UNIVERSITI PUTRA MALAYSIA

ADAPTIVE MANAGEMENT FRAMEWORK FOR GROWTH RESPONSE ANALYSIS OF TOMATO IN CONTROLLED ENVIRONMENT PLANT PRODUCTION SYSTEMS

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By

RAMIN SHAMSHIRI

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

November 2014

DEDICATION

To my beloved ones, Esmat, Aziz and Dr. Katrin Shamshiri

And with reverence to Dr. M. Rajabi and Dr. Farhang Holakouee

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Words would have been silent without you

تقدیم به عزیزانم – مادرم عصمت – پدرم عزیز – و خواهرم دکتر کاترین شمشیری

همراه با قدردانی و احترام به دکتر م – رجبی و دکتر فرهنگ هلاکویی

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که اگر نبودند واژه ها میمردند

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

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Chairman : Proffessor. Wan Ishak Wan Ismail, PhD, Ir
Faculty : Engineering

High demands for quality agricultural products require practicing modern techniques of resource management in controlled environment plant production systems (CEPPS). The cost of growing inside closed-field is generally higher than producing in open-field; therefore a comprehensive understanding and analysis of environment responses (ER), plant requirements and growth responses (GR) are necessary to embrace uncertainties in such environments.

An adaptive management framework (AMF) was developed and used in this study for defining and determining foundation classes (climate control parameters) and objects (tomato crop at different growth stages and light condition) in a bio-production system like CEPPS. The flexible architecture of the framework with a self-tuning configuration database enables it to work with different culture classes and objects within which many specific scenarios may be modeled and analyzed. This design proposes a systematic approach for the immense environmental data analyzing tasks with the overall objective of providing knowledge-based information for achieving optimal climate condition. The framework adaptive database was built according to peer-reviewed published works that define probability of successful production of tomato (*Lycopersicon Esculentum*) as individual growth response functions (GRF) for air temperature and relative humidity (RH) at five growth stages (GS) and under three light conditions (night, sun, cloud). Background knowledge from scientific literatures was used with a numerical method approach in developing response functions for vapor pressure deficit (VPD). The framework was used in two separate case studies: (i) open-field, with total of 126 data collection days (from June to December, 2013) and (ii) closed-field (including three environments, denoted by A: OFE, B: PFCE, and C: PPCE) with 11 days of data collection. The output results were generated for one-day and multi-days based analysis, including preliminary statistics and inferences, dynamic visualization plots, environment responses (ER) to optimal parameter *x* (where *x* represents temperature, RH or VPD), growth responses (GR) analysis, optimization and reference selection, comparison factors, maximum guaranteed and actual growth response, performance curves, adaptability factors, light-condition based analysis and prediction models. A new term, digital growth response map, was introduced and demonstrated, providing time-specific information on environment performance.

For each case study, environment responses, ER(x), at three references (GR=0, GR=0.55 and GR=1) were calculated for all growth stages. Factorial design was used to determine variation in data due to different months and stages. Results of ER analysis indicated possible savings of energy up to 62% at growth stage=1, 17% at stage=2 and 30% at stage=3 to 5, in providing ideal climate condition for closed-field production of tomato. In addition, analysis of growth responses, showed that averaged probability of successful production, associated with temperature, RH and VPD (denoted by GR(T), GR(RH) and GR(VPD)) were 0.71, 0.69 and 0.75 respectively. It was observed that in each month, minimum values of GR(T), regardless of growth stage, occurred between 11:00am to 7:00pm. While this trend was significant for GR(RH) at stage=1, the minimum values of GR(RH) for stage=2 and stage=3-to-5 appeared from 2:00am to 6:00am. The results light-condition-based analysis showed that maximum temperature and VPD values occur at sun condition, with peak values between 11:00am to 4:00pm, when RH is at minimum, and the lowest VPD values belong to night hours. It was found that the averaged GR(x) based on light conditions depends on the growth stage. For example, in the open-field case study, at stage=1, averaged GR(T) in the entire 6 months was found to be the highest at night times compared with sun and cloud light conditions, while at stage=2 to 5, sun condition had the highest average value for GR(T). The result of the second case study indicated significant difference between three environments in the peak-hours of energy requirement. It was observed that at temperature between 20°C to 30°C, RH between 80% and 100%, and VPD between 0.1kPa to 1.2kPa, all three environments are almost equally providing same growth condition for tomato, however, as temperature starts rising above 30°C, differences in the environments starts growing.

