UNIVERSITI PUTRA MALAYSIA

ECOLOGICAL STUDIES OF ASIAN CITRUS PSYLLID Diaphorina citri KUWAYAMA (HEMIPTERA: PSYLLIDAE) AND ITS PARASITOID Tamarixia radiata WATERSTON (HYMENOPTERA: EULOPHIDAE) ON CITRUS IN MALAYSIA

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By

HASSAN SULE

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

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DEDICATION

I dedicate this thesis to my lovely mother ***Hauwa****, my wife* ***Aishatu*** *and my sons* ***Suleman*** and ***Umar*** *for their patience and support during my study in Malaysia*

Thanks and loving you all

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirements for the degree of Doctor of Philosophy

ECOLOGICAL STUDIES OF ASIAN CITRUS PSYLLID *Diaphorina citri* KUWAYAMA (HEMIPTERA: PSYLLIDAE) AND ITS PARASITOID *Tamarixia radiata* WATERSTON (HYMENOPTERA: EULOPHIDAE) ON CITRUS IN MALAYSIA

By

HASSAN SULE

May 2013

Chairperson : Professor Rita Muhamad Awang, PhD

Faculty : Agriculture

Production of citrus worldwide is being threatened by an invasive pest *Diaphorina citri* Kuwayama, (Asian citrus psyllid) which is regarded as the most important and efficient vector of bacterium, *Liberobacter asiaticum* that causes citrus greening disease. The prime concern in increasing production of all citrus fruits is the obstacles posed by the invasive psyllid,*D. citri*, and lack of sufficient understanding of its population parameters and dynamic, which are essential for development of reliable prediction system and management strategies. The present study was conducted with the objectives of establishing life table and demographic parameters of *D. citri*, its seasonal fluctuations and dispersion, feeding, oviposition behaviour, parasitism rate and nymphal preference of *Tamarixia radiata*. Life table studies, choice and no choice assays and parasitism studies were conducted at the insectary of Universiti Putra Malaysia. While population sampling was carried out at Padang Ipoh, Ulu Terengganu, Malaysia. The result of the life table studies showed that, highest mortality in first instar nymphs (40.23%) with k-value of 0.22 and (25.59%)

mortality in 2^{nd} instar nymphs with k-value of 0.13 are the key mortality factors regulating the population size. The intrinsic rate of natural increase (r_m) was 0.026 per female per day and daily finite rate of increase was 1.023 per female per day, with a mean generation time of 26.53 days. The net reproductive rate of the population was 2.004 and the population doubling time was 26.46 days. The results of choice and no choice assays showed significant number of adult,*D. citri* were attracted to plants with young flush leaves for oviposition and feeding. When two host plants were assayed together in Y-tube olfactormeter, significantly more number of the adults selected Y-tube arm with *Citrus suhuiensis* leaves than Y tube arm with *Murraya paniculata* leaves. Likewisewhen the main pure compounds of the two plants were assayed together in olfactometer, significantly more number of adult *D. citri* were attracted to β-pinene and β-linalool (main compounds of*C. suhuiensis*) than tocaryophyllene (main compounds of*M. paniculata*). Population sampling data revealed that, *D. citri*adultsin the study area, had fourapparent population peaks appearing in months of March and June, 2011 and Febuary - March and June, 2012. While, *D. citri* immatures had two apparent population peaks appearing and in the months of July, 2011 and March, 2012. Furthermore, population of *D. citri*adultswere found to be more abundant on the upper canopy, leaf growth stage 1 and northern cardinal point. The Correlation analysis showed that population of *D. citri*adultswas strongly correlated with number of flush leaves (r = 0.93) and modaretly correleted with temperature (r = 0.45), while population of immatures was only correlated with flush leaves. However, the stepwise regression analysis between the observed population and the environmental parameters showed that only flush leaves contributed to the build up/ fluctuation of *D. citri* population.Spatial distribution pattern analysis of the psyllid on *C. suhiensis* using various indices of population dispersion and regression models showed an aggregated distribution. Parasitism study revealed that, significantly more number of 5th and 4th instars nymph were parasitized by adult,*T. radiata* compared to the remaining nymphal stages. Similarly, when 3rd, 4th and 5th instars nymphs were assayed in choice experiment, significantly more number of older nymphs were parasitized by adult,*T. radiata*. Furthermore, functional responses of *T. radiata* to different densities of 3rd, 4th and 5th instars nymphs of *D. citri*showeda type II functional response, with 1.11, 0.60 and 0.71 handling time, and 21.62, 39.99 and 34.04 attack rate,respectively. Therefore, based on results obtained in this study, β-pinene and β-linalool could be use for monitoring and trapping of *D. citri*. Monitoring should be initiated when plants have started to produce flush leaves and continue until the end of the flushing season and monitoring interval could be weekly or every 10 days on at least 35 trees in every 1.5 hectare plot. When control measure is required, it should be done on tree by tree basis since *D. citri* showed aggregated distribution and effort should be concentrated on the upper canopies of the trees.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PENGAJIAN EKOLOGI PSYLLID ASIA LIMAU *Diaphorina citri* KUWAYAMA (HEMIPTERA: PSYLLIDAE) DAN PARASITOID *Tamarixia radiata* WATERSTON (HYMENOPTERA: EULOPHIDAE) PADA LIMAU DI MALAYSIA

