

**DEVELOPING THE PLANT DISEASE MODEL TO
MANAGE THE COCOA BLACK POD DISEASE**



ALBERT LING SHENG CHANG

UMS
UNIVERSITI MALAYSIA SABAH

**FACULTY OF SCIENCE AND NATURAL
RESOURCES
UNIVERSITI MALAYSIA SABAH
2019**

**DEVELOPING THE PLANT DISEASE MODEL TO
MANAGE THE COCOA BLACK POD DISEASE**

ALBERT LING SHENG CHANG



**THISIS SUBMITTED IN FULFILLMENT FOR THE
DEGREE OF DOCTOR OF PHILOSOPHY**

**FACULTY OF SCIENCE AND NATURAL
RESOURCES
UNIVERSITI MALAYSIA SABAH
2019**

UNIVERSITI MALAYSIA SABAH

BORANG PENGESAHAN STATUS TESIS

JUDUL: **DEVELOPING THE PLANT DISEASE MODEL TO MANAGE THE COCOA BLACK POD DISEASE**

IJAZAH: **DOKTOR FALSAFAH (MATEMATIK DENGAN EKONOMI)**

Saya **ALBERT LING SHENG CHANG**, Sesi **2014-2019**, mengaku membenarkan tesis Doktorat ini disimpan di Perpustakaan Universiti Malaysia Sabah dengan syarat-syarat kegunaan seperti berikut:-

1. Tesis ini adalah hak milik Universiti Malaysia Sabah
2. Perpustakaan Universiti Malaysia Sabah dibenarkan membuat salinan untuk tujuan pengajian sahaja.
3. Perpustakaan dibenarkan membuat salinan tesis ini sebagai bahan pertukaran antara institusi pengajian tinggi.
4. Sila tandakan (/):

SULIT

(Mengandungi maklumat yang berdarjah keselamatan atau kepentingan Malaysia seperti yang termaktub di dalam AKTA RAHSIA 1972)

TERHAD

(Mengandungi maklumat TERHAD yang telah ditentukan oleh organisasi/badan di mana penyelidikan dijalankan)

TIDAK TERHAD

Disahkan Oleh,

ALBERT LING SHENG CHANG
DS1411001T

(Tandatangan Pustakawan)

Tarikh : 17 September 2019

(Prof. Dr. Ho Chong Mun)
Penyelia Utama

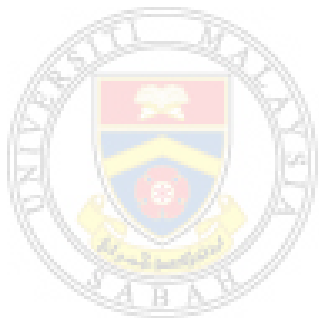
DECLARATION

I hereby declare that the material in this thesis is my own except for quotations, excerpts, equations, summaries and references, which have been duly acknowledged.

12 September 2019

.....
Albert Ling Sheng Chang

DS1411001T



UMMS
UNIVERSITI MALAYSIA SABAH

CERTIFICATION

NAME : **ALBERT LING SHENG CHANG**
Matrik No. : **DS1411001T**
TITLE : **DEVELOPING THE PLANT DISEASE MODEL
TO MANAGE THE COCOA BLACK POD
DISEASE**
DEGREE : **DOCTOR OF PHILOSOPHY
(MATHEMATICS WITH ECONOMICS)**
VIVA DATE : **03 SEPTEMBER 2019**

CERTIFIED BY;

- 1. SUPERVISORY COMMITTEE CHAIRMAN**
Professor Dr. Ho Chong Mun

Signature

- 2. SUPERVISORY COMMITTEE MEMBER**
Associate Professor Dr. Chong Khim Phin

- 3. SUPERVISORY COMMITTEE MEMBER**
Associate Professor Dr. Darmesah Gabda

ACKNOWLEDGMENTS

I would like to thank "God – The Almighty" for providing me the gracious gifts of all strength with patience and courage bestowed upon me to overcome various challenges during the accomplishment of this thesis.

With great pleasure, I would like to express my deepest gratitude to my supervisors, Professor Dr. Ho Chong Mun, Associate Professor Dr. Chong Khim Phin, and Dr. Darmesah Gabda for their valuable guidance, precious suggestions, affectionate criticism and inspiring help in accomplishing this thesis. Without their help, I would not have brought this thesis into its present form.

