rearing of the adult of *Thrips palmi* Karny on dry leaf powder of cucumber, eggplant and tomato. *Japanese Journal of Applied Entomology and Zoology*, *36*(1), 52–54. https://doi.org/10.1303/JJAEZ.36.52.

Kumar, V. Kakkar, G. Palmer, C. McKenzie, C. L. and Osborne, L. S. (2016). Thrips management program for horticultural crops. *EDIS-Online Extension Publication.*, pp. 1–7.

Kundoo, A. A., Campus, S., Showket Ahmad Dar, I., Muntazir Mushtaq, I., Zaffar Bashir, I., Saleem Dar, M., Shaheen Gul, I., Tawseef Ali, M., Gulzar, S., Showket Ahmad Dar, C., Ahmad Dar, S., Mushtaq, M., Bashir, Z., and Gul, S. (2018). Role of neonicotinoids in insect pest management: A review. *Journal of Entomology and Zoology Studies*, *6*(1).

Lakshmi, K. V., Wightman, J. A., Reddy, D. V. R., Rao, G. V. R., Buiel, A. A. M., and Reddy, D. D. R. (1995). Transmission of peanut bud necrosis virus by *Thrips palmi* in India. *In:* B. L. Parker, M. Skinner, and T. Lewis (Eds.), *Thrips Biology and Management*. Springer, Boston, MA, pp. 179-184. https://doi.org/10.1007/978-1-4899-1409-5_26.

Layland, J. K., Upton, M., and Brown, H. H. (1994). Monitoring and identification of *Thrips palmi* Karny (Thysanoptera : Thripidae). *Australian Journal of Entomology*, *33*(2), 169–173. https://doi.org/10.1111/j.1440-6055.1994.tb00946.x.

Leighl, T. F. (1995). Bionomics of cotton thrips: A Review. *In:* B. L. Parker, M. Skinner, and T. Lewis (Eds.), *Thrips Biology and Management.* Springer, Boston, MA, pp. 61–70. https://doi.org/10.1007/978-1-4899-1409-5_5.

Lewis, J. S. (1968). *The thrips or Thysanoptera of Illinois*. Natural history survey division. State of Illinois, Urbana. vol. 29. 365 pp.

Lewis, T. (1959). A comparison of water traps, cylindrical sticky traps and suction traps for sampling thysanopteran populations at different levels. *Entomologia Experimentalis et Applicata*, *2*(3), 204–215. https://doi.org/10.1111/J.1570-7458.1959.TB00434.X.

Lewis, T. (1973). *Thrips, their biology, ecology and economic importance.* Academic Press, London. https://en.wikipedia.org/wiki/Thrips.

Lewis, W. J., Van Lenteren, J. C., Phatak, S. C., and Tumlinson, J. H. (1997). A total system approach to sustainable pest management. *Proceedings of the National Academy of Sciences of the United States of America*, *94*(23), 12243–12248. https://doi.org/10.1073/pnas.94.23.12243.

Logan, J. A., Wollkind, D. J., Hoyt, S. C., and Tanigoshi, L. K. (1976). An analytic model for detection of temperature dependent rate phenomena in arthropods. *Environmental Entomologymology*, *5*, 1133–1140.

Lu, F. M. (1990). Color preference and using silver mulches to control the onion thrips, *Thrips tabaci* Lindeman. *Chinese Journal of Entomology*, *10*(3), 337–342. https://www.cabdirect.org/cabdirect/abstract/19921165622.

Li, H. B., Shi, L., Lu, M. X., Wang, J. J., and Du, Y. Z. (2011). Thermal tolerance of *Frankliniella occidentalis:* effects of temperature, exposure time, and gender. *Journal of Thermal Biology*, *36*(7), 437-442..

Luong, L. C. (2008). *Investigations into aspects of biology of tubular black thrips, Haplothrips victoriensis Bagnall (Thysanoptera; Phlaeothripidae) in South Australia*. University of Adelaide, Australia.

MacLeod, A., Head, J., and Gaunt, A. (2004). An assessment of the potential economic impact of *Thrips palmi* on horticulture in England and the significance of a successful eradication campaign. *Crop Protection*, *23*(7), 601–610. https://doi.org/10.1016/j.cropro.2003.11.010.

Mainali, B. P., and Lim, U. T. (2010). Circular yellow sticky trap with black background enhances attraction of *Frankliniella occidentalis* (Pergande) (Thysanoptera: Thripidae). *Applied Entomology and Zoology*, *45*(1), 207–213. https://doi.org/10.1303/aez.2010.207.

Malik, M. F., Nawaz, M., Ellington, J., Sanderson, R., and El-Heneidy, A. H. (2009). Effect of Different Nitrogen Regimes on Onion Thrips, *Thrips tabaci* Lindemann, on Onions, *Allium cepa* L. *Southwestern Entomologist*, *34*(3), 219–225. https://doi.org/10.3958/059.034.0303.

Mandal, S. M. A., and Patnaik, N. C. (2008). Interspecific abundance and seasonal incidence of aphids and aphidophagous predators associated with cabbage. *Journal of Biological Control*, *22*(1), 195-198. https://www.cabdirect.org/cabdirect/abstract/20083260328.

Mao, L., Chang, Y., Yang, F., Zhang, L., Zhang, Y., and Jiang, H. (2018). Attraction effect of different colored cards on thrips Frankliniella intonsa in cowpea greenhouses in China. *Scientific Reports*, *8*(1), 1–6. https://doi.org/10.1038/s41598-018-32035-8.

Maris, P. C., Joosten, N. N., Goldbach, R. W., and Peters, D. (2007). Tomato spotted wilt virus infection improves host suitability for its vector *Frankliniella occidentalis*. *Phytopathology*, *94*(7), 706–711. https://doi.org/10.1094/phyto.2004.94.7.706.

Mason, J. M. and, and Heinz, K. M. (2002). Biology of *Thripinema nicklewoodi* (Tylenchida), an obligate parasite of *Frankliniella occidentalis* (Thysanoptera). *Journal of Nematology*, *34*(4), 332. /pmc/articles/PMC2620589/?report=abstract.

McNeill, S., and Southwood, T. R. E. (1978). Aspects of plant and animal coevolution. The role of nitrogen in the development of insect/plant relationships. Academic press, London, pp. 77-98.

Mehle, N., and Trdan, S. (2012). Traditional and modern methods for the identification of thrips (Thysanoptera) species. *Journal of Pest Science*, *85*(2), 179–190. https://doi.org/10.1007/s10340-012-0423-4.

Michielini, J. P., Yi, X., Brown, L. M., Gao, S. M., Orians, C., and Crone, E. E. (2024). Novel host plant use by a specialist insect depends on geographic variation in both the host and herbivore species. *Oecologia*, *204*(1), 95-105.

Minaei, K. (2014). A new species of Eremiothrips from Iran (Thysanoptera: Thripidae). *Acta Entomologica Musei Nationalis Pragae*, *54*(1), 29–34. https://www.biotaxa.org/AEMNP/article/view/5369.

Mirab-balou, M. and Xue-xin, C. (2011). The Megalurothrips Genus-Group in Iran (Thysanoptera: Thripidae). *Munis Entomology and Zoology*, *6*(2), 944–952.