The proposed approach can be used to evaluate any environment for greenhouse production, and to provide required information for management decisions such as scheduling efficiencies, site-selection, cost evaluation, energy prediction and risk assessments associated with each task.

Abstrak tesis dibentangkan untuk Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk Ijazah Doktor Falsafah

RANGKA KERJA PENGURUSAN ADAPTIVE UNTUK ANALISIS SAMBUTAN PERTUMBUHAN TOMATO DALAM PERSEKITARAN TERKAWAL LOJI SISTEM PENGELUARAN

Oleh

RAMIN SHAMSHIRI

November 2014

Pengerusi : Proffessor. Wan Ishak Wan Ismail, PhD, Ir
Fakulti : Kejuruteraan

Permintaan yang tinggi untuk produk pertanian yang berkualiti memerlukan pengamalan teknik moden bagi pengurusan sumber dalam sistem pengeluaran kilang persekitaran terkawal (CEPPS). Kos untuk membesar dalam ladang tertutup secara umumnya adalah lebih tinggi daripada ladang terbuka; oleh itu, pemahaman yang menyeluruh dan analisis faktor persekitaran (tindak balas alam sekitar atau ER) dan keperluan tumbuhan (tindak balas pertumbuhan atau GR) adalah penting untuk merangkumi ketidaktentuan CEPPS, dengan objektif utama untuk mencapai hasil yang tinggi pada perbelanjaan yang rendah, untuk mengekalkan persekitaran yang kompetitif.

Rangka kerja pengurusan ‘adaptive’ (AMF) telah diperkenalkan dan digunakan dalam kajian ini untuk menerangkan dan menentukan kelas asas (parameter kawalan cuaca) dan objek (tanaman tomato pada peringkat pertumbuhan dan keadaan cahaya yang berbeza) dalam sistem bio-pengeluaran seperti CEPPS. Seni bina fleksibel rangka kerja dengan pangkalan data konfigurasi sendiri (DB) membolehkan ia bekerja dengan kelas-kelas yang berbeza budaya dan objek di mana banyak senario tertentu boleh dimodelkan dan dianalisis. Reka bentuk ini mencadangkan suatu pendekatan yang sistematik untuk tugas menganalisis data alam sekitar yang besar dengan objektif keseluruhan, untuk memberi maklumat berdasarkan pengetahuan, untuk mencapai keadaan iklim yang baik. ‘Adaptive’ DB dibina mengikut kerja-kerja ulasan yang diterbitkan yang menentukan kebarangkalian dan kejayaan penghasilan tomato (Lycopersicon esculentum), sebagai fungsi tindak balas pertumbuhan individu (GRF) untuk suhu udara dan kelembapan relatif (RH) pada lima peringkat pertumbuhan (GS) dan di bawah tiga keadaan cahaya (malam, matahari, mendung). Fungsi-fungsi ini telah digunakan dalam membangunkan fungsi tindak balas defisit tekanan wap (VPD). Rangka kerja yang telah dilaksanakan dan model yang dicadangkan telah disahkan melalui dua kes kajian berbeza: satu dijalankan bagi ladang terbuka, dengan jumlah 126 hari (untuk kajian perbandingan antara 6 bulan dari Jun hingga Disember 2013) dan satu lagi untuk ladang tertutup (termasuk tiga persekitaran, ditandakan oleh A: OFE, B: PFCE, dan C: PPCE) dengan 11 hari dari pengumpulan data. Keputusan hasil keluaran telah dihasilkan untuk satu hari dan analisis berasaskan berbilang hari, termasuklah statistik awal dan kesimpulan, plot visualisasi dinamik, maklum balas alam sekitar (ER) untuk x optimum (di mana x mewakili suhu, RH atau VPD), analisis tindak balas