I acknowledge my heartfelt thanks to Lembaga Koko Malaysia (LKM), especially the previous and present Director General of LKM, Datuk Dr. Lee Choon Hui and Datin Norhaini Udin for sponsoring my study and provided the supports in allowing me to use the LKM's facilities and field plot for my study. Besides that, I also would like to thank two Deputy Director General of LKM, Dr. Ramle Kasin and Dr. Ahmad Kamil Mohd. Jaaffar, and the Director of Cocoa Upstream Technology Division, Haya Ramba for their encouraging supports during my thesis preparation.

I would like to express my respectful gratitude to my examiners, examiner 1, examiner 2 and examiner 3 who have given a lot of input and suggestions for the improvement of my thesis.

I would also like to extend my sincerest thanks and appreciation to my supporting staff in the fields, Sarinah Ambia, Zamri Kamari, Jenrry Sompokon and Yahya Mohd. Noor for their hard work in helping me for data collection. Without their help this thesis would have never been accomplished as it should be.

I personally would like to express my sincere gratitude to my beloved parents, my late father Ling Sing Kee, my mother Wee Buo Choo, my parent-in-law, my sisters, my colleagues, and also all my friends who have supported me with their prayers and blessings. And to the special one my beloved wife Wong Shuk Shyan, my daughter Daphne Ling Mei Ying and my son Darren Ling Yong Li who always standing by my side with all helps and cooperation at the time when I most needed it.

The last but not least, to all parties who have involved either directly or indirectly in the completion of this thesis, thank you so much for all of your help, guidance, and supports.

Thank you.

Albert Ling Sheng Chang

12 September 2019

ABSTRACT

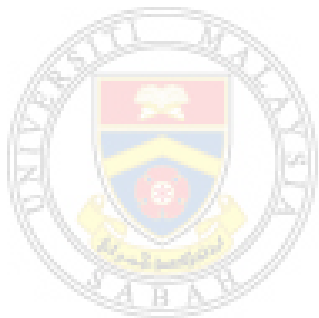
Cocoa smallholder in Malaysia facing a problem of low productivity for the past 10 years and one of the reasons was due to the cocoa black pod disease. The resistant breeding was the best long term solution to the cocoa black pod disease problem that need a reliable screening technique to predict the disease severity progress and identify the resistance level of genotypes. As for the short term solutions, it is important to know which combination of control measures is effective in controlling the cocoa black pod disease incidence. Fungicide application was the most preferred control measure by the cocoa smallholders and can be effectively applied by forecasting when the cocoa disease incidence was likely to be at economic threat. Currently, there are no existing statistical model that can be used for predicting disease severity and estimating the area under disease progress curve to rank the genotype's resistant level in cocoa and also statistical model that can forecast the disease incidence and used in decision making for fungicide application. This study has four objectives to be achieved. The first objective is to develop the nonlinear statistical model of the cocoa black pod severity progress using Monomolecular, Exponential, Logistic and Gompertz models and followed by estimating the Area Under Disease Progress Curve (AUDPC) on four cocoa genotypes of different resistant categories (i.e. KKM 4 (susceptible), KKM 5 (moderately susceptible), BR 25 (moderately resistant) and QH1003 (resistant) at two pod development stages (i.e. young pod and mature pod). The measurements for disease severity was made daily for a duration of six days after inoculated with *Phytophthora palmivora*. The results of study has identified Gompertz model as the best fitted nonlinear model with the smallest values of the Akaike Information Criterion test and the Bayesian Information Criterion test. The second objective is to determine resistance of cocoa genotypes against the cocoa black pod disease by using AUDPC value. The results of study showed the estimated AUDPC value proved that the new protocol of screening the mature genotype's resistant level to the cocoa black pod disease severity gave 100% accuracy with similar results to the field assessment compared to standard assessment that gave 50% accuracy. The third objective is to develop a statistical model to forecast the cocoa black pod incidence by comparing ARIMA approach and ARIMAX approach. The results of the study proved ARIMAX models, known as combination linear regression and the ARIMA process performance better than ARIMA models based on the mean squared error, root mean squared error and mean absolute error. The fourth objective is to estimate losses from the cocoa black pod incidence by using the best fitted model developed in this study. The results showed integrated treatment of pruning, fungicide application and phytosanitary gave the lowest forecasted economic losses, followed by the integrated treatment of pruning and phytosanitary and then integrated treatment of fungicide application and phytosanitary. In conclusion, the Gompertz model built on disease severity in this study can potentially assist breeders to determine the genotypes' resistant level to the cocoa black pod disease while the ARIMAX model built on disease incidence can guide the cocoa farmers to decide when to apply fungicide based on the expected losses and the cost of applying fungicide.