Oleh

HASSAN SULE

Mei 2013

Pengerusi : Profesor Rita Muhamad Awang, PhD

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Pengeluaran limau di seluruh dunia sedang diancam oleh perosak invasif *Diaphorina citri* Kuwayama, (Psyllid limau Asia) yang dianggap sebagai vektor bakteria yang paling penting dan berkesan, *Liberobacter asiaticum* yang menyebabkan penyakit citrus greening. Kebimbangan utama dalam meningkatkan pengeluaran semua buah-buahan sitrus adalah halangan yang ditimbulkan oleh psyllid invasif, *D. citri*, dan kekurangan pemahaman yang mencukupi tentang parameter populasi dan dinamik, yang penting untuk pembangunan sistem ramalan yang dipercayai dan strategi pengurusan. Kajian ini telah dijalankan dengan objektif mewujudkan jadual hidup dan parameter demografi *D. citri*, naik turun bermusim dan penyebaran, makan, tingkah laku oviposit, kadar parasit dan keutamaan nimfa daripada *Tamarixia radiata*. Kajian jadual hidup, ujian pilihan dan tiada pilihan dan kajian parasit telah dijalankan di insectary Universiti Putra Malaysia. Manakala persampelan populasi telah dijalankan di Padang Ipoh, Ulu Terengganu, Malaysia. Hasil kajian jadual hidup menunjukkan bahawa, kematian tertinggi dalam instar nimfa pertama

(40.23%) dengan nilai-k 0.22 dan (25.59%) kematian instar nimfa kedua dengan nilai-k 0.13 adalah faktor utama kematian yang mengawal saiz populasi. Kadar intrinsik pertambahan semula jadi (r_m) adalah 0.026 setiap betina setiap hari dan peningkatan kadar harian terhingga adalah 1.023 untuk setiap betina setiap hari, dengan masa generasi purata 26.53 hari. Kadar pembiakan bersih populasi adalah 2.004 dan masa dua kali ganda populasi adalah 26.46 hari. Keputusan ujian pilihan dan tiada pilihan menunjukkan sejumlah besar dewasa, *D. citri* tertarik kepada tumbuh-tumbuhan dengan daun pucukuntuk oviposit dan makan. Apabila dua tumbuhan perumah telah diuji bersama-sama dalam olfactormeter tiub-Y, jumlah lebih banyak daripada dewasa lengan tiub-Y dipilih dengan daun *Citrus suhuiensis* daripada lengan tiub-Y dengan daun *Murraya paniculata*. Begitu juga apabila sebatian utama tulen dua pokok telah diuji bersama-sama dalam olfactometer, bilangan lebih banyak dewasa *D. citri* tertarik kepada β-pinene dan β-linalool (sebatian utama *C. suhuiensis*) daripada caryophyllene (sebatian utama *M* . *paniculata*). Data persampelan populasi menunjukkan bahawa, *D. citri* dewasa dalam kawasan kajian, mempunyai empat puncak populasi jelas yang terdapat dalam bulan Mac dan Jun, 2011 dan Febuari - Mac dan Jun, 2012. Walaupun, *D. citri*yang belum matang mempunyai dua puncak populasi jelas muncul dan pada bulan Julai, 2011 dan Mac, 2012. Tambahan pula, populasi*D. citri* dewasa didapati lebih banyak di kanopi atas, peringkat pertumbuhan daun 1 dan mata angin utara. Analisis korelasi menunjukkan bahawa populasi*D. citri* dewasa kuat dikaitkan dengan beberapa daun pucuk (r = 0.93) dan berkorelasi sederhana dengan suhu (r = 0.45), manakala populasi belum matang hanya berkait rapat dengan daun pucuk. Walau bagaimanapun, analisis regresi langkah demi langkah di antara populasi yang diperhatikan dan parameter persekitaran menunjukkan bahawa hanya daun pucuk menyumbang kepada pembentukan / turun naik populasi *D. citri*.Analisis corak pengedaran spatial psyllid pada *C. suhiensis* menggunakan pelbagai indeks penyebaran populasi dan model regresi menunjukkan taburan agregat. Kajian Parasitisme menunjukkan bahawa, bilangan lebih banyak daripada instar nimfa ke-5 dan instar nimfa ke-4 telah dihuni oleh dewasa, *T. radiata* berbanding peringkat nimfa yang tinggal. Begitu juga, apabila instar nimfake-3, ke-4 dan ke-5 telah diuji dalam eksperimen pilihan, jumlah lebih banyak daripada nimfa tua telah dihuni oleh dewasa, *T. radiata*. Tambahan pula, tindak balas fungsi *T. radiata* untuk ketumpatan yang berbeza instar nimfa ke-3, ke-4 dan ke-5 *D. citri* menunjukkan tindak balas berfungsijenis II, dengan 1.11, 0.60 dan 0.71 masa pengendalian, dan 21.62, 39.99 dan 34.04 kadar serangan, masing-masing. Oleh itu, berdasarkan keputusan yang diperolehi dalam kajian ini, β-pinene dan β-linalool boleh digunakan untuk memantau dan memerangkap *D. citri*. Pemantauan harus dimulakan apabila tumbuhan telah mula mengeluarkan daun pucuk dan berterusan sehingga akhir musim pemutikkan dan pemantauan berselang boleh dilakukan secara mingguan atau setiap 10 hari pada sekurang-kurangnya 35 pokok di setiap plot 1.5 hektar. Apabila langkah kawalan diperlukan, ia perlu dilakukan di atas pokok demi pokok semasa*D. citri* menunjukkan taburan agregat dan usaha perlu tertumpu pada kanopi atas pokok.