Mochiah, M. B., Banful, B., Fening, K. O., Amoabeng, B. W., Offei Bonsu, K., Ekyem, S., Braimah, H., and Owusu-Akyaw, M. (2011). Botanicals for the management of insect pests in organic vegetable production. *Journal of Entomology and Nematology*, *3*(6), 85–97.

Mochiah, M. B., Frimpong-Anin, K., Ibrahim, A., and Augustine, A. D. (2019). Efficacy of Sauveur 62 EC for the management of fall armyworm *Spodoptera frugiperda* (Lepidoptera: Noctuidae) on Maize (*Zea mays* L.). *International Journal of Current Research*, *11*(10), 7836–7840. https://doi.org/10.24941/ijcr.36789.10.2019.

MoFA. (2020). *Greater Accra Region*. Retrieved 12 May 2021 from https://mofa.gov.gh/site/directorates/regional-directorates/greater-accra-region.

Mohammed, S., Lamoree, M., Ansa-Asare, O. D., and de Boer, J. (2019). Review of the analysis of insecticide residues and their levels in different matrices in Ghana. *Ecotoxicology and*

Environmental Safety, *171*, 361–372. https://doi.org/10.1016/j.ecoenv.2018.12.049.

Momol, M. T., Olson, S. M., Funderburk, J. E., Stavisky, J., and Marois, J. J. (2004). Integrated management of tomato spotted wilt on field-grown tomatoes. *Plant Disease*, *88*(8), 882–890. https://doi.org/10.1094/PDIS.2004.88.8.882.

Moritz, G. (1994). Pictorial key to the economically important species of Thysanoptera in Central Europe. *EPPO Bulletin*, *24*(1), 181-208.

Moritz, G., Delker, C., Paulsen, M., Mound, L. A., and Burgermeister, W. (2000). Modern methods for identification of Thysanoptera. *EPPO Bulletin*, *30*(3–4), 591–593. https://doi.org/10.1111/j.1365-2338.2000.tb00953.x.

Moritz, G., Mound, L. A., Morris, D. C., and Goldarazena, A. A. (2004a). *Pest thrips of the world – visual and molecular identification of pest thrips. Cd-rom published by OBIT, Brisbane.* Retrieved 2 February 2021 from http://thripsnet.zoologie.uni-halle.de/key-server-neu/data/09070302-040a-4006-8c08-0e0105060801/media/Html/index.html.

Moritz, G., Kumm, S., and Mound, L. (2004b). Tospovirus transmission depends on thrips ontogeny. *Virus Research*, *100*(1), 143-149. https://doi.org/10.1016/j.virusres.2003.12.022.

Moritz, G., Brandt, S., Triapistyn, S., and Subramanian, S. (2013). Identification and information tools for pest thrips in East Africa (QAAFI Biological Information Technology, University of Queensland). Retrieved 12 May 2021 from http://thripsnet.zoologie.uni-halle.de/key-server-neu/data/03030c05-030b-4107-880b-0a0a0702060d/media/Html/index.html.

Morse, J. G., and Hoddle, M. S. (2006). Invasion biology of thrips. *Annual Review of Entomology*, *51*, 67–89. https://doi.org/10.1146/annurev.ento.51.110104.151044.

Morsello, S. C., Groves, R. L., Nault, B. A., and Kennedy, G. G. (2008). Temperature and precipitation affect seasonal patterns of dispersing tobacco thrips, *Frankliniella fusca*, and onion thrips, *Thrips tabaci* (Thysanoptera: Thripidae) caught on sticky traps. *Environmental Entomology*, *37*(1), 79–86. https://doi.org/10.1603/0046-225x(2008)37[79:tapasp]2.0.co;2.

Mound, L. A., Heming, B. S., and Palmer, J. M. (1980). Phylogenetic relationships between the families of recent Thysanoptera (Insecta). *Zoological Journal of the Linnean Society*, *69*(2), 111–141. https://doi.org/10.1111/J.1096-3642.1980.TB01934.X.

Mound, L. A., Heming, B. S., and Palmer, J. M. (1981). Phylogenetic relationships between some genera of Thripidae (Thysanoptera). *Entomologica Scandinavica*, *15*, 153–170.

Mound, L. A. and Teulon, D. A. J. (1995). Thrips as opportunists. *In:* B. L. Parker, M. Skinner, and T. Lewis (Eds.), *Thrips biology and management*. Springer, Boston, MA, pp. 3–19. https://doi.org/10.1007/978-1-4899-1409-5.

Mound, L. A. (1997). Biological diversity. *In:* T. Lewis (Ed.), *Thrips as crop pests*. CAB International, Wallingford, UK, pp. 197–216.

Mound, L. A., and Collins, D. W. (2000). A South East Asian pest species newly recorded from Europe: T*hrips parvispinus* (Thysanoptera: Thripidae), its confused identity and potential quarantine significance. *European Journal of Entomology*, *97*(2), 197–200. https://doi.org/10.14411/eje.2000.037.

Mound, L A. (2002). So many thrips - so few tospoviruses. *In;* R. Marullo and L. Mound (Eds.), *Thrips and Tospoviruses; Proceedings of the 7TH International Sumposium on Thysanoptera*. Australian National Insect Collection, Canberra, Australia.

Mound, L A. (2005). Thysanoptera: Diversity and Interactions. *Annual Review of Entomology*, *50*(1), 247–269. https://doi.org/10.1146/annurev.ento.49.061802.123318.

Mound, L. A. (2010). Species of the genus Thrips (Thysanoptera, Thripidae) from the Afro-tropical Region. *Zootaxa*, *2423*(1), 1–24.

Mound, L A. (2018). Biodiversity of Thysanoptera. *Insect Biodiversity: Science and Soceity*, 2, 483–499. https://doi.org/10.1002/9781118945582.ch18.

Muhire, B. M., Varsani, A. and Martin, D. P. (2014) 'SDT: A virus classification tool based on pairwise sequence alignment and identity calculation', *PLoS One*, *9*(9). pone.0108277.

Muniappan, R. Shepard, B, M., Gerald R., and Ooi, P. (2012). *Arthropod Pests of Horticultural Crops in Tropical Asia*. CABI, London.

Murai, T. (2000). Effect of temperature on development and reproduction of the onion thrips, *Thrips tabaci* Lindeman (Thysanoptera: Thripidae), on pollen and honey solution. *Applied Entomology and Zoology*, *35*(4), 499–504. https://doi.org/10.1303/AEZ.2000.499.

Murai, T., and Loomans, A. J. M. (2001). Evaluation of an improved method for mass-rearing of thrips and a thrips parasitoid. *Entomologia Experimentalis et Applicata*, *101*(3), 281–289. https://doi.org/10.1046/j.1570-7458.2001.00913.x.

Murata, M., Hariyama, T., Yamahama, Y., Toyama, M., and Ohta, I. (2018). In the presence of red light, cucumber and possibly other host plants lose their attractability to the melon thrips Thrips palmi (Thysanoptera: Thripidae). *Applied Entomology and Zoology*, *53*(1), 117–128. https://doi.org/10.1007/s13355-017-0537-5.

Murata, M., Yamahama, Y., and Hariyama, T. (2021). Synergistic effects of the red light and blue traps on control of *Thrips palmi* (Thysanoptera: Thripidae). *Journal of Economic Entomology*, *114*(2), 627-631. https://doi.org/10.1093/jee/toaa312.