ABSTRAK

MEMBANGUNKAN MODEL PENYAKIT TUMBUHAN UNTUK MENGURUS PENYAKIT BUAH KOKO HITAM

*Pekebun kecil koko di Malaysia menghadapi masalah produktiviti yang rendah sejak 10 tahun yang lalu dan salah satu sebabnya adalah penyakit buah hitam koko. Pembiakbakaan yang rintang adalah penyelesaian jangka panjang terbaik untuk masalah penyakit buah koko hitam yang memerlukan teknik penyaringan dengan kebolehpercayaan untuk meramalkan perkembangan keparahan penyakit dan mengenal pasti tahap kerintangan genotip. Bagi penyelesaian jangka pendek, adalah penting untuk mengetahui kombinasi kawalan yang berkesan dalam mengawal kejadian penyakit buah hitam koko. Penggunaan racun kulat adalah kawalan yang paling disukai oleh pekebun kecil koko dan boleh digunakan dengan berkesan dengan meramal bila kejadian penyakit buah hitam koko mungkin berada pada ancaman ekonomi. Pada masa ini, tidak ada model statistik sedia ada yang boleh digunakan untuk meramalkan keparahan penyakit dan menganggarkan kawasan di bawah keluk perkembangan penyakit untuk menilai tahap kerintangan genotip dalam koko dan juga model statistik yang boleh meramalkan kejadian penyakit dan digunakan dalam membuat keputusan untuk aplikasi racun kulat. Kajian ini mempunyai empat objektif untuk dicapai. Objektif pertama adalah untuk membangunkan model statistik tak linear untuk perkembangan keparahan buah hitam koko menggunakan model Monomolecular, Eksponen, Logistik dan Gompertz dan diikuti dengan menganggarkan luas di bawah keluk perkembangan penyakit (AUDPC) pada empat genotip koko berlainan kategori kerintangan (iaitu KKM 4 (rentan), KKM 5 (sederhana rentan), BR 25 (sederhana rintang) dan QH1003 (rintang) di dua peringkat pembangunan buah koko (iaitu buah muda dan buah matang). Pengukuran untuk keparahan penyakit dibuat setiap hari selama enam hari selepas diinokulasi dengan *Phytophthora palmivora*. Dapatan kajian telah mengenalpasti model Gompertz sebagai model tak linear tersuai terbaik dengan nilai terkecil dari ujian Kriteria Maklumat Akaike dan ujian Kriteria Maklumat Bayesian. Objektif kedua adalah menentukan rintangan genotip koko terhadap penyakit buah hitam koko dengan menggunakan nilai AUDPC. Dapatan kajian menunjukkan nilai anggaran AUDPC membuktikan bahawa protokol baru untuk menyaring paras kerintangan genotip yang matang terhadap keparahan penyakit buah hitam koko memberikan ketepatan 100% dengan hasil yang serupa dengan penilaian lapangan berbanding penilaian piawai yang memberikan ketepatan 50%. Objektif ketiga adalah membangunkan model statistik untuk meramalkan kejadian buah hitam koko dengan membandingkan pendekatan ARIMA dan pendekatan ARIMAX. Dapatan kajian membuktikan model ARIMAX, yang dikenali sebagai kombinasi regresi linear dengan proses ARIMA memberikan prestasi yang lebih baik daripada model ARIMA berdasarkan ralat min kuasa dua, ralat punca min kuasa dua dan ralat min mutlak. Objektif keempat adalah untuk menganggarkan kerugian dari kejadian buah hitam koko dengan menggunakan model tersuai terbaik yang dibangunkan dalam kajian ini. Keputusan menunjukkan rawatan bersepadu seperti pemangkasan, aplikasi racun kulat dan fitosanitari memberikan ramalan kerugian ekonomi yang paling rendah, diikuti dengan rawatan bersepadu seperti*