pertumbuhan (GR) untuk mencari kebarangkalian (Pr) untuk mencapai parameter optimum, simulasi interaksi antara tindak balas persekitaran dan tindak balas pertumbuhan (ER-GR) untuk pemilihan rujukan yang optimum dan pengelakkan rujukan kritikal, faktor perbandingan, maksimum terjamin dan pertumbuhan tindak balas sebenar, graf prestasi, faktor adaptasi, analisis dan ramalan model berasaskan keadaan cahaya. Satu istilah baru, peta tindak balas pertumbuhan (GRM), telah diperkenalkan dan didemonstrasikan oleh unjuran ortogon. Bagi setiap kes kajian, tindak balas alam sekitar untuk parameter ER(x), dirujukan pada tiga tahap tindak balas pertumbuhan (GR = 0, GR = 0.55 dan GR = 1) telah ditentukan pada setiap peringkat pertumbuhan. Reka bentuk faktorial digunakan untuk menentukan perubahan dalam data disebabkan perubahan bulan dan tahap. Keputusan analisis ER menunjukkan kemungkinan simpanan tenaga sehingga 62% pada peringkat pertumbuhan = 1, 17% pada tahap = 2 dan 30% pada peringkat = 3-5, dalam menyediakan keadaan iklim yang sesuai untuk pengeluaran tomato di persekitaran yang terkawal. Di samping itu, analisis sambutan pertumbuhan, GR(x), pada peringkat pertumbuhan yang berbeza menunjukkan bahawa kebarangkalian purata pengeluaran berjaya, yang berkaitan dengan suhu, RH dan VPD didapati 0.71, 0.69 dan 0.75 masing-masing. Ia juga diperhatikan bahawa pada hari-hari tertentu, purata Pr(T) ialah 0.65 pada setiap GS. Kebarangkalian ini untuk RH adalah 0.8 di peringkat satu, 0.67 pada peringkat 2 dan 0.72 pada peringkat 3-ke-5. Keputusan menunjukkan bahawa pada setiap bulan, nilai minimum Pr(T), tidak kira peringkat pertumbuhan, berlaku antara pukul 11 pagi dan 7 petang. Walaupun trend ini adalah penting bagi Pr(RH) pada peringkat = 1, nilai minimum Pr (RH) untuk peringkat = 2 dan peringkat = 3-ke-5 muncul diantara pukul 2 hingga 6 pagi. Keputusan hipotesis yang diuji untuk tomato menunjukkan bahawa GR kepada suhu, RH dan VPD mempunyai nilai min yang berbeza di bawah keadaan cahaya yang berbeza, serta menunjukkan bahawa suhu maksimum dan nilai-nilai VPD (bersamaan dengan RH minimum) berlaku pada keadaan matahari, dengan suhu dan VPD mempunyai nilai puncak mereka antara pukul 11 pagi sehingga 4 petang, apabila RH adalah minimum (nilai VPD terendah tergolong dalam jam malam). Ia didapati bahawa purata GR (x) berdasarkan keadaan cahaya bergantung kepada peringkat pertumbuhan. Sebagai contoh, dalam kajian kes di ladang terbuka, pada peringkat = 1, purata GR (T) di seluruh 6 bulan didapati lebih tinggi pada masa-masa malam berbanding dengan matahari dan keadaan mendung, manakala pada peringkat = 2 hingga 5, keadaan matahari mempunyai nilai purata tertinggi bagi GR(T). Hasil daripada kes kajian yang kedua menunjukkan perbezaan yang signifikan antara tiga persekitaran di puncak-jam bagi keperluan tenaga. Ia adalah diperhatikan bahawa pada suhu antara 20 °C hingga 30 °C, RH di antara 80% dan 100%, dan VPD antara 0.1kPa hinnga 1.2kPa, ketiga-tiga persekitaran yang hampir sama menyediakan keadaan pertumbuhan yang sama bagi tomato, walaubagaimanapun, semakin suhu mula meningkat melebihi 30 °C, perbezaan dalam persekitaran mula berkembang. Dengan mengambil kira semua keputusan, pendekatan yang dicadangkan boleh digunakan untuk menilai mana-mana persekitaran untuk pengeluaran tomato, dan untuk menyediakan keputusan pengurusan seperti kecekapan penjadualan, mencari tempat-tempat yang paling sesuai di negara untuk pembinaan sistem CEPP, penilaian kos, ramalan puncak-jam khusus keperluan tenaga dan penilaian risiko yang berkaitan dengan setiap tugas.