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I certify that a Thesis Examination Committee has met on 27 May 2013 to conduct the final examination of Hassan Sule on his thesis entitled "Ecological Studies of Asian Citrus Psyllid *Diaphorina citri* Kuwayama (Hemiptera: Psyllidae) and its Parasitoid *Tamarixia radiata* Waterston (Hymenoptera: Eulophidae) on Citrus in Malaysia" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the degree of Doctor of Philosophy.

Members of the Thesis Examination Committee were as follows:

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted asfulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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DECLARATION

I declare that the thesis is my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously, and is not concurrently, submitted for any other degree at Universiti Putra Malaysia or any other institutions.

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HASSAN SULE

Date: 27 May 2013

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CHAPTER 1

INTRODUCTION

Citrus are the most important fruit tree crop (Abbate *et al*., 2012; Ashkevari *et al*., 2012), it is ranked first in the world with respect to production among fruits (Ladaniya, 2008), and also in trade value internationally among all fruits (Norberg, 2008). Citrus are grown commercially in more than 140 countries around the world (UNCTAD, 2009). According to FAO (2011) the world total annual production of citrus was approximately 123 million tonnes in 2010. World's largest citrus-producing countries include Brazil, China, the United State, Mexico, India and Spain. Of these countries, Brazil, the US, and Mexico are the world's largest producers of oranges, whilst China produces most of the world's mandarins, and India is the world's largest producer of lemons and limes.

Until the year 1990; Malaysia had planted 533,000 ha of citrus with a total of 3100MT of citrus fruit production. In 2011 the planted area increased to 796,800 ha with a total fruit production of 4179MT (MOA, 2011), with most of the crop grown in commercial orchards, backyard orchards and small holdings in various parts of peninsula Malaysia. The major producing areas in Peninsula Malaysia are Terengganu, Pahang, Kelantan and Selangor (Azizah and Zazali, 2005), while in Sarawak are Samarahan, Sarikei, Bintulu and Sibu division (Eng, 2007).

This growing potential of the fruit industry is being threatened by an invasive pest (psyllid), *Diaphorina citri* kuwayama. *D. citri* has been known to occur in Asia for many years (Chen *et al*., 2010) and was first recognized as major pest of citrus in India (Yang *et al*., 2006) and has slowly spread throughout southern Asia, the Arabian Peninsula, to some islands in the Indian Ocean, the Americas and to Reunion and Mauritius. Also the psyllid is reported to be present in China, Myanmar, Taiwan, The Philippines, Malaysia, Indonesia, Sri Lanka, Pakistan, Thailand, Nepal, Hong Kong, Ryukhu Islands and Afghanistan (Hall, 2008a; Halbert and Manjunath, 2004)

The Asian citrus psyllid *D. citri* is regarded as one of the most important pests of citrus (Hall, 2008a) because it is known to be the most efficient vector of bacterium *Liberobacter asiaticum* that cause citrus greening disease or huanglungbing (Tsai, *et al*., 2002). The symptoms of development of greening disease are yellowing or boltchy pattern of citrus leaves, followed by the development of chlorosis and the tree exhibits stunted growth, the fruit becomes misshapen, inedible and drop prematurely (Westbrook, *et al*., 2011). According to Halbert and Manjunath (2004) and Tsai and Liu (2000), the tree could degenerate in two to three years into a non-productive state, which can lead to eventual death of the tree in approximately five to eight years.

Control measures commonly practiced by growers when both the insect and the pathogen are present is spraying with chemical insecticide (Wang *et al*, 2002), which was regarded as the easiest strategy (Tolley, 1990). The use of other control measures such as use of bio pesticides, cultural techniques and control with natural enemies are still very limited in Southeast Asia, where greening disease still poses a threat to citrus production.