pemangkasan dan fitosanitari dan kemudian rawatan bersepadu melibatkan aplikasi racun kulat dan fitosanitari. Kesimpulannya, model Gompertz yang dibangunkan atas keparahan penyakit dalam kajian ini berpotensi membantu pembiakbaka untuk menentukan tahap kerintangan genotip terhadap penyakit buah hitam koko manakala model ARIMAX yang dibangunkan atas kejadian penyakit dapat membimbing petani koko untuk membuat keputusan bila menggunakan racun kulat berdasarkan kepada jangkaan kerugian dan kos untuk mengaplikasi racun kulat.



UMS
UNIVERSITI MALAYSIA SABAH

TABLE OF CONTENTS

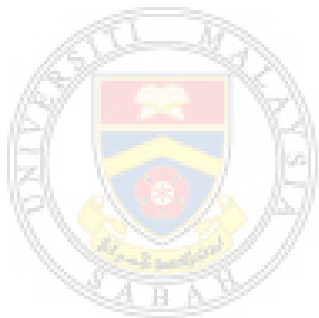
	Page
TITLE	i
DECLARATION	ii
CERTIFICATION	iii
ACKNOWLEDGEMENT	iv
ABSTRACT	v
ABSTRAK	vi
TABLE OF CONTENTS	viii
LIST OF TABLES	xiii
LIST OF FIGURES	xvii
LIST OF ABBREVIATIONS	xxi
LIST OF APPENDICES	xxii
CHAPTER 1: INTRODUCTION	1
1.1 Introduction	1
1.2 Contribution of Cocoa Industry to the Malaysia Economy	3
1.3 Economic Impact of Cocoa Black Pod Disease and Its Management	10
1.4 Problem Statement	13
1.5 Objectives of the Study	17
1.6 Significance of Study	17
1.7 Scope of Study	19
1.8 Organization of Thesis	20
CHAPTER 2: LITERATURE REVIEW	21
2.1 Introduction	21
2.2 Review on Cocoa Black Pod Disease	21

2.2.1	Biology and Epidemiology of Cocoa Black Pod Disease	21
2.2.2	Infection Progress and Symptoms of Cocoa Black Pod Disease	24
2.2.3	Factors involved in Cocoa Black Pod Disease Expression	27
2.2.4	Control Method and Management of Cocoa Black Pod Disease	30
2.3	Review on Statistical Model on Plant Disease Severity Progress	31
2.3.1	Existing Plant Disease Progress Models	32
2.3.2	Assessment Method used in Screening the Cocoa Genotypes	37
2.4	Review on Plant Disease Forecasting Model Development	39
2.4.1	Existing Plant Disease Forecasting Models	40
2.4.2	Model Building Approach	56
2.5	Summary of Literature Review	58
CHAPTER 3: RESEARCH METHODOLOGY		60
3.1	Research Design	60
3.2	Development of Statistical Model on Cocoa Black Pod Severity	61
3.2.1	Experimental Design and Sampling Method	61
3.2.2	Measuring the Disease Severity	67
3.2.3	Fitting the Disease Severity Progress Curve	68
3.2.4	Validation of the Nonlinear Models	73
3.2.5	Estimating the Area Under Disease Progress Curve (AUDPC)	74
3.3	Development of Forecasting Model on Cocoa Black Pod Incidence	74
3.3.1	Study Sites and Experimental Design	75
3.3.2	Sampling Method	80

3.3.3	Variables and Its Measurement	82
3.3.4	Procedures of Data Collection and Analysis	88
3.3.5	Splitting Data Set into Model Building Set and Validation Set	89
3.3.6	Descriptive Statistics	90
3.3.7	Effect of Treatments and Pod Development Stage with ANOVA Test	90
3.3.8	Building the Disease Forecasting Model Using ARIMA Approach	98
3.3.9	Building the Disease Forecasting Model Using ARIMAX Approach	107
3.3.10	Model Validation	118
3.4	Computer Software for Statistical Analysis	119
CHAPTER 4:	RESULTS	120
4.1	Introduction	120
4.2	Development of Statistical Model on Cocoa Black Pod Severity	121
4.2.1	Pod Phenology	121
4.2.2	Disease Severity	122
4.2.3	The Disease Severity Progress Curve Fitted Models	124
4.2.4	Estimating the Area Under Disease Progress Curve (AUDPC) for Fitted Models	138
4.2.5	Comparing Cocoa Genotype's Resistance Level on Black Pod Disease	142
4.3	Development of Forecasting Model on Cocoa Black Pod Incidence	144
4.3.1	Trend of Cocoa Black Pod Incidence at Four Treatments	145
4.3.2	Effect of Treatments and Pod Development Stage on Cocoa Black Pod Incidence	144
4.3.3	Climates Pattern at Study Plot	148