Murphy, G., Ferguson, G., and Shipp, L. (2014). *Thrips in Greenhouse Crops - Biology, Damage and Management*. *Ontario Ministry of Agriculture, Food and Rural Affairs Factsheet*, 03-077. http://omafra.gov.on.ca/english/crops/facts/14-001.htm.

Muvea, A. M., Waiganjo, M. M., Kutima, H. L., Osiemo, Z., Nyasani, J. O., and Subramanian, S. (2014). Attraction of pest thrips (Thysanoptera: Thripidae) infesting French beans to coloured sticky traps with Lurem-TR and its utility for monitoring thrips populations. *International Journal of Tropical Insect Science*, *34*(3), 197–206. https://doi.org/10.1017/S174275841400040X.

Nagata, T. (1999). *Competence and specificity of thrips in the transmission of tomato spotted wilt virus*. PhD dissertation, Agricultural University Wageningen, The Netherlands.

Nagata, T., Almeida, A. C. L., Resende, R. O., and Avila, A. C. (2002). The transmission specificity and efficiency of tospoviruses. *In:* R. Marullo and L. Mound (Eds.), *Thrips and Tospoviruses; Proceedings of the 7TH International Sumposium on Thysanoptera*. Australian National Insect Collection, Canberra, Australia.

Nderitu J. H., Waturu C. N., Olubayo F., Aura J. and Kasina J. (2001). Current French bean pests and disease management at Mwea Tebere, Central Kenya. *In:* J. M. Wesonga, T. Losenge, C. K. Ndung'u, K. Ngamau, F. K. Ombwara, S. G. Agong, A. Fricke, B. Hau, and H. Stu¨ tzel (Eds.), *Proceedings of the Horticulture Seminar on Sustainable Horticultural Production in the Tropics*. University of Hannover and German Academic Exchange Service (DAAD), Germany, pp. 118–122.

Ndlela, S., Niassy, S., and Mohamed, S. A. (2022). Important alien and potential native invasive insect pests of key fruit trees in Sub-Saharan Africa: advances in sustainable pre-and post-harvest management approaches. *CABI Agriculture and Bioscience*, *3*(1), 1-46.

Ngakou, A., Tamò, M., Parh, I. A., Nwaga, D., Ntonifor, N. N., Korie, S., and Nebane, C. L. N. (2008). Management of cowpea flower thrips, *Megalurothrips sjostedti* (Thysanoptera, Thripidae), in Cameroon. *Crop Protection*, *27*(3–5), 481–488. https://doi.org/10.1016/j.cropro.2007.08.002.

Ngosong, N. T., Boamah, E. D., and Fening, K. O. (2020). The efficacy of two bio-rational pesticides on insect pests complex of two varieties of white cabbage (*Brassica oleracea* var . capitata L .) in the coastal Savannah region of Ghana. *Phytoparasitica*, *49*(3), 397-406.

Nkafu, N. T., Fening, K. O., Ajonglefac, M. F., and Afreh-Nuamah, K. (2024). Influence of sticky trap color, host plant species, and weather factors on the population dynamics of thrips species in Southern Ghana. Environmental Entomology, nvae024. https://doi.org/10.1093/ee/nvae024.

Nkafu, N. T., Fening, K. O., and Afreh-Nuamah, K. (Unpublished). Diversity and abundance of thrips on export vegetables in Ghana. African Regional Postgraduate Programme in Insect Science, University of Ghana.

Nonaka, K. and Nagai, K. (1983). Ecology and control of the thrips infesting fruit vegetables. 7. Control of Thrips palmi using UV-cut film. *Kyushu Agricultural Research*, *45*, 119–120.

North, R.C. and Shelton, A. M. (1986). Ecology of Thysanoptera within cabbage fields. *Environmental Entomology*, *15*, 520–526.

OEPP/EPPO. (2018a). PM 7/3 (3) *Thrips palmi*. *Bulletin OEPP/EPPO Bulletin*, *48*(3), 446–460. https://doi.org/10.1111/epp.12545.

OEPP/EPPO. (2018b). *A1 and A2 lists of pests recommended for regulation as quarantine pests*. Vol. 2, pp. 1-18.

Okolle, N. J., Afari-Sefa, V., Bidogeza, J. C., Tata, P. I., and Ngome, F. A. (2016). An evaluation of smallholder farmers' knowledge, perceptions, choices and gender perspectives in vegetable pests and diseases control practices in the humid tropics of Cameroon. *International Journal of Pest Management*, *62*(3), 165–174. https://doi.org/10.1080/09670874.2016.1184772.

Omo-Ikerodah, E. E., Fatokun, C. A., and Fawole, I. (2009). Genetic analysis of resistance to flower bud thrips (*Megalurothrips sjostedti*) in cowpea (*Vigna unguiculata* [L.] Walp.). *Euphytica*, *165*(1), 145–154. https://doi.org/10.1007/s10681-008-9776-4.

Oparaocha, E. T., and Okigbo, R. N. (2003). Thrips (Thysanoptera) of vegetable crops (okro , spinach , garden Egg and Pumpkin) Grown in Southeastern Nigeria. *Plant Protection Science*, *39*(4), 132. https://doi.org/10.17221/3832-PPS.

Owusu-ansah, F., Afreh-Nuamah, K., Obeng-Ofori, D., and Ofosu-Budu, K. G. (2001). Managing infestation levels of major insect pests of garden eggs (*Solanum integrifolium* L.) with aqueous neem seed extracts. *Journal of the Ghana Science Association*, *3*(3), 70–84.

https://doi.org/10.4314/jgsa.v3i3.17769.

Palmer, J. M. (1990). Identification of the common thrips of tropical Africa (Thysanoptera: Insecta). *Tropical Pest Management*, *36*(1), 27–49. https://doi.org/10.1080/09670879009371431.

Pankeaw, K., Ngampongsai, A., Permkam, S., and Rukadee, O. (2011). Abundance and distribution of thrips (Thysanoptera: Thripidae) in mangosteen (*Garcinia mangostana* L.) grown in single-and mixed-cropping systems. *Songklanakarin Journal of Science and Technology*, *33*(3).

Pappu, H. R., Jones, R. A. C., and Jain, R. K. (2009). Global status of tospovirus epidemics in diverse cropping systems: Successes achieved and challenges ahead. *Virus Research*, *141*(2), 219–236. https://doi.org/10.1016/j.virusres.2009.01.009.

Paré, P. W., and Tumlinson, J. H. (1999). Plant volatiles as a defense against insect herbivores. *Plant Physiology*, *121*(2), 325–332. https://doi.org/10.1104/PP.121.2.325.

Park, C. G., Kim, H. Y., and Lee, J. H. (2010). Parameter estimation for a temperature-dependent development model of *Thrips palmi* Karny (Thysanoptera: Thripidae). *Journal of Asia-Pacific Entomology*, *13*(2), 145–149. https://doi.org/10.1016/j.aspen.2010.01.005.

Parrella, M. P., and Lewis, T. (1997). Integrated pest management (IPM) in field crops. *In:* Lewis T (ed.), *Thrips as Crop Pests*. CAB International, Wallingford, UK, pp. 595–614.

Pasian, C., and Lindquist, R. K. (2011). Sticky traps : a useful tool for pest- scouting programs. *Florinet Floriculture Newsletter*, pp. 1–13.