Control measures using chemical pesticides has a lot of unhelpful effects on the environment such as pollution, insecticide resistance, resurgence of primary pest, upsurge of secondary pest, killing of non target and beneficial insects, residues in plant products (Weathersbee and Mckenzie, 2005) and health implication to the applicant/ farmer. Thus, developing management strategy for *D. citri*, which integrates environmental friendly measures, is necessary in order to curtail the menace of greening disease.

Many biotic and abiotic factors such as natural enemies, host plants, other organisms and environment are involved in occurrence and distribution of insects including psyllids. Having information and understanding of the interaction of those factors to the population build up of pest will pave a way in developing reliable strategy for pest management decision. Therefore, to develop this strategy, understanding the ecology of the pest is of paramount importance, however, basic knowledge on the ecology of *D. citri* is lacking in Malaysia, where the pest and the disease pose a potential threat to citrus industry.

The main objective of the present study were to determine *D. citri* interaction with its environment, through the following specific objectives

1. To establish life table and demographic parameters of *D. citri*.
2. To study the population dynamics and and develop sampling plan for *D. citri*.
3. To investigate feeding and oviposition behaviour of *D. citri* and its response to volatiles emitted by the host plants *Citrus suhuiensis* and *Murraya paniculata*.
4. To determine parasitism, nymphal preference for parasitization and functional response of *Tamarixia radiata* on *D. citri.*

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Appendix A

Table A.1 Analysis of variance for distribution of adult, *D. citri* on different canopy strata of *C. suhuiensis*

Source of variance	DF	Sum of squares	Mean square	F
Treatment	1	1332.25	1332.25	6.33*
Error	34	7161.39	210.63	
Total	35	8493.64		

* = significant, P<0.05

Table A.2 Analysis of variance for distribution of adult, *D. citri* on different cardinal point of *C. suhuiensis*

Source of variance	DF	Sum of squares	Mean square	F
Treatment	3	575.22	191.74	3.17*
Error	68	4107.22	60.40	
Total	71	4682.44		

*= significant, P<0.05

Table A.3 Analysis of variance for distribution of adult, *D. citri* on different leaves growth stages of *C. suhuiensis*

Source of variance	DF	Sum of squares	Mean square	F
Treatment	3	1853.82	617.94	7.59**
Error	68	5537.17	81.43	
Total	71	7390.99		

**=highly significant, P<0.01

APPENDICES

Appendix B

Table B.1 Analysis of variance for number of *D. citri* feeding site selection in no choice assay with different leaf growth stages of *C. suhuiensis* and exposure time

Source of variance	DF	Sum of squares	Mean square	F
Treatment				
Leaves growth stage	2	14.71	7.36	19.47**
Exposure time	2	1.65	0.82	2.18 ns
LGS * ET	4	1.82	0.46	1.21ns
Error	36	13.60	0.37	

**=highly significant, P<0.01; ns = not significant; LGS = Leaf growth stage; ET = Exposure time

Table B.2 Analysis of variance for number of *D. citri* eggs in no choice assay with different leaf growth stages *of C. suhuiensis* and exposure time

Source of variance	DF	Sum of squares	Mean square	F
Treatment				
Leaves growth stage	2	2191.60	1095.80	801.80**
Exposure time	2	180.13	90.07	65.90**
LGS * ET	4	360.27	90.07	65.90**
Error	36	49.20	1.37	

**=highly significant, P<0.01; LGS = Leaf growth stage; ET = Exposure time

Table B.3 Analysis of variance for number of *D. citri* feeding site selection in no choice assay with different leaf growth stages of *M. paniculata* and exposure time

Source of variance	DF	Sum of squares	Mean square	F
Treatment				
Leaves growth stage	2	14.71	7.36	19.47**
Exposure time	2	1.64	0.82	2.18ns
LGS * ET	4	1.82	0.46	1.21ns
Error	36	13.60	0.38	

**=highly significant, P<0.01; ns = not significant; LGS = Leaf growth stage; ET = Exposure time

Table B.4 Analysis of variance for number of *D. citri* eggs in no choice assay with different leaf growth stages of *M. paniculata* and exposure time

Source of variance	DF	Sum of squares	Mean square	F
Treatment				
Leaves growth stage	2	1462.58	731.29	539.48**
Exposure time	2	117.64	58.82	43.39**
LGS * ET	4	222.22	55.55	40.98**
Error	36	48.80	1.36	

**=highly significant, P<0.01; LGS = Leaf growth stage; ET = Exposure time

Table B.5 Analysis of variance for number of *D. citri* feeding site selection in choice assay within different leaf growth stages of *C. suhuiensis* and exposure time

Source of variance	DF	Sum of squares	Mean square	F
Treatment				
Leaves growth stage	2	28.93	14.47	118.36**
Exposure time	2	0.13	0.07	0.55ns
LGS * ET	4	0.53	0.13	1.09ns
Error	36	4.40	0.12	