4.3.4	Building the Disease Forecasting Model Using ARIMA Approach	149
4.3.5	Building the Disease Forecasting Model Using ARIMAX Approach	170
4.3.6	Model Validation	195
4.3.7	Estimating Losses from Cocoa Black Pod Disease Incidence	198
4.3.8	Decision Making On Fungicide Application	201
CHAPTER 5:	DISCUSSION	207
5.1	Introduction	207
5.2	Pod Phenology and Disease Severity	207
5.3	Objective I: To Develop the Statistical Model and Estimate the Area Under Disease Progress Curve (AUDPC) of the Cocoa Black Pod Severity Progress by using Nonlinear Models	209
5.3.1	Nonlinear Statistical Models on the Disease Severity	209
5.3.2	Estimation of the Area Under Disease Progress Curve (AUDPC) of the Cocoa Black Pod Severity	210
5.4	Objective II: To Determine Resistance of Cocoa Genotypes against the Cocoa Black Pod Disease by using Area Under Disease Progress Curve (AUDPC)	210
5.4.1	Cocoa Genotype's Resistance Level on Cocoa Black Pod Disease	210
5.5	Objective III: To Develop the Statistical Model to Forecast the Cocoa Black Pod Incidence by comparing ARIMA Approach and ARIMAX Approach	211
5.5.1	Effect of Four Treatments and Pod Development Stage on Cocoa Black Pod Incidence	211
5.5.2	Effect of Climatic Variables on Cocoa Black Incidence	212
5.5.3	The Statistical Model for Forecasting the Cocoa Black Pod Incidence using ARIMA Approach	213
5.5.4	The Statistical Model for Forecasting the Cocoa Black Pod Incidence using ARIMAX Approach	215
5.5.5	The Best Fitted Model Among All Selected Models	219

	Based on the Forecasting Performance	
5.6	Objective IV: To Estimate the Losses from the Cocoa Black Pod Incidence by Using the Best Fitted Model Developed in this Study	221
5.6.1	Strategy in Making Decision on Fungicide Application	222
CHAPTER 6:	CONCLUSION AND RECOMMENDATIONS	224
6.1	Conclusion	224
6.2	Limitations of Study and Recommendations for Future Studies	230
REFERENCES		232
APPENDICES		250



UMS
UNIVERSITI MALAYSIA SABAH

LIST OF TABLES

	Page
Table 1.1: Export value on cocoa beans and cocoa products for 2011 to 2018	6
Table 2.1: Nonlinear models used to describe temporal disease progress	35
Table 2.2: Example of disease progress models used in different crops	36
Table 2.3: Example of plant disease forecasting model with regression analysis	44
Table 2.4: Polynomial models used in quantified cocoa black pod disease	46
Table 2.5: Example of ARIMA models application in agriculture	51
Table 2.6: Example of ARIMAX models application	55
Table 3.1: Template for data recording of the cocoa black pod disease incidence	84
Table 3.2: Two-way ANOVA test	96
Table 3.3: Patterns in ACF and PACF in specifying ARIMA models	103
Table 3.4: Decision rules for the D-W test	116
Table 4.1: Summary statistics of pod phenology	121
Table 4.2: The growth of cocoa black pod lesion over six days after inoculation	122
Table 4.3: The cocoa black pod severity disease progress over six days after inoculation	123
Table 4.4: Estimation of four nonlinear models for young genotype BR 25	127
Table 4.5: Estimation of four nonlinear models for young genotype KKM 4	128
Table 4.6: Estimation of four nonlinear models for young genotype KKM 5	129
Table 4.7: Estimation of four nonlinear models for young genotype QH 1003	130