Phillips, P. A., Bekey, R. S., and Bailey, J. B. (1995). Early harvest to manage greenhouse thrips in avocado. *In:* B. L. Parker, M, Skinner and T. Lewis (Eds.), *Thrips Biology and Management*. Springer, Boston, MA, pp. 419–422. https://doi.org/10.1007/978-1-4899-1409-5_66.

Pizzol, J., Reynaud, P., Bresch, C., Rabasse, J., Biondi, A., Desneux, N., ... and Poncet, C. (2017). Diversity of Thysanoptera species and associated host plants in Southern France. *Journal of Mediterranean Ecology*, *15*, 13-27.

Pourian, H., Mirab-balou, M., Alizadeh, M., and Orosz, S. (2009). Study on biology of onion thrips, *Thrips tabaci* lindeman (thysanoptera : thripidae) on cucumber (var. sultan) in laboratory conditions. *Journal of Plant Protection Research*, *49*(4), 0–4. https://doi.org/10.2478/v10045-009-0061-x.

Prasannakumar, N. R., Venkataravanappa, V., Rachana, R. R., Sridhar, V., and Govindappa, M. R., Basavarajappa, M. P., ... and Samuel, D. K. (2021). Status of the outbreak of *Thrips parvispinus* (Karny) on chilli in Karnataka. *Pest Management in Horticultural Ecosystems*, *27*(2), 286-290.

Priesner. (1960). A monograph of the Thysanoptera of Egyprian deserts. *Pubis Institude Desert Egypte*, 13, 1-59.

Przybylska, A., Fiedler, Z., Fraęckowiak, P., and Obreepalska-Steeplowska, A. (2018). Real-time PCR assay for distinguishing Frankliniella occidentalis and *Thrips palmi* Arnika Przybylska, Zaneta Fiedler, Aleksandra Obreępalska-Steęplowska. *Bulletin of Entomological Research*, *108*(3), 413–420. https://doi.org/10.1017/S0007485317000177.

Monteiro, R. C., Roberto, A. Zucchi., and Laurence, A. M. (1995). Record of *Thrips palmi* Karny, 1925 (Thysanoptera: Thripidae) in the state of São Paulo, Brazil. *Rev. de Agricultura, Piracicaba*, *70*(1), 53–55.

Nielsen, A.L., Hamilton, G.C., and Matadha, D. (2008). Developmental rate estimation and life table analysis for *Halyomorpha halys* (Hemiptera: pentatomidae). *Environ. Entomol. 37*, 348–355.

Rachana, R. R., Roselin, P., Amutha, M., Sireesha, K., and Reddy, G. N. (2022). Invasive pest, *Thrips parvispinus* (Karny) (Thysanoptera: Thripidae) – a looming threat to Indian agriculture. *Current Science*, *122*(2), 211–213. https://doi.org/10.18520/cs/v122/i2/211-213.

Razzak, M. A., Seal, D. R., Stansly, P. A., Liburd, O. E., and Schaffer, B. (2019). Host preference and plastic mulches for managing melon thrips (Thysanoptera: Thripidae) on field-grown vegetable crops. *Environmental Entomology*, *48*(2), 434–443. https://doi.org/10.1093/ee/nvz010.

Reed, J. T., and Sukamto, S. (1995). Thrips and tomato spotted wilt virus in a Mississippi peanut field. *In:* B. L. Parker, M. Skinner, and T. Lewis (Eds.), *Thrips Biology and Management*. Springer, Boston, MA, pp. 171–173. https://doi.org/10.1007/978-1-4899-1409-5_24.

Reitz, S. R. (2002). Seasonal and wPlant distribution of Frankliniella thrips (Thysanoptera: Thripidae) in North Florida Tomatoes. *Florida Entomologist*, *85*(3), 431–439. https://doi.org/10.1653/0015-4040(2002)085[0431:sawpdo]2.0.co;2.

Reitz, S. R. (2008). Comparative bionomics of *Frankliniella occidentalis* and *Frankliniella tritici*. *Florida Entomologist*, *91*(3), 474–476. https://bioone.org/journals/florida-entomologist/volume-91/issue-3/0015.

Reitz, S. R., Yearby, E. L., Funderburk, J. E., Stavisky, J., Momol, M. T., and Olson, S. M. (2003). Integrated management tactics for *Frankliniella* thrips (Thysanoptera: Thripidae) in field-grown pepper. *Journal of Economic Entomology, 96,* 1201-1214. https://doi.org/10.1093/jee/96.4.1201.

Reitz, S. R. (2009). Biology and Ecology of the Western Flower Thrips (Thysanoptera: Thripidae): The Making of a Pest. *Florida Entomologist*, *92*(1), 7–13. https://doi.org/10.1653/024.092.0102.

Renukadevi, P., Prema, M. S., Ganapathy, N., Mohankumar, S., and Kennedy, J. S. (2018). (PDF) Efficacy of different botanical extracts on *Thrips palmi* in cotton. *Journal of Pharmacognosy and Phytochemistry*, *7(2)*, 2824-2829.

Riis, L. (2021). Tackling thrips in the greenhouse. Growertalks. Retrieved 8 August 2022 from https://www.growertalks.com/Article/?articleid=25174.

Riley, D., Sparks, A., Srinivasan, R., Kennedy, G., Fonsah, G., Scott, J., and Olson, S. (2017). Thrips: biology, ecology, and management. *In: Sustainable Management of Arthropod Pests of Tomato*. Elsevier Inc. https://doi.org/10.1016/B978-0-12-802441-6.00003-6.

Rosenheim, J. A., Welter, S. C., Johnson, M. W., Mau, R. F. L., and Gusukuma-Minuto, L. R. (1990). Direct feeding damage on cucumber by mixed-species infestations of *Thrips palmi* and *Frankliniella occidentalis* (Thysanoptera: Thripidae). *Journal of Economic Entomology*, *83*(4), 1519–1525. https://doi.org/10.1093/jee/83.4.1519.

Rueda, A.., Shelton, A. M. (1995). *Onion Thrips. Global Crop Pests.* Cornell International Intitute for Food, Agriculture and Development, Cornell Univ., Ithaca NY. Retrieved 7 May 2021 from http://web.entomology.cornell.edu/shelton/veg-in- sects-global/english/thrips.html.

Saeed, R., Abbas, N., Razaq, M., Mahmood, Z., Naveed, M., and Ur Rehman, H. M. (2018). Field evolved resistance to pyrethroids, neonicotinoids and biopesticides in *Dysdercus koenigii* (Hemiptera: Pyrrhocoridae) from Punjab, Pakistan. *Chemosphere*, *213*, 149–155. https://doi.org/10.1016/J.CHEMOSPHERE.2018.09.042.

Salas, J. (2004). Evaluation of cultural practices to control *Thrips palmi* (Thysanoptera: Thripidae) on green pepper. *Entomotropica*, *1*(19), 39–46. https://www.redalyc.org/pdf/2091/209117865008.pdf

Salifu, A. B. (1982). *Biology of Cowpea Flower Thrips and Host Plant Resistance*. PhD dissertation, University of Ghana.

Samler, J. A. (2012). *Abundance and species diversity of thrips (Thysanoptera: Thripidae) in cotton, soybean, and peanut in Southeast Virginia, and Evaluation of Cyantraniliprole for Thrips Management*. MSc thesis, Virginia Polytechnic Institute.