**=highly significant, P<0.01; ns = not significant; LGS = Leaf growth stage; ET = Exposure time

Table B.6 Analysis of variance for number of *D. citri* eggs in choice assay within different leaf growth stages of *C. suhuiensis* and exposure time

Source of variance	DF	Sum of squares	Mean square	F
Treatment				
Leaves growth stage	2	2073.60	1036.80	576.00**
Exposure time	2	145.60	72.80	40.44**
LGS * ET	4	291.20	72.80	40.44**
Error	36	64.80	1.80	

**=highly significant, P<0.01; LGS = Leaf growth stage; ET = Exposure time

Table B.7 Analysis of variance for number of *D. citri* feeding site selection in choice assay within different leaf growth stages of *M. paniculata* and exposure time

Source of variance	DF	Sum of squares	Mean square	F
Treatment				
Leaves growth stage	2	23.33	11.67	87.50**
Exposure time	2	0.00	0.00	0.00ns
LGS * ET	4	1.87	0.47	3.50*
Error	36	4.80	0.13	

**=highly significant, P<0.01; *= significant, P<0.05; LGS = Leaf growth stage; ET = Exposure time

Table B.8 Analysis of variance for number of *D. citri* eggs in choice assay within different leaf growth stages of *M. paniculata* and exposure time

Source of variance	DF	Sum of squares	Mean square	F
Treatment				
Leaves growth stage	2	1724.98	862.49	1093.30**
Exposure time	2	122.84	61.42	77.86**
LGS * ET	4	232.89	58.22	73.80**
Error	36	28.40	0.79	

**=highly significant, P<0.01; LGS = Leaf growth stage; ET = Exposure time

Table B.9 Analysis of variance for number of *D. citri* feeding site selection in choice assay between newly expanded leaves of the host plants and exposure time

Source of variance	DF	Sum of squares	Mean square	F
Treatment				
Plant Species	1	4.03	4.03	8.96**
Exposure time	2	0.07	0.03	0.07ns
PLS * ET	2	2.07	1.03	2.30ns
Error	24	10.80	0.45	

**=highly significant, P<0.01; ns = not significant; PLS = Plant species; ET = Exposure time

Table B.10 Analysis of variance for number of *D. citri* eggs in choice assay between newly expanded leaves of the host plants and exposure time

Source of variance	DF	Sum of squares	Mean square	F
Treatment				
Plant Species	1	36.30	36.30	7.24*
Exposure time	2	793.87	396.93	79.12**
PLS * ET	2	16.80	8.40	1.67ns
Error	24	120.40	5.02	

**=highly significant, P<0.01; *= significant P<0.05; ns = not significant; PLS = Plant species; ET = Exposure time

Table B.11 Analysis of variance for number of *D. citri* feeding site selection in choice assay between completely hardened leaves of the host plants and exposure time

Source of variance	DF	Sum of squares	Mean square	F
Treatment				
Plant Species	1	2.70	2.70	6.00*
Exposure time	2	0.07	0.03	0.07ns
PLS * ET	2	1.40	0.70	1.56ns
Error	24	10.80	0.45	

**=highly significant, P<0.01; *= significant P<0.05; ns = not significant; PLS = Plant species; ET = Exposure time

Table B.12 Analysis of variance for number of *D. citri* eggs in choice assay between completely hardened leaves of the host plants and exposure time

Source of variance	DF	Sum of squares	Mean square	F
Treatment				
Plant Species	1	9.63	9.63	7.41*
Exposure time	2	0.27	0.13	0.10ns
PLS * ET	2	0.27	0.13	0.10ns
Error	24	31.20	1.30	

*= significant P<0.05; ns = not significant; PLS = Plant species; ET = Exposure time

Table B.13 Analysis of variance for number of *D. citri* feeding site selection in choice assay between plant without leaves of the host plants and exposure time

Source of variance	DF	Sum of squares	Mean square	F
Treatment				
Plant Species	1	0.53	0.53	2.29ns
Exposure time	2	0.47	0.23	1.0ns
PLS * ET	2	0.07	0.03	0.14ns
Error	24	5.60	0.23	

ns = not significant; PLS = Plant species; ET = Exposure time

Table B.14 Analysis of variance for number of *D. citri* feeding site selection in choice assay between different leaf growth stage of the host plant combined together and exposure time

Source of variance	DF	Sum of squares	Mean square	F
Treatment				
Plant Species	5	85.73	17.15	57.16**
Exposure time	2	0.07	0.03	0.11ns
PLS * ET	10	2.60	0.26	0.87ns
Error	72	21.60	0.30	

**=highly significant, P<0.01; ns = not significant; PLS = Plant species; ET = Exposure time

Table B.15 Analysis of variance for number of *D. citri* eggs in choice assay between different leaf growth stage of the host plant combine together and exposure time