Table 4.8:	Estimation of four nonlinear models for mature genotype BR 25	131
Table 4.9:	Estimation of four nonlinear models for mature genotype KKM 4	132
Table 4.10:	Estimation of four nonlinear models for mature genotype KKM 5	133
Table 4.11:	Estimation of four nonlinear models for mature genotype QH1003	134
Table 4.12:	Comparing four nonlinear models at young pod	135
Table 4.13:	Comparing four nonlinear models at mature pod	136
Table 4.14:	Rank of genotype's resistant level	142
Table 4.15:	Summary statistics on weekly cocoa black pod disease incidence	145
Table 4.16:	Normality test on untransformed data	146
Table 4.17:	Homogeneity of variances test on untransformed data	146
Table 4.18:	Analysis of Variance (ANOVA) on untransformed data	147
Table 4.19:	Multiple means comparison test on untransformed data	147
Table 4.20:	Result of ADF Test in Treatment 1	150
Table 4.21:	Result of ADF Test in Treatment 2	150
Table 4.22:	Result of ADF Test in Treatment 3	150
Table 4.23:	Result of ADF Test in Treatment 4	150
Table 4.24:	Results of Fitted ARIMA models in Treatment 1	156
Table 4.25:	Results of Fitted ARIMA models in Treatment 2	157
Table 4.26:	Results of Fitted ARIMA models in Treatment 3	158
Table 4.27:	Results of Fitted ARIMA models in Treatment 4	159
Table 4.28:	Results of the Ljung-Box Q test on residuals	168
Table 4.29:	Results of the AIC test and BIC test	169
Table 4.30:	Result of ADF Test on weekly total rainfall data	171

Table 4.31:	Result of ADF Test on weekly relative humidity data	172
Table 4.32:	Result of ADF Test on weekly mean temperature	172
Table 4.33:	Result of ADF Test on weekly minimum temperature	172
Table 4.34:	Result of ADF Test on weekly maximum temperature	173
Table 4.35:	Granger Causality test involved climate variables in treatment 1	174
Table 4.36:	Granger Causality test involved climate variables in treatment 2	174
Table 4.37:	Granger Causality test involved climate variables in treatment 3	176
Table 4.38:	Granger Causality test involved climate variables in treatment 4	176
Table 4.39:	Climate variable candidates selected by Granger Causality test	177
Table 4.40:	Correlation analysis on climate variables in Treatment 1	180
Table 4.41:	Correlation analysis on climate variables in Treatment 2	181
Table 4.42:	Correlation analysis on climate variables in Treatment 3	182
Table 4.43:	Correlation analysis on climate variables in Treatment 4	183
Table 4.44:	Stepwise regression analysis in Treatment 1	185
Table 4.45:	Stepwise regression analysis in Treatment 2	185
Table 4.46:	Stepwise regression analysis in Treatment 3	186
Table 4.47:	Stepwise regression analysis in Treatment 4	187
Table 4.48:	ADF Test on residuals from stepwise regression in Treatment 1	188
Table 4.49:	ADF Test on residuals from stepwise regression in Treatment 2	188
Table 4.50:	ADF Test on residuals from stepwise regression in Treatment 3	188
Table 4.51:	ADF Test on residuals from stepwise regression in Treatment 4	188

Table 4.52:	Durbin-Watson (DW) test on SRM residuals	189
Table 4.53:	Fitted ARIMAX(2,1,1) model with $DTmax_t - 7$ in Treatment 1	191
Table 4.54:	Fitted ARIMAX(1,0,0) model with $Tmax_t$ in Treatment 2	192
Table 4.55:	Fitted ARIMAX(1,1,1) model with DRH_{t-4} in Treatment 3	192
Table 4.56:	Fitted ARIMAX(1,1,2) model with both DRH_{t-6} and $DTmin_{t-5}$ in Treatment 4	192
Table 4.57:	Fitted ARIMAX(1,1,2) model with DRH_{t-6} in Treatment 4	192
Table 4.58:	Fitted ARIMAX(1,1,2) model with $DTmin_{t-5}$ in Treatment 4	193
Table 4.59:	Ljung-Box Q test on residuals from ARIMAX models	193
Table 4.60:	Actual versus forecasted values in Treatment 1	196
Table 4.61:	Actual versus forecasted values in Treatment 2	196
Table 4.62:	Actual versus forecasted values in Treatment 3	197
Table 4.63:	Actual versus forecasted values in Treatment 4	197
Table 4.64:	Estimation of the losses in four treatments for 89 weeks	200
Table 4.65:	Parameters used in decision making of fungicide spraying	201
Table 4.66:	Forecasted cocoa black pod incidence on 26 December 2016 in treatment 2	203
Table 4.67:	Estimated parameters in decision making of fungicide spraying	204
Table 4.68:	Tawau's cocoa dried bean prices on 19 December 2016	205
Table 4.69:	Malaysian Cocoa grade specifications	205