Sanabria, M. C., Amrbrecht, I., and Gutiérrez, C. (2008). Diversidad de estafilínidos (Coleoptera: Staphylinidae) en cinco sistemas productivos de los Andes Colombianos. Revista Colombiana de Entomología. *Revista Colombiana de Entomología*, *34*, 217–223.

Sanjta, S., and Chauhan, U. (2015). Survey of thrips (Thysanoptera) and their natural enemies in vegetables from mid hills of Himachal Pradesh. *The Ecoscan*, *9*(3 and 4), 713–715. http://www.theecoscan.in/JournalPDF/93and411 suman sanjta.pdf.

Schauff, M. E. (2001). *Collecting and preserving insects and mites. Techniques and tools. Systematic 626 Entomology Laboratory. Agricultural Research Service, USDA, Mis, 627.*

Seal, D. R., Kumar, V., Kakkar, G., and Mello, S. C. (2013). Abundance of adventive *Thrips palmi* (Thysanoptera: Thripidae) populations in Florida during the first sixteen years. *Florida Entomologist*, *96*(3), 789–796. https://doi.org/10.1653/024.096.0312.

Seal, D.R. (2005). Management of melon thrips, *Thrips palmi* Karny (Thysanoptera: Thripiae) using various chemicals. *Proceedings of the Florida State Horticultural Society*, *118*, 119–124.

Seal, D. R. (2004). Management of melon thrips , *Thrips palmi* karny (Thysanoptera: Thripidae): An integrated approach using chemical , cultural , and biological agents. *Proceedings of the Florida State Horticultural Society*, *117*, 63–68.

Sharpe, P. J. H., Curry, G. L., and DeMichele, D. W. (1977). Distribution models of organism development times. *Journal Theoretical Biol*ology, *66*, 21–36.

Sharpe, P. J. H., and DeMichele, D. W. (1977). Reaction kinetics of poikilotherm development. *Journal of Theoretical Biol*ology, *64*, 649–670.

Shipp, J. L., Binns, M. R., Hao, X., and Wang, K. (1998). Economic injury levels for Western flower thrips (Thysanoptera : Thripidae) on greenhouse sweet pepper. *Journal of Economic Entomology*, *91*(3), 671–677.

Shipp, L. J. (1995). Monitoring of Western Flower Thrips on glasshouse and vegetable crops. *In:* B. L. Parker, M, Skinner, and T. Lewis (Eds.), *Thrips Biology and Management*. Springer, Boston, MA, pp. 547–555. https://doi.org/10.1007/978-1-4899-1409-5_81.

Shuangshuang, G. (2018). *The role of aggregation pheromone in the interspecies interaction of thrips*. PhD dissertation, Zhejiang Normal University, China.

Sims, K. R., Funderburk, J. E., Reitz, S. R., and Boucias, D. G. (2009). The impact of a parasitic nematode, *Thripinema fuscum*, on the feeding behavior and vector competence of *Frankliniella fusca*. *Entomologia Experimentalis et Applicata*, *132*(2), 200–208. https://doi.org/10.1111/J.1570-7458.2009.00884.X.

Singh, D., Shaktawat, R. P. S., and Naruka, I. S. (2013). Performance of novel insecticides for management of onion thrips, *Thrips tabaci* L. *Journal of Applied Horticulture*, *15*(2), 114–116.

Skendžić, S., Zovko, M., Živković, I. P., Lešić, V., and Lemić, D. (2021). The impact of climate change on agricultural insect pests. *Insects*, *12*(5). https://doi.org/10.3390/INSECTS12050440.

Slansky, F., and Scriber, J. M. . (1985). Food consumption and utilization. *In:* L. I. Kerkut and G. A. Gilbert (Eds.), *Comprehensive insect physiology biochemistry and pharmacology* , Volume 4. Pergamon Press. Oxford, pp. 87–163. https://cir.nii.ac.jp/crid/1571135649226440064#citations_container.

Sodjah, D., and Aliyah, B. (2019). *Ghana: MoFA Suspends Four Vegetables to the EU*. Retrieved 1 June 2019 from https://allafrica.com/stories/201905300371.html.

Soto-Adames, F. N. (2020). Pest alert-*Thrips parvispinus* (Karny) (Patent No. FDACS-P-01926). *Florida Department of Agriculture and Consumer Services, Division of Plant Industry*. (FDACS-P-01926). Retrieved 21 July 2021 from https://www.fdacs.gov/content/download/93435/file/PESTALERT-Thripsparvispinus%28Karny%29.pdf.

Sprague, D. M. and Funderburk, J. E. (2017). Entomopathogenic nematodes of *Thrips Thripinema* spp. (Nematoda: Tylenchida: Allantonematidae). *EDIS*, *5*, 1–4. file:///C:/Users/ibyb/Downloads/IN1175-Dgz2vvraz1.pdf.

Sridhar, V., and Rachana, R. R., Prasannakumar, N. R., Venkataravanappa, V., Sireesha, K., Kumari, D. A., ... and Reddy, M. K. (2021). Dominance of invasive species, Thrips parvispinus (Karny) over the existing chilli thrips, Scirtothrips dorsalis Hood on chilli in the southern states of India with a note on its host range: A likely case of species displacement. *Pest Management in Horticultural Ecosystems*, *27*(2), 132-136.

Srinivasan, R. (2009). *Insect and mite pests on eggplant. A field guide for identification and management (Vol. 9, No. 729). AVRDC-WorldVegetableCenter*. https://doi.org/10.1079/9780851993577.0339.

Streets of Ghana, (2021). Tuba (Ga South Municipality District) street guide and map. Retrieved 9 August 2022 from https://ghana-streets.openalfa.com/tuba.

Stern, V. M., Smith, R. F., Bosch, R. van den, and Hagen, K. (1957). The integrated control concept. *Hilgardia*, *29*, 81–101.

Stinner, R. E., Gutierrez, A. P., and Butler, G. D. (1974). An algorithm for temperature-dependent growth rate simulation. *The Canadian Entomologist*, *106*(5), 519–524. https://doi.org/10.4039/ENT106519-5.

Strong, D. R., Lawton, J. H., and Southwood, S. R. (1984). *Insects on plants. Community patterns and mechanisms*. Blackwell Scientific Publications. Retrieved 13 November 2021 from https://www.cabdirect.org/cabdirect/abstract/19840515077.

Stuart, R. R., Gao, Y., and Lei, Z. (2011). Thrips: pests of concern to China and the United States. *Agricultural Sciences in China*, *10*(6), 867–892. https://doi.org/10.1016/S1671-2927(11)60073-4.

Subba, B. and, and Ghosh, S. K. (2016). Population dynamics of thrips (*Thrips Tabaci* L.) Infesting tomato (*Lycopersicon Esculentum* (L.) and their sustainable management. *International Journal of Agricultural Science and Research (IJASR)*, *6*(3), 473–480.

Sunitha, N. D., and Narasamma. (2018). Ecofriendly management of thrips in capsicum under protected condition. *Journal of Entomology and Zoology Studies*, *6*(1), 617–621. www.entomoljournal.com.

