OPTIMIZATION OF TAILOR-MADE FERTILIZER FORMULATION AND EXPERIMENTAL VALIDATION FOR EGGPLANT AND TOMATO

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DEDICATION

This thesis is dedicated to my parents and husband for their endless love, encouragement, and continuous support. I could not have completed my thesis without them. It is also dedicated to my main supervisor for her guidance, patient, and faith.

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ABSTRACT

Population growth in Malaysia has led to continuous demand for food as well as fertilizer production. It has become a consistent challenge to increase plant production with high profitability to sustain plant growth and yield. Chemical fertilizers are preferable to provide optimal nutrient balance. Its consistent nutrient demand for growing healthy plants is needed to avoid nutrient deficiency and toxicity. Thus, a proper fertilizer formulation for tropical plants needs to be developed for efficient fertilizer use, cost effectiveness and reduce environmental pollutions. Therefore, a systematic methodology to design fertilizer formulation for tropical plant is developed and reported in this study using computer aided approach that included three specific objectives. Objective 1 is to establish the plant nutrient requirement and fertilizer component databases. The databases comprised of 18 plants and 20 fertilizers data documented in Microsoft excel that included the plant requirements by different types of plants, fertilizer market prices, fertilizer nutrient contents, fertilizer dosage by growth stages and irrigation scheduling. Objective 2 was to develop a systematic methodology to design a fertilizer using computer-aided approach. The fertilizer design was formulated as a linear optimization problem with objective function to minimize fertilizer cost subjected to plant nutrient requirements. The optimization problem was translated into mathematical models that comprised of a linear objective function and constraints and solved using linear programming with MATLAB®. The fertilizer design methodology was applied for one case study only, which was the formulation of fertilizer for eggplant. The obtained fertilizer formulation was verified using manual calculation with aid of Microsoft excel to ensure the models were valid. The results from MATLAB® gave similar fertilizer cost that fulfilled the plant requirements as compared to the manual calculation using Microsoft excel. Objective 3 was to verify the performance of the designed fertilizer formulations obtained from objective 2 by analyzing the growth and yield of plants. However, due to time constraints, only eggplants and tomatoes were selected to be tested. The experimental procedure included the preparation of seeds, medium, automated irrigation system, fertilizer, seedling transplant, data collection and plant growth observation. The measurement recorded were number of flowers, height of plant, number and weight of fruits. For eggplant, the formulated fertilizer (FF) cost was 16% cheaper than the commercial fertilizer (CF) with higher cumulative number of eggplant flowers, higher average height of plant stem and higher cumulative number of eggplants. In tomato experiment, the cost of formulated fertilizer was 4.6% lower than the CF with insignificant change in soil pH, higher height of tomato plant until the 4th week after transplanting and slightly lower cumulative yield of tomato plants. Overall, the FF formulation presents better performance and plant growth with high yield and cost effective as compared to the CF formulation.