LIST OF FIGURES

		Page
Figure 1.1:	Malaysia's cocoa upstream performance	2
Figure 1.2:	Annual gross domestic product (GDP) of cocoa sector Source	4
Figure 1.3:	Main cocoa grinding countries	7
Figure 1.4:	Number of employments in cocoa sector for year 2012	8
Figure 1.5:	Number of employments in cocoa sector for year 2018	8
Figure 1.6:	Supply and demand of cocoa beans in Malaysia	10
Figure 2.1:	Cocoa hybrid tree	22
Figure 2.2:	Cocoa clonal tree	22
Figure 2.3:	Sporangia	23
Figure 2.4:	Sporangium with zoospores	23
Figure 2.5:	Chlamydospores	23
Figure 2.6:	Distribution map of <i>Phytophthora palmivora</i> on cocoa	24
Figure 2.7:	A ripe cocoa pod infected by <i>Phytophthora palmivora</i>	26
Figure 2.8:	Unripe cocoa pod infected by <i>Phytophthora palmivora</i>	26
Figure 2.9:	Unripe cocoa pod with increased signs of black pod	26
Figure 2.10:	The cocoa pod severely infected	26
Figure 2.11:	The disease triangle	27
Figure 2.12:	Four different plant disease progress models	34
Figure 2.13:	The main focus of literature review	59
Figure 3.1:	Sampled pod cleaning prior to inoculation	62
Figure 3.2:	Confirming the isolated <i>Phytophthora palmivora</i>	62
Figure 3.3:	A single point inoculation was performed on the pod	62
Figure 3.4:	Inoculated pods of young KKM 5	63

Figure 3.5:	Inoculated pods of mature KKM 5	63
Figure 3.6:	Inoculated pods of young KKM 4	64
Figure 3.7:	Inoculated pods of mature KKM 4	64
Figure 3.8:	Inoculated pods of young BR 25	65
Figure 3.9:	Inoculated pods of mature BR 25	65
Figure 3.10:	Inoculated pods of young QH 1003	66
Figure 3.11:	Inoculated pods of mature QH 1003	66
Figure 3.12:	(a) Prolate spheroid model used to estimate pod surface; (b) Pod with black lesion; and (c) Ellipse model used to estimate lesion area	68
Figure 3.13:	Field 5B in CRDC Madai, Sabah used in the study	75
Figure 3.14:	The experimental layout in Field 5B, CRDC Madai, Sabah	76
Figure 3.15:	The label used to represent the cocoa tree in the subplot	76
Figure 3.16:	The cocoa plot applied with Treatment 1	78
Figure 3.17:	The cocoa plot applied with Treatment 2	78
Figure 3.18:	The cocoa plot applied with Treatment 3	79
Figure 3.19:	The control cocoa plot that labeled as Treatment 4	79
Figure 3.20:	Pruning activities in plots applied with Treatments 1 and 2	80
Figure 3.21:	Team involved in data collection	81
Figure 3.22:	Team members recorded the black pods disease incidence	81
Figure 3.23:	WatchDog Microstation	83
Figure 3.24:	Microclimate data transferred from data logger to computer	83
Figure 3.25:	Tipping Bucket Rain Gauge	85
Figure 3.26:	The rain collector is connected to data logger for rainfall recording	86