Takabayashi, J., Dicke, M., and Posthumus, M. A. (1994). Volatile herbivore-induced terpenoids in plant-mite interactions: Variation caused by biotic and abiotic factors. *Journal of Chemical Ecology 1994 20:6*, *20*(6), 1329–1354. https://doi.org/10.1007/BF02059811.

Tamò, M., Baumgärtner, J., Delucchi, V., and Herren, H. R. (1993). Assessment of key factors responsible for the pest status of the bean flower thrips *Megalurothrips sjostedti* (Thysanoptera: Thripidae) in West Africa. *Bulletin of Entomological Research*, *83*(2), 251–258. https://doi.org/10.1017/S000748530003474X.

Tamò, M., Arodokoun, D. Y., Zenz, N., Tindo, M., Agboton, C., and Adeoti, R. (2002). *Challenges and opportunities for enhancing sustainable cowpea production*. Retrieved 21 January 2021 from https://books.google.com.gh/books?hl=enandlr=andid=UlqoafcwWnUCandoi=fndandpg=PA81anddq=Tamò+et+al.,+1993+natural+enemies+of+thripsandots=C3Ohyck2ojandsig=3JSdN2tjv29NeJaTw1F1flyhQoUandredir_esc=y#v=onepageandq=Tamò et al.%2C 1993 natural enemies of thripsandf=false.

Tan, J. L., Ooi, P. A. C., and Khoo, G. (2016). Thrips on eggplant, chilli and bell pepper in Cameron Highlands, Malaysia. *Serangga*, *21*(1), 71–85.

Tang, L. D., Zhao, H. Y., Fu, B. L., Han, Y., Liu, K., and Wu, J. H. (2016b). Colored sticky traps to selectively survey thrips in cowpea ecosystem. *Neotropical Entomology*, *45*(1), 96–101. https://doi.org/10.1007/s13744-015-0334-1.

Tanzubil, P. B. (1991). Control of some insect pests of cowpea (*Vigna unguiculuta*) with neem (*Azadirachta indica* a juss.) in Northern Ghana. *Tropical Pest Management*, *37*(3), 216–217. https://doi.org/10.1080/09670879109371585.

Tanzubil, P. B., Zakariah, M., and Alem, A. (2008). Integrating host plant resistance and chemical control in the management of cowpea pests. *Australian Journal of Crop Science*, *2*(3), 115–120.

Terry, L. I. (1997). Host selection, communication and reproductive behaviour. *In:* T. Lewis (ed.), *Thrips as crop pests.* CAB International, Wallingford, UK, pp. 65-118. https://www.cabdirect.org/cabdirect/abstract/19981100116.

Teulon, D. A. J., Davidson, M. M., Hedderley, D. I., James, D. E., Fletcher, C. D., Larsen, L., Green, V. C., and Perry, N. B. (2007). 4-Pyridyl carbonyl and related compounds as thrips lures: Effectiveness for onion thrips and New Zealand flower thrips in field experiments. *Journal of Agricultural and Food Chemistry*, *55*(15), 6198–6205. https://doi.org/10.1021/jf070389a.

Teulon, D. A. J., and Penman, D. R. (1990). Host Records for the New Zealand flower thrips (Thrips obscuratus (Crawford) Thysanoptera: Thripidae). *New Zealand Entomologist*, *13*(1), 46–51. https://doi.org/10.1080/00779962.1990.9722591.

Thrips-ID. (2022). *Dr. Manfred R. Ulitzka's website on Thysanoptera*. Retrieved 10 January 2022 from https://www.thrips-id.com/en/.

ThripsWiki. (2019). *ThripsWiki-providing information on the World's thrips*. Retrieved 12 June 2019 from http://thrips.info/w/index.php?search=tubuliferaandtitle=Special%3ASearchandgo=Go.

Timm, A. E., Stiller, M., and Frey, J. E. (2008). A molecular identification key for economically important thrips species (Thysanoptera: Thripidae) in Southern Africa. *African Entomology*, *16*(1), 68–75. https://doi.org/10.4001/1021-3589-16.1.68.

Todd, J. W., Culbreath, A. K., Chamberlin, J. R., Beshear, R. J., and Mullinix, B. G. (1995). Colonization and population dynamics of thrips in peanuts in the Southern United States. *In:* B. L. Parker, M. Skinner, and T. Lewis (Eds.), *Thrips Biology and Management*. Springer, Boston, MA, pp. 453–460. https://doi.org/10.1007/978-1-4899-1409-5_71.

Tonnang, E. Z. H., Juarez, H., Carhuapoma, P., Gonzales, J. C., Mendoza, D., Sporleder, M., Simon, R., and Kroschel, J. (2013). *ILCYM – Insect Life Cycle Modeling. A software package for developing temperature-based insect phenology models with applications for local, regional and global analysis of insect population and mapping. Lima, Peru: International Potato Center*. Retrieved 3 January 2021 from http://www.cipotato.org.

Trichilo, P. J., and Leigh, T. F. (1988). Influence of resource quality on the reproductive fitness of flower thrips (Thysanoptera: Thripidae). *Annals of Entomological Society of America*, *81*(1), 64–70. http://aesa.oxfordjournals.org/.

Triplehorn, C. A., Johnson, N. F., and Borror, D. J. (2005). *Borror and Delong's introduction to the study of insects*. Thomson Brooks/Cole, Belmont, California.

Tsai, J. H., Yue, B. S., Funderburk, J. E., and Webb, S. E. (1996). Effect of plant pollen on growth and reproduction of *Frankliniella bispinosa*. *Acta Horticulturae*, *431*, 535–541. https://doi.org/10.17660/ACTAHORTIC.1996.431.50.

Tyagi, K., Kumar, V., Singha, D., and Chakraborty, R. (2015). Morphological and DNA barcoding evidence for invasive pest thrips, *Thrips parvispinus* (Thripidae: Thysanoptera), Newly Recorded From India. *Journal of Insect Science*, *15*(1), 105. https://doi.org/10.1093/jisesa/iev087.

Tyler-julian, K. (2013). *A novel push-pull method of integrated pest management of thrips and Tospoviruses on peppers and tomaoes*. MSc thesis, University of Florida.

Uzel, J. (1895). *Monografie řádu Thysanoptera (Monograph on Thysanoptera). Hradec Králové. Kvart. 500 pp. (in Czech and German).*

Varenhorst, A. J., and O'Neal, M, E. (2012). The response of natural enemies to selective insecticides applied to soybean. *Evironmental Entomology*, *41*(6), 1565–1574.

https://doi.org/10.1603/EN12068.

Velayudhan, R., and Annadurai, R. S. (1986). Pollination potential of thrips (Insecta: Thysanoptera) in some Solanaceous plants. *Proceedings: Animal Sciences*, *95*(1), 109–116. https://doi.org/10.1007/BF03179364.

Vierbergen, G., Kucharczyk, H., and Kirk, W. D. (2010). A key to the second instar larvae of the Thripidae of the Western Palaearctic region (Thysanoptera). *Tijdschrift voor Entomologie*, *153*(1), 99-160.

Vos, J. G. M., Sastrosiswojo, S., Uhan, T. S., Setiawati, W., and Lembang, W. J. (1991). Thrips on hot pepper in Java, Indonesia. *Thrips in Southeast Asia. Proceeding Regional Consultation Workshop. Bangkok, Thailand,* Vol. 13, pp. 18-28.