Source of variance	DF	Sum of squares	Mean square	F
Treatment				
Plant Species	5	5372.59	714.52	522.82**
Exposure time	2	224.62	112.31	82.18**
PLS * ET	10	450.84	45.08	32.99**
Error	72	98.40	1.37	

**=highly significant, P<0.01; PLS = Plant species; ET = Exposure time

Table B.16 Analysis of variance for responses of *D. citri* to *C. suhuiensis* odour versus blank in Y-tube olfactometer and exposure time

Source of variance	DF	Sum of squares	Mean square	F
Treatment	1	9.19	9.19	13.97**
Exposure time	2	0.50	0.25	0.38ns
Treat * ET	2	3.50	1.75	2.66ns
Error	24	27.63	0.66	

**=highly significant, P<0.01; ns = not significant; Treat = Treatment; ET = Exposure time

Table B.17 Analysis of variance for responses of *D. citri* to *M. paniculata* odour versus blank in Y-tube olfactometer and exposure time

Source of variance	DF	Sum of squares	Mean square	F
Treatment	1	16.33	16.33	40.35**
Exposure time	2	3.88	1.94	4.79*
Treat * ET	2	2.04	1.02	2.52ns
Error	24	17.00	0.40	

**=highly significant, P<0.01; *= significant, P < 0.05; ns = not significant; Treat = Treatment; ET = Exposure time

Table B.18 Analysis of variance for responses of *D. citri* to *C. suhuiensis* odour versus *M. paniculata* in Y-tube olfactometer and exposure time

Source of variance	DF	Sum of squares	Mean square	F
Treatment	1	16.33	16.33	44.98**
Exposure time	2	10.79	5.40	14.86**
Treat * ET	2	3.29	1.65	4.53*
Error	24	15.25	0.36	

**=highly significant, P<0.01; *= significant, P < 0.05; Treat = Treatment; ET = Exposure time

Table B.19 Analysis of variance for responses of *D. citri* to β-pinene versus blank in Y-tube olfactometer and exposure time

Source of variance	DF	Sum of squares	Mean square	F
Treatment	1	396.03	396.03	1080.09**
Exposure time	2	12.20	6.10	16.64**
Treat * ET	2	11.66	5.83	15.91**
Error	24	8.80	0.37	

**=highly significant, P<0.01; Treat = Treatment; ET = Exposure time

Table B.20 Analysis of variance for responses of *D. citri* to β-linalool versus blank in Y-tube olfactometer and exposure time

Source of variance	DF	Sum of squares	Mean square	F
Treatment	1	433.20	433.20	633.95**
Exposure time	2	4.47	2.23	3.27ns
Treat * ET	2	9.80	4.90	7.17**
Error	24	16.40	0.68	

**=highly significant, P<0.01; ns = not significant; Treat = Treatment; ET = Exposure time

Table B.21 Analysis of variance for responses of *D. citri* to caryophyllene versus blank in Y-tube olfactometer and exposure time

Source of variance	DF	Sum of squares	Mean square	F
Treatment	1	104.53	104.53	128.00**
Exposure time	2	11.27	5.63	6.90**
Treat * ET	2	4.07	2.03	2.49ns
Error	24	19.60	0.82	

**=highly significant, P<0.01; ns = not significant; Treat = Treatment; ET = Exposure time

Table B.22 Analysis of variance for responses of *D. citri* to β-pinene versus caryophyllene in Y-tube olfactometer and exposure time

Source of variance	DF	Sum of squares	Mean square	F
Treatment	1	270.00	270.00	540.00**
Exposure time	2	22.47	11.23	22.47**
Treat * ET	2	11.40	5.70	11.40**
Error	24	12.00	0.50	

**=highly significant, P<0.01; Treat = Treatment; ET = Exposure time

Table B.23 Analysis of variance for responses of *D. citri* to β-linalool versus caryophyllene blank in Y-tube olfactometer and exposure time

Source of variance	DF	Sum of squares	Mean square	F
Treatment	1	403.33	403.33	1100.00**
Exposure time	2	12.600	6.30	17.18**
Treat * ET	2	15.27	7.63	20.82**
Error	24	8.80	0.37	

**=highly significant, P<0.01; Treat = Treatment; ET = Exposure time

Appendix C

Table C.1 Analysis of variance for Host stage parasitism of *D. citri* nymphs by *T. radiata*

Source of variance	DF	Sum of squares	Mean square	F
Treatment	4	33403.70	8350.91	111.23**
Error	20	1501.55	75.08	
Total	24	34905.19		

**=highly significant, P<0.01

Table C.2 Analysis of variance for host stage preference of *T. radiata* when offered 3rd and 4th instars of *D. citri* nymphs

Source of variance	DF	Sum of squares	Mean square	F
Treatment	1	16.90	16.90	24.14**
Error	8	5.60	0.70	
Total	9	22.50		

**=highly significant, P<0.01

Table C.3 Analysis of variance for host stage preference of *T. radiata* when offered 3rd and 5th instars of *D. citri* nymphs