Figure 3.27:	WatchDog data logger of 1000 Series Micro Station	88
Figure 3.28:	The protection shield to house the data logger	88
Figure 3.29:	Box-Jenkins Modelling Approach	99
Figure 3.30:	ARIMAX Model building procedure	108
Figure 4.1:	Progress of mean lesion diameter on four young genotypes	124
Figure 4.2:	Progress of disease severity on four young genotypes	125
Figure 4.3:	Progress of mean lesion diameter on four mature genotypes	125
Figure 4.4:	Progress of disease severity on four mature genotypes	126
Figure 4.5:	AUDPC for cocoa young pod of genotype BR 25	138
Figure 4.6:	AUDPC for cocoa young pod of genotype KKM 4	138
Figure 4.7:	AUDPC for cocoa young pod of genotype KKM 5	139
Figure 4.8:	AUDPC for cocoa young pod of genotype QH 1003	139
Figure 4.9:	AUDPC for cocoa mature pod of genotype BR 25	140
Figure 4.10:	AUDPC for cocoa mature pod of genotype KKM 4	140
Figure 4.11:	AUDPC for cocoa mature pod of genotype KKM 5	141
Figure 4.12:	AUDPC for cocoa mature pod of genotype QH 1003	142
Figure 4.13:	Weekly black pod incidence from February 2015 to December 2016 for four treatments	144
Figure 4.14:	Climate data recorded from February 2015 to December 2016	149
Figure 4.15:	ACF and PACF plots on transformed data for 80 weeks data in Treatment 1	152
Figure 4.16:	ACF and PACF plots on untransformed data for 80 weeks data in Treatment 2	153
Figure 4.17:	ACF and PACF plots on transformed data for 80 weeks data in Treatment 3	154

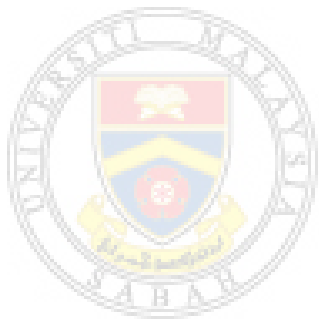
Figure 4.18:	ACF and PACF plots on transformed data for 80 weeks data in Treatment 4	155
Figure 4.19:	ACF and PACF plots on residuals of ARIMA(1,1,1) in Treatment 1	162
Figure 4.20:	ACF and PACF plots on residuals of ARIMA(2,1,1) in Treatment 1	162
Figure 4.21:	ACF and PACF plots on residuals of ARIMA(2,1,0) in Treatment 1	163
Figure 4.22:	ACF and PACF plots on residuals of ARIMA(0,1,2) in Treatment 1	163
Figure 4.23:	ACF and PACF plots on residuals of ARIMA(0,1,1) in Treatment 1	164
Figure 4.24:	ACF and PACF plots on residuals of ARIMA(1,0,0) in Treatment 2	164
Figure 4.25:	ACF and PACF plots on residuals of ARIMA(0,0,1) in Treatment 2	165
Figure 4.26:	ACF and PACF plots on residuals of ARIMA(1,1,1) in Treatment 3	165
Figure 4.27:	ACF and PACF plots on residuals of ARIMA(0,1,1) in Treatment 3	166
Figure 4.28:	ACF and PACF plots on residuals of ARIMA(1,1,2) in Treatment 4	166
Figure 4.29:	Fungicide of Halex Copper-Oxy 84	206

LIST OF ABBREVIATIONS

ACF	-	Autocorrelation Function
ADF	-	Augmented Dickey–Fuller
AIC	-	Akaike Information Criterion
ANOVA	-	Analysis of Variance
AR	-	Autoregressive
ARIMA	-	Autoregressive Integrated Moving Average
ARIMAX	-	Autoregressive Integrated Moving Average with Exogenous Variables
BIC	-	Bayesian Information Criterion
CRDC	-	Cocoa Research and Development Center
DAI	-	Day after inoculation
DF	-	Dickey–Fuller
DMRT	-	Duncan’s Multiple-Range Test
MA	-	Moving Average
MAE	-	Mean Absolute Error
MLE	-	Maximum Likelihood Estimation
MSE	-	Mean Square Error
PACF	-	Partial Autocorrelation Function
RMSE	-	Root Mean Squared Error
SAS	-	Statistical Analysis System
SRM	-	Stepwise Regression Model
SSR	-	Regression Sum of Squares
VIF	-	Variance Inflation Factor

LIST OF APPENDICES

		Page
Appendix A	Losses Estimation in Four Treatments from February 2015 to December 2016	250
Appendix B	List of Publications	266



UMMS
UNIVERSITI MALAYSIA SABAH