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

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This is to confirm that:

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CHAPTER 1

INTRODUCTION

1.1. Background

The increasing world population has changed food production scenario over the last decades. Land area in 91 developing countries, which is not in use for crop production is 2.4 times greater than the area in use (FAO, 2012). Since the available land cannot be increased, controlled environment plant production systems (CEPPS) has been employed as a solution to make more efficient use of space in hands. High demands for quality agricultural product necessitates practicing various methods of modern technologies including automation and mechanization in different scopes of CEPPS. A modern commercial CEPPS is designed to provide high yields at low expenses, and to keep production competitive through automatic control of the environmental parameters, such as air temperature, relative humidity (RH), light level and Carbon Dioxide (CO_2) concentration. This can be quiet challenging due to the lack of information and the complexity of the dynamic system that is influenced by changes of internal and external factors (i.e., changes in external wind speed or temperature which affects the RH of inside environment). In contrast to cold arid climates, the main objective of CEPP in TL is not to provide a warm-humid atmosphere, but to protect crop against instabilities of external conditions, such as heavy seasonal rainfalls, typhoons, extreme solar radiation, high temperature, high relative humidity (RH), disease, insects and birds. Insufficient production of tomato in the scarce highlands of Malaysia requires additional development of horticulture facilities to move into lowlands. The crop cultivation in TL environments by using the enhanced agricultural machine has not reached the optimal crop production as crop is still subjected to various stresses such as heavy rainfall, insects and extreme solar radiation. The high temperature and ambient RH are major issues in providing ideal environmental condition. In addition, investigation of several plant production sites in TL Malaysia revealed that evaporative cooling in the form of misting, pad-and-fan, and swamp cooling are currently utilized in major commercial CEPPS in Malaysia. It was also observed that these systems have not reached their optimal potential due to inefficient methods of manipulating crop growth microenvironments.

Plant-based engineering have changed from basic structures to advanced controlled environments for optimizing the productivity of plants and human labor. This has been a big field of study for many years, however, much work has been done for colder climate conditions as oppose to hot climates. Recently, researchers and growers have become very interested in this line of research in subtropical and tropical conditions. New concepts for CEPPS has been introduced and developed in the works of Ting, (1999); Ting et al., (2002) and Ting, (2013). Modern controlled environment bio-production systems are required to exhibit integration of automation, biological culture requirements, and environmental control through the concept of phytomation and Automation-Culture-Environment oriented SYStems analysis (ACESYS) as defined by Ting et al., (2002) and Ting, (2013)). Although this is a quiet challenging task due to the lack of information and complexity of the dynamic system that is influenced by changes of internal and external factors, but the ability of management decisions to influence such system can embrace uncertainties through modeling and integrated learning approach. Several uncertainties with CEPPS includes climate variability and environment response (ER), inadequate knowledge or defective understanding of the system states and resources, and lack of information about plant-and-environment interactions and the relationships between biological and ecological system.

One of the main factors to be considered with CEPPS in tropical lowland (TL) environments is the sustainability of operations and supply chain by utilizing available resource management. Ting, (2013) states: "the purpose of object-oriented approach in CEPPS is to develop a set of foundation classes that can be used to effectively describe the components of closed plant production systems". This requires comprehensive understanding of the interaction between crop's growth response (GR) and environment characteristics. Peer-reviewed published literatures define tomato's (*Lycopersicon Esculentum*) growth response as individual functions of air-temperature and relative humidity (RH) at five different growth stages (GS) and light conditions (sun, night, cloud). The convolution of several possible scenarios and combination of culture classes (climate control parameters) and objects (tomato crop at different GS) in this scheme necessitates computer-based analysis program within a systematic framework approach such as adaptive management (Figure 1). The flexibility of such framework depends on its database to work with different culture classes and objects by which many specific scenarios may be modeled and analyzed.