Waiganjo, M.M., Gitonga, L.M. and Mueke, J. . (2008). Effects of weather on thrips population dynamics. *African Journal of Horticulture Sci*ence, *1*, 82–90.

Walker, F. (1852). *List of the Specimens of Homopterous insects in the collection of the British Museum. Part IV, London, Order 3, Physapoda, published by British Museum, printed by Edward Newman, 1094–1118 (compiled from Haliday).*

Wang, R., Lan, Z., and Ding, Y. (1982). Studies on mathematical models of the relationship between insect development and temperature. *Acta Ecol. Sin.*, *2*(1), 47–57.

Welter, S. C., Rosenheim, J. A. Y. A., Johnson, M. W., Mau, R. F. L., and Gusukuma-minuto, L. R. (1990). Effects of *Thrips palmi* and western flower thrips (Thysanoptera: Thripidae) on the yield, growth, and carbon allocation pattern in cucumbers. *Journal of Economic Entomology*, *83*(5), 2092–2101. https://doi.org/10.1093/jee/83.5.2092.

Wiesenbom, W. D., and Morse, J. G. (1988). The mandible and maxillary sty lets of *Scirtothrips citri* (Moulton) (Thysanoptera: Thripidae). The *Pan-Pacific Entomologist*, *64*, 39-42.

Wilson, T. H. (1975). A monograph of the subfamily Panchaetothripinae (Thysanoptera: Thripidae). *Memoires of the American Entomological Institute*, Vol. 23.

Wolcott, G. N. (1951). The insects of Puerto Rico. *Puerto Rico University Journal of Agriculture*, *32*(3), 417-748.

Yadav, R., and Chang, N. T. (2012a). Age-stage, two sex-life table of *Thrips palmi* Karny (Thysanoptera: Thripidae) on eggplant. *Academic Journal of Entomology*, *5*(3), 151-157. https://doi.org/10.5829/idosi.aje.2012.5.3.531.

Yadav, R., and Chang, N. T. (2012b). Temperature-dependent development and life table parameters of *Thrips palmi* (Thysanoptera: Thripidae) on eggplant. *Applied Entomology and Zoology*, *47*(4), 301-310. https://doi.org/10.1007/s13355-012-0114-x.

Yadav, R., and Chang, N. T. (2014). Effects of temperature on the development and population growth of the melon thrips, *Thrips palmi*, on eggplant, *Solanum melongena*. *Journal of Insect Science*, *14*(1). https://doi.org/https://doi.org/10.1093/jis/14.1.78.

Yadav, R., and Chang, N. T. (2013). Economic thresholds of *Thrips palmi* (Thysanoptera: Thripidae) for eggplants in a greenhouse. *Applied Entomology and Zoology*, *48*(2), 195–204. https://doi.org/10.1007/s13355-013-0172-8.

Yano, E. (2004). Recent Development of biological control and IPM in greenhouses in Japan. *Journal of Asia-Pacific Entomology*, *7*(1), 5–11. https://doi.org/10.1016/S1226-8615(08)60195-8.

Yaseen, A. A. (2014). *Gynaikothrips uzeli* (Thysanoptera: Phlaeothripidae), new record from Tartous, Syria. *Journal of Insect Science*, *14*(1). https://doi.org/10.1093/JISESA/IEU135.

Yasunaga, T. (1997). The flower bug genus Orius WOLFF (Heteroptera: Anthocoridae) from Japan and Taiwan, Part III. *Applied Entomology and Zoology*, *32*(2), 387–394. https://doi.org/10.1303/AEZ.32.387.

Yong, C. S. (2015). *Species composition and host association of thrips (Thysanoptera) in the Eastern and Greater Accra.* Mphil thesis, University of Ghana.

Yu, D., Huang, P., Chen, Y., Lin, Y., Akutse, K. S., Lan, Y., and Wei, H. (2018). Effects of flower thrips (Thysanoptera: Thripidae) on nutritional quality of banana (Zingiberales: Musaceae) buds. *PLoS ONE*, *13*(8). https://doi.org/10.1371/JOURNAL.PONE.0202199.

Yudin, L. S., Cho, J. J., and Mitchell, W. C. (1986). Host range of western flower thrips, *Frankliniella occidentalis* (Thysanoptera: Thripidae), with special reference to *Leucaena glauca*. *Environmental Entomology*, *15*(6), 1292–1295. https://doi.org/10.1093/ee/15.6.1292.

Yudin, L. S., Mitchell, W. C., and Cho, J. J. (1987). Color preference of thrips (Thysanoptera: Thripidae) with reference to aphids (Homoptera: Aphididae) and leafminers in Hawaiian Lettuce Farms. *Journal of Economic Entomology*, *80*(1), 51–55. https://doi.org/10.1093/JEE/80.1.51.

Zhang, L., and Young, G. R. (1998). IPM of melon thrips, *Thrips palmi* Karny (Thysanoptera: Thripidae), on eggplant in the top end of the Northern Territory. *Proceedings of the Sixth Workshop on Tropical Agricultural Entomology Darwin. Technical Bulletin NO. 288*, 101–

111.