Source of variance	DF	Sum of squares	Mean square	F
Treatment	1	40.00	40.00	72.73**
Error	8	4.40	0.55	
Total	9	44.40		

**=highly significant, P<0.01

Table C.4 Analysis of variance for host stage preference of *T. radiata* when offered 4rd and 5th instars of *D. citri* nymphs

Source of variance	DF	Sum of squares	Mean square	F
Treatment	1	0.40	0.40	1.60ns
Error	8	2.00	0.25	
Total	9	2.40		

ns = not significant

Appendix D

Table D.1 Total rainfall, rainy days, average monthly temperature and relative humidity from March 2011 to July 2012 in Felda Bukit Bidang, Kuala Barang, Terengganu, Malaysia.

Month	Year	Total Rainfall (mm)	Rainy Days	Average Temperature (^{0}C)	Average Relative Humidity (%)
March	2011	227.1	23	25.3	84.3
April	2011	378.1	11	26.4	84.7
May	2011	235.0	14	26.9	86.3
June	2011	173.0	16	26.8	85.5
July	2011	222.9	14	26.7	84.6
August	2011	444.0	18	26.2	85.2
September	2011	326.5	15	26.2	84.8
October	2011	497.9	26	26.3	85.7
November	2011	1087.2	23	25.3	85.9
December	2011	837.6	22	25.2	89.9
January	2012	561.1	20	25.0	89.8
February	2012	72.7	17	25.3	84.9
March	2012	365.2	14	26.1	83.3
April	2012	225.4	13	25.3	85.3
May	2012	302.3	19	27.1	84.6
June	2012	94.5	8	27.0	83.9
July	2012	186.5	11	26.8	84.1

Appendix E

Figure E.1: Essential oil of *Citrus suhuiensis* leaves analyzed by GC-MS. Quantitative data were obtained from the electronic integration of the peak areas.