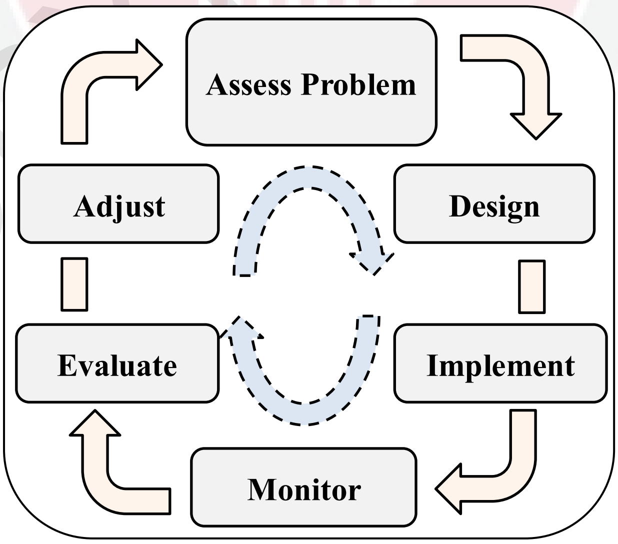

Figure 1. Diagram of the adaptive management process

Adaptive management framework (AMF) concept is a suitable tool for defining and determining foundation classes and objects in bio-production systems like CEPPS. Diagram of AMF as explained by Williams et al. (2009) and Whicker et al. (2008) is shown by Figure 1. The steps in the process are shown by rectangular, the arrows are the direction of the process, and the central spiral highlights the goal of arriving at a compromising decision based on a shared set of objectives developed through the iterative process. The principles of adaptive management (Figure 1) suggests using the best available knowledge to design and implement management plans, while establishing an institutional structure that enables learning from outcomes to adjust and improve future decision making (McLain and Lee, 1996). It carefully monitors the possible outcomes of the system to advance scientific understanding and help adjust policies or operations as part of an iterative learning process. This structured approach is an efficient method in developing decision support tools for systems design, management, and operation by recognizing the importance of natural variability in contributing to ecological resilience and productivity.

1.2. Problem Statement

Tomato has been grown successfully in the highlands of Malaysia but the production is insufficient to meet the large market. This necessitates additional development of horticulture facilities to move into lowlands, which has less favourable climate for greenhouse cultivation, due to the problems associated with high temperature and relative humidity and lack in appropriate control system and management strategy for the crop growing micro-environment. Investigation of several crop production sites in tropical lowlands (TL) of Malaysia revealed that CEPPS, mostly imported from Australia and the Netherlands, are operating on traditional controls with evaporative cooling systems (misting or high-pressure fog and pad-and-fan) and without proper modifications and adaptation for TL environments. It was found that greenhouse production in these regions has not reached its optimum potential, resulting average tomato yield of 80 tons/ha.

According to the United Nations Food and Agricultural Organization (FAO, 2012) reports, good commercial yield for open-field tomato is between 45 to 65 metric tons per hectare (tons/ha), and for greenhouse production is between 400 to 600 tons/ha. Total world production of tomato in 2012 has been 161,793,834 tons out of which Malaysia produced 135,010 metric tons resulting in 0.083% of the total (Figure 2), and world rank of 74 between 122 tomato producer countries (Indonesia, with the same climate condition, is producing 887,556 tons, about 6.5 times more than Malaysia, with the world rank of 22^{nd}). In 2012, combined average field and greenhouse yields of tomato in Malaysia was reported 109 tons/ha, leading to 351.5% increase in production quantity and 275.8% in yields compared to 2009 statistics (FAO, 2012).

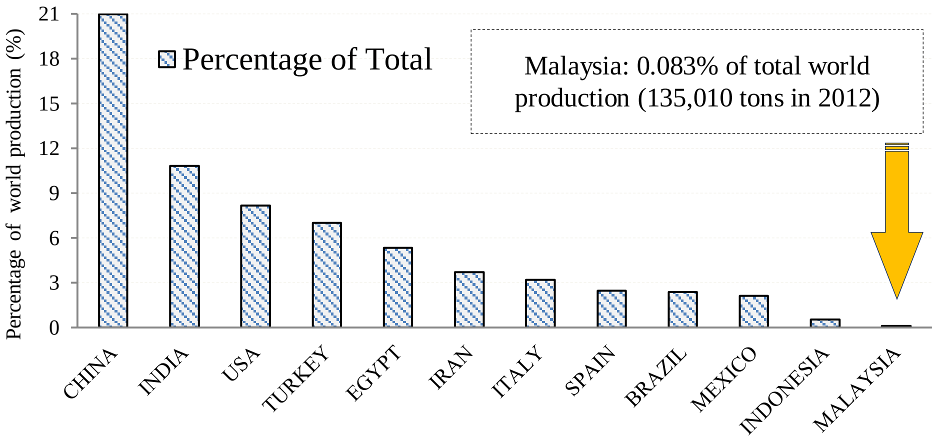

Figure 2. Percentage of total world production of tomato in the top 10 countries, Malaysia (world rank 74) and Indonesia (world rank 22)

While utilization of CEPPS technology under TL condition might seem redundant for conventional crops, there are still a number of complications that prevent a successful open-field production. These include extreme winds, seasonal storms and heavy rainfalls or even occasional water shortage, beside invasion of pests and diseases (Figure 3). In the other hand, major concern with CEPPS under TL condition is the crop stress due to the ambient high temperature, leading to confined air with high VPD that reduces plant evapotranspiration rate and cause production failure (Figure 4).