ABSTRAK

Peningkatan. populasi penduduk di Malaysia telah menyebabkan permintaan berterusan terhadap makanan serta pengeluaran baja. Ia menjadi cabaran yang konsisten untuk meningkatkan pengeluaran tanaman dengan keuntungan yang tinggi untuk mengekalkan pertumbuhan dan hasil tanaman. Baja kimia adalah lebih baik untuk menyediakan keseimbangan nutrien yang optimum. Permintaan nutrien yang konsisten untuk tanaman yang sihat diperlukan untuk mengelakkan kekurangan dan keradangan nutrien. Oleh itu, rekabentuk baja yang bersesuaian untuk tumbuhan tropika perlu dibangunkan bagi pengunaan baja yang cekap, kos yang efektif dan mengurangkan pencemaran alam sekitar. Oleh itu, kaedah yang sistematik untuk mereka bentuk formulasi baja untuk tumbuhan tropika dibangunkan dan dilaporkan dalam kajian ini menggunakan pendekatan berbantukan komputer yang merangkumi tiga objektif spesifik. Objektif 1 adalah untuk mewujudkan pengkalan data bagi keperluan nutrien tanaman dan komponen baja. Pangkalan data terdiri daripada 18 tanaman dan 20 jenis baja yang disimpan dalam Microsoft excel yang merangkumi keperluan nutrien mengikut jenis tanaman yang berbeza, harga pasaran baja, kandungan nutrien baja, dos baja mengikut peringkat pertumbuhan serta jadual pengairan. Objektif 2 adalah untuk membangunkan kaedah yang sistematik untuk mereka bentuk baja menggunakan pendekatan berbantukan komputer. Reka bentuk baja dirumus sebagai masalah pengoptimuman berkadar terus dengan fungsi objektif untuk meminimumkan kos baja mengikut keperluan nutrien tumbuhan. Masalah pengoptimuman diterjemahkan dalam model matematik yang terdiri daripada fungsi objektif yang berkadar terus dengan kekangan, dan diselesaikan menggunakan pengaturcaraan berkadar terus menggunakan MATLAB®. Kaedah reka bentuk baja yang dibangunkan, digunapakai untuk satu kajian kes sahaja iaitu reka bentuk baja bagi terung. Formulasi baja yang diperolehi disemak menggunakan pengiraan manual dengan bantuan Microsoft excel untuk memastikan model adalah sah. Hasil daripada MATLAB® memberikan kos baja yang sama yang memenuhi keperluan tanaman berbanding pengiraan manual menggunakan Microsoft excel. Objektif 3 adalah untuk mengesahkan prestasi formulasi baja yang diperolehi daripada objektif 2 dengan menganalisis pertumbuhan dan hasil tanaman. Namun, disebabkan oleh kekangan masa, hanya tanaman terung dan tomato sahaja dilaksanakan ujikaji. Prosedur ujikaji termasuk penyediaan benih, media, sistem pengairan automatik, baja, pemindahan anak pokok, pengumpulan data dan pemerhatian pertumbuhan tanaman. Pengukuran yang direkodkan adalah bilangan bunga, ketinggian tumbuhan serta bilangan dan berat hasil sayuran. Untuk terung, kos baja (FF) yang dirumus adalah 16 % lebih murah daripada baja komersial (CF) dengan bilangan bunga terung yang lebih tinggi, ketinggian purata batang tumbuhan yang lebih tinggi dan bilangan buah terung yang lebih tinggi. Dalam ujikaji tomato, kos baja yang dirumus adalah 4.6 % lebih rendah daripada CF dengan perubahan yang tidak ketara dalam pH tanah, ketinggian tumbuhan tomato yang lebih tinggi sehingga minggu ke-4 selepas pemindahan dan sedikit hasil kumulatif tomato. Secara keseluruhan, formulation FF memberikan prestasi dan pertumbuhan tanaman yang lebih baik dengan hasil yang lebih tinggi dengan kos yang efektif berbanding dengan formulasi CF.

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LIST OF ABBREVIATIONS

ADP	-	Adenosine diphosphate
ATP	-	Adenosine triphosphate
CEC	-	Cation Exchange Capacity
EC	-	Electroconductivity
FAO	-	Food and Agriculture Organization
DGP	-	Gross Domestic Product
GACSA	-	Global Alliance for Climate-Smart Agriculture
GAMS	-	General Algebraic Modelling System GAMS
HDPE	-	High-density polyethylene
IFA	-	International Fertilizer Association
KeTTHA	-	Ministry of Energy, Green Technology and Water
LP	-	Linear programming
MARDI	-	Malaysian Agricultural Research and Development Institute
MATLAB®	-	Matrix Laboratory
PVC	-	Polyvinyl chloride
SDGs	-	Sustainable development goals
SSR	-	Self-sufficiency ratio
WFO	-	World Farmer Organization