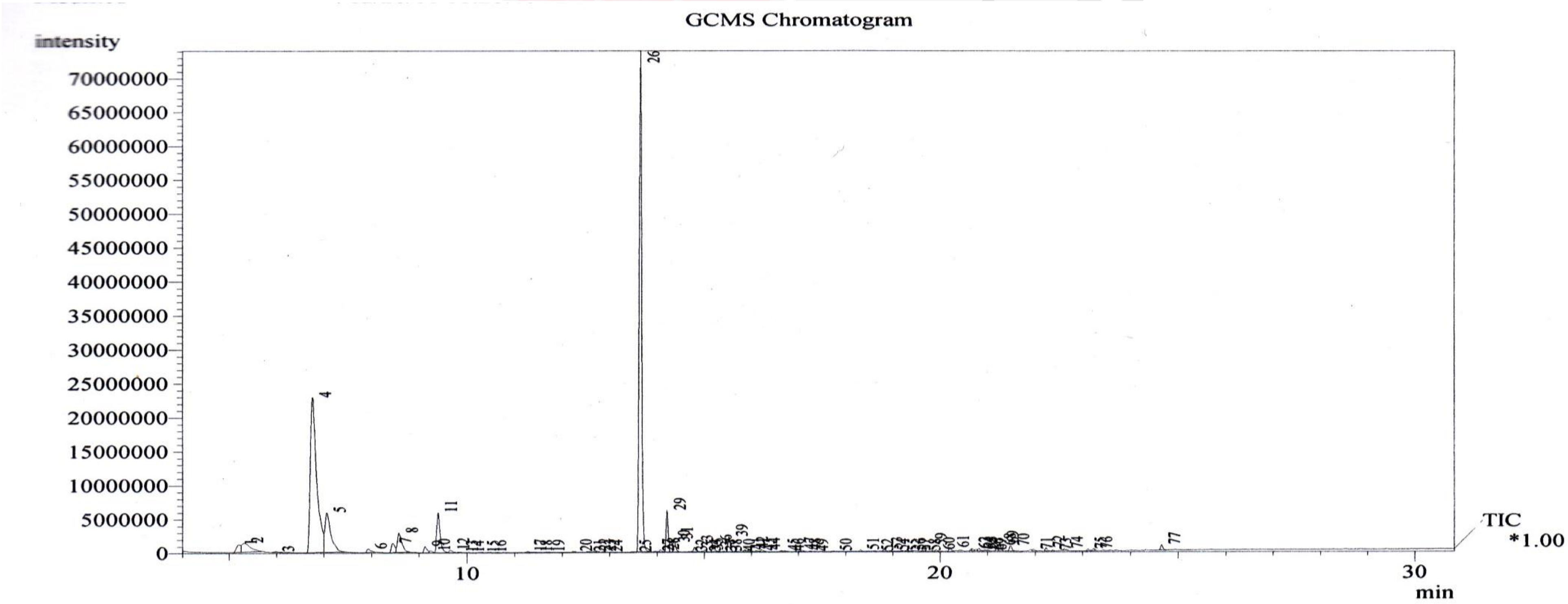
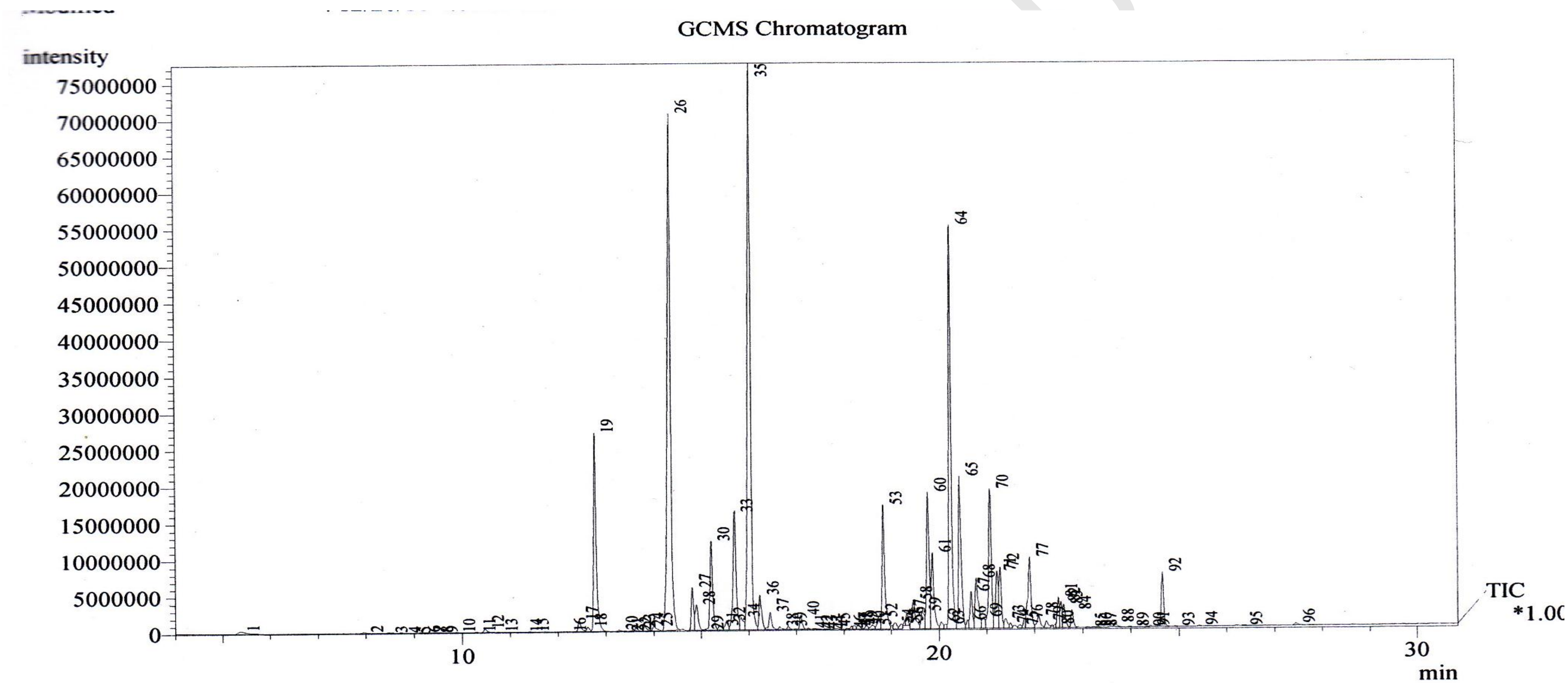


Figure E.2: Essential oil of *Murraya paniculata* leaves analyzed by GC-MS. Quantitative data were obtained from the electronic of the peak areas.



BIODATA OF STUDENT

The student was born on April 24, 1971 in Numan, Adamawa State, Nigeria. He obtained General Certificate of Education in 1987 from Government Technical Secondary School, Numan, Adamawa State, Nigeria. After completion of secondary education he proceeded to University of Maiduguri, where he obtained Bachelor of Agricultural Science degree with specialization in plant protection in the year 1995. He started his working carrier as Agricultural officer with Savannah Sugar Company limited, Numan. Later he moved to Afcott, Nigeria Plc as an extension officer, in-charge of Talasse zone. In 2002, he abandoned the private sector and joined Adamawa State University, Mubi, Nigeria and in 2007, he enrolled for Master of Science degree in Agricultural Entomology in the Department of Crop Science, Faculty of Agriculture, Abubakar Tafawa Balewa University, Bauchi, Nigeria. Furthermore, in February 2010, he registered for Doctor of Philosophy (PhD) programme in the field of Entomology in the Department of Plant Protection, Faculty of Agriculture, Universiti Putra Malaysia. The Author is married to Aishatu Arabi and has two sons, Suleman and Umar.

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