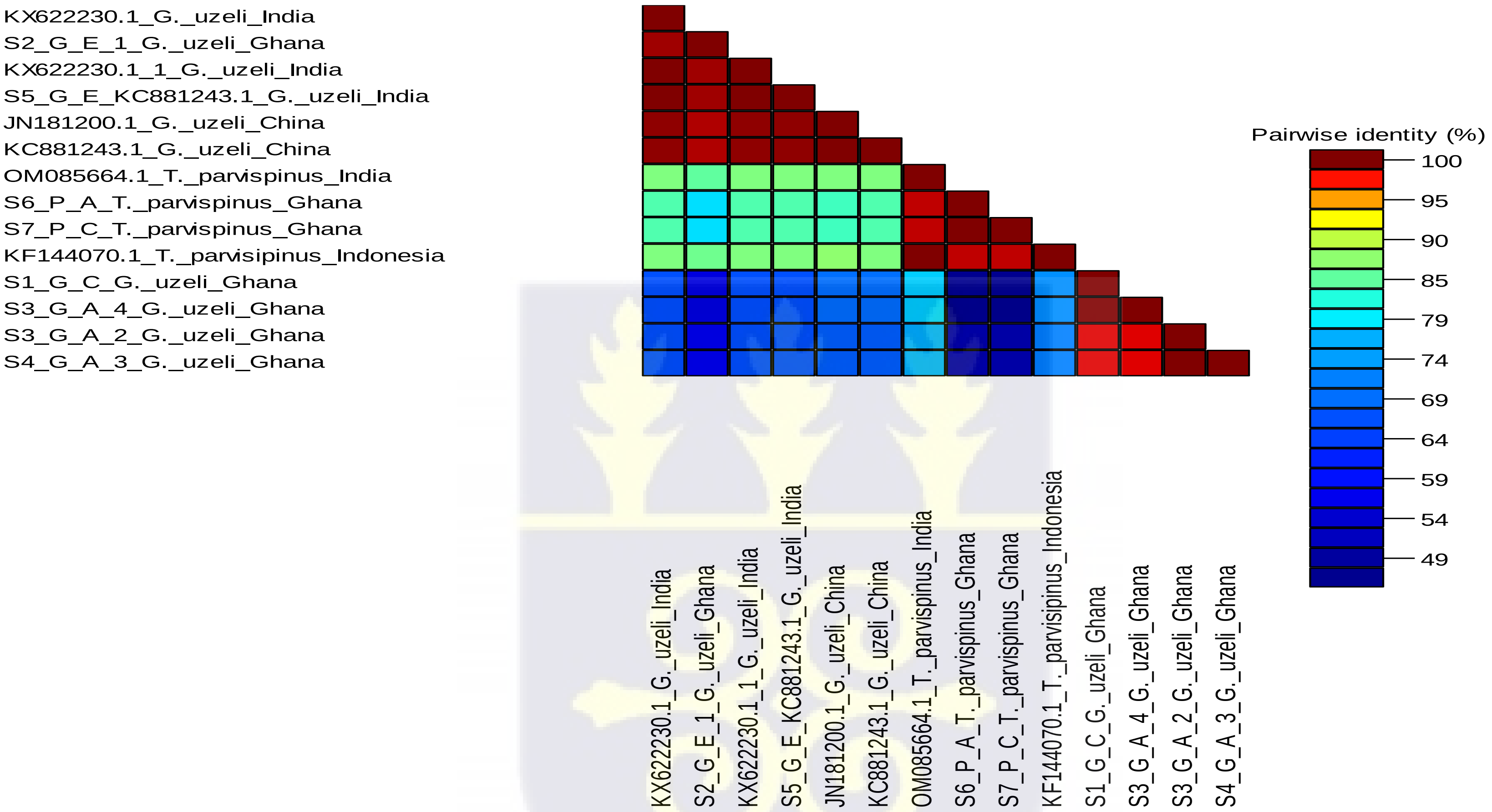
Appendices

Appendix 1. Comparison of mean abundance of thrips identified on major host plants across regions.

Chilli		Mean thrips
	Accra	7.62 (0.18)
	Eastern	6.25 (0.21)
	Central	8.25 (0.14)
Eggplant	Accra	18.75 (0.22)
	Eastern	18.88 (0.31)
	Central	19.25 (0.11)
Turia	Accra	26.01 (0.23)
	Eastern	24.63 (0.12)
	Central	47.13 (0.15)

Standard errors in parenthesis

Appendix 2. Pairwise comparison of CO1 gene sequences. Sequences generated through sequencing for *Gyainakothrips uzeli* and *Thrips parvispinus* and some comparator sequences from GenBank. The percentage similarity computed using SDT software.



Appendix 3. ANOVA table showing the interaction effect of thrips species with sticky trap colour in the first season.

			Sum of Squares	df	Mean Square	F	Sig.
T. parvispinus * Trap colour	Between Groups	(Combined)	156005.33	2	78002.67	1.73	0.187
		Linearity	16900.00	1	16900.00	0.38	0.543
		Deviation from Linearity	139105.33	1	139105.33	3.09	0.085
	Within Groups		2296356.00	51	45026.59		
	Total		2452361.33	53			
*T. tabaci** Trap colour	Between Groups	(Combined)	6967.11	2	3483.56	1.28	0.287
		Linearity	6833.78	1	6833.77	2.51	0.119
		Deviation from Linearity	133.33	1	133.33	0.05	0.826
	Within Groups		138879.72	51	2723.12		
	Total		145846.83	53			
F. schultzei * Trap colour	Between Groups	(Combined)	93124.00	2	46562.00	3.377	0.042
		Linearity	196.00	1	196.00	.014	0.906
		Deviation from Linearity	92928.00	1	92928.00	6.740	0.012
	Within Groups		703198.83	51	13788.21		
	Total		796322.83	53			

Appendix 4. ANOVA table showing a significant interaction effect of thrips species with sticky trap colour in the second season.

			Sum of Squares	df	Mean Square	F	Sig.
T. parvispinus * Trap colour	Between Groups	(Combined)	2949552	2	1474775.8	6.61	0.003
		Linearity	861493.4	1	861493.36	3.861	0.055
		Deviation from Linearity	2088058	1	2088058.2	9.359	0.004
	Within Groups		11378157	51	223101.12		
	Total		14327709	53			
F. schultzei * Trap colour	Between Groups	(Combined)	218000.1	2	109000.07	3.881	0.027
		Linearity	93712.52	1	93712.516	3.336	0.074
		Deviation from Linearity	124287.6	1	124287.63	4.425	0.04
	Within Groups		1432533	51	28088.889		
	Total		1650534	53			
T. tabaci * Trap colour	Between Groups	(Combined)	119185.1	2	59592.557	9.595	0
		Linearity	33656.96	1	33656.96	5.419	0.024
		Deviation from Linearity	85528.15	1	85528.153	13.77	0.001
	Within Groups		316763.8	51	6211.054		
	Total		435948.9	53			

Appendix 5. Differences between insect numbers for the major and minor season (t-test).

Insect species	Season				
	First	Second	t value	P	
T. parvispinus	58.25+4.18	872.43+118.23	6.882	<.0000	
T. tabaci	35.83+5.071	168.59+19.90	7.754	0.001	
F. schultzei	16.68+2.79	335.17+40.98	6.467	0.008	

Appendix 6. ANOVA table showing the treatments effect on thrips in the major season of the Deciduous Forest agroecological zone.

		Sum of Squares	df	Mean Square	F	Sig.
1DBS	Between Groups	57.333	5	11.467	.265	0.926
	Within Groups	778.000	18	43.222		
	Total	835.333	23			
3DAS	Between Groups	2440.968	5	488.194	38.183	< 0.001
	Within Groups	230.139	18	12.785		
	Total	2671.106	23			
5DAS	Between Groups	3098.190	5	619.638	15.190	<0.001
	Within Groups	734.250	18	40.792		
	Total	3832.440	23			
9DAS	Between Groups	2198.556	5	439.711	9.031	< 0.001
	Within Groups	876.389	18	48.688		
	Total	3074.944	23			

Appendix 7. ANOVA table showing the treatments effect on thrips in the major season of the Coastal Savannah agroecological zone.

		Sum of Squares	df	Mean Square	F	Sig.
1DBS	Between Groups	159.875	5	31.975	0.91	0.494
	Within Groups	629.750	18	34.986		
	Total	789.625	23			
3DAS	Between Groups	1867.708	5	373.542	43.03	< 0.001
	Within Groups	156.250	18	8.681		
	Total	2023.958	23			
5DAS	Between Groups	2055.708	5	411.142	21.37	< 0.001
	Within Groups	346.250	18	19.236		
	Total	2401.958	23			
9DAS	Between Groups	1937.708	5	387.542	12.363	< 0.001
	Within Groups	564.250	18	31.347		
	Total	2501.958	23			

Appendix 8. Some pest species found on *Solanum melongena* during the on-field experiment.

Eggplant skeletonizer damage

Selepa docilis larvae

Damage by EFSB

Green sting bug, *Nezara viridula*

Leucinodes africensis adult

Green peach aphids, *Myzus persicae*

Flea beetle

Damage by spider mite

Tiger moth

Z. variegatus nymph

Z. variegatus adults

Hoverfly larva

Ladybird larva

unidentified

Green plant hopper

Plume moth

Rhyparochromus sp.


Tomato hornworn


Mealybug


Anoplocnemis curvipes

Appendix 9. Damage assessment of *L. Africensis* on eggplant fruit, score 1-5