LIST OF SYMBOLS

A_{eq}	-	Coefficient matrix
A_{error}	-	Starting error matrix
A_{tab}	-	Adding constraints
B	-	Boron
B_{eq}	-	Independent terms
C	-	Carbon
C	-	Cost of fertilizer sources
C_R	-	Required concentration
C_{opt}	-	Optimal concentration
Ca	-	Calcium
Ca^{2+}	-	Calcium ion
Cd	-	Cadmium
CO_2	-	Carbon dioxide
Cu	-	Copper
Fe	-	Ferum
Fe^{2+}	-	Ferrous ions
Fe^{3+}	-	Ferric ions
H	-	Hydrogen
Hg	-	Mercury
$H_2PO_4^-$	-	Primary orthophosphate ion
HPO_4^{2-}	-	Secondary orthophosphate ion
H_3BO_3	-	Boric acid
K	-	Potassium
K_2O	-	Potassium oxide
linprog	-	Linear programming solver
M	-	Concentration of nutrient
Mg	-	Magnesium
Mn	-	Manganese
Mo	-	Molybdenum
MOP	-	Muriate of potash

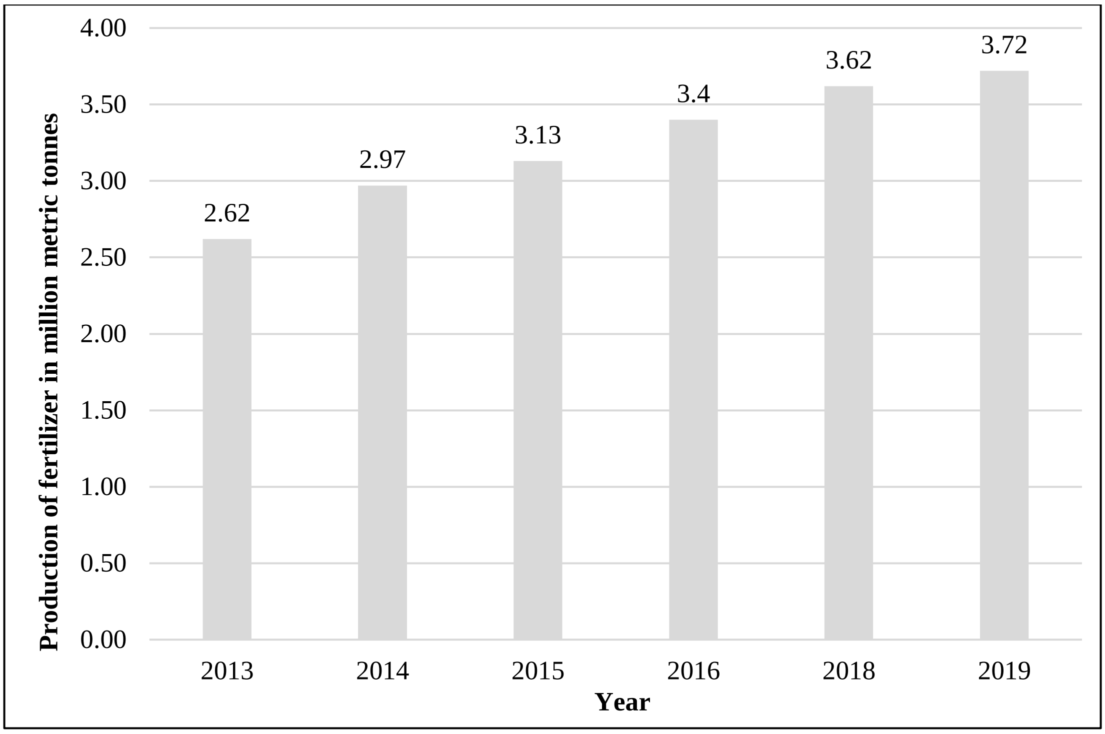

Figure 1.2 Fertilizer production in Malaysia for year 2013-2019 (Muller, 2020)

Fertilizer contains chemical nutrients that are divided into two nutrient categories which is macronutrient and micronutrient. All the nutrients fulfil specific functions in plants and the optimum supply of essential nutrient for growing healthy plants are needed to avoid deficiency and toxicity. As a primary macronutrient, it plays a major role in global food production where macronutrients are used in large quantities. Micronutrients are required in very small amounts but are