Figure 3. Heavy seasonal rainfalls and drainage problem in TL Malaysia, a constraint for open-field production

Figure 4: Perished cabbage in a local greenhouse in TL Malaysia, an example of improper environmental control, resulting crop damage and production failure

1.3. Research Objectives

The overall objective of this research was to design and implement an adaptive management framework that provides comprehensive evaluation of different environments (open-field and closed-field) for production of tomato. Major specific objectives were as follow:

1. Design and development of the framework (Software and Hardware)
2. Monitoring open-field and closed-field environments in tropical lowland condition for preliminary statistical inferences
3. Development of Growth Response Functions for Vapor Pressure Deficit
4. Development of environment response model
5. Determining Probability of achieving successful production
6. Development of optimization toolbox

1.4. Research scope

This research is about probabilities; optimization and responses associated with plant production environments. Profitability and investment returns of a modern CEPPS are tightly linked to site-selection, optimal control and risk assessment of management options. An adaptive management framework was designed, developed and introduced in this research to respond to the needs of modern CEPPS managers with an iterative processing tool that acknowledged complexity and uncertainty, and to help manager's difficulty in understanding the systems' dynamics and plant's responses. The concentration of the research is on tomato; however, the framework database can be modified to be used with different crops provided that their growth response functions are available. The two case studies (open-field and closed-field plant production environments) that were carried out are meant to demonstrate practical application of the framework and the proposed concepts for sample environments in tropical lowlands conditions of Malaysia; however the application of this framework is not limited to specific environment or climate condition. The framework can be used as an independent tool to investigate growth response and environment responses for any plant production system. The concentration of analysis modules is on the effects of temperature, RH, vapor pressure deficit (VPD) and their interaction in different light condition. Other parameter affecting plant's life, including carbon dioxide (CO_2), soil condition and PH level were not in the scope of this study. This research is not about thermodynamic analysis, instrumentation control, or plant physiology. The framework was implemented in MATLAB® programming language through coding of various main and sub-functions stored as `m-files`. It should be noted that the algorithms and codes can be easily modified for implementation in other computing languages which was not in the scope of this study.

1.5. Research contributions

This study contributes to the knowledge-based information. It provides a systematic process of incorporating new and existing knowledge that can be used in developing management decisions for achieving optimum environment-and-growth response by CEPPS growers of tomato in TL Malaysia. The present AAF was designed to allow production managers to ask "what-if" type questions for further quantitative inclusion and avoid possible detriment of action. It also provides an in-depth rigorous analysis tool for decision making or decision procrastination when facing uncertainties. It can help for enhancing scheduling efficiency, and guiding investments through different simulated scenarios that are based on information analysis to support optimal restoration strategies. Some of the specific application includes (but not limited) the following:

- ✓ Integrated energy efficient strategies in closed-field production of tomato
- ✓ Conclude some unique and new information and knowledge that provides valuable insight to Malaysian growers and beyond
- ✓ Understanding limitations and balancing between input and output expectancies
- ✓ Improved technology and increasing returns
- ✓ Provide business attraction for local investments and workers by minimizing energy requirements and eliminating tedious tasks operations
- ✓ Increase production quality and quantity to satisfy market demand
- ✓ Technology adaptation by keeping balance between fixed and flexible automation for various crop production

The outcome of this research can contribute to other crop models that estimates plant responses to the environment, it can be used in task planning algorithms for hierarchical decomposition of climate management as described by Albright, (2001), in decision support systems with application for dynamic greenhouse climate control strategies (Körner and Straten, 2008), and in economic models of tomato for energy conservation (Short et al., 1980) and energy efficient greenhouse crop productions (Short et al., 2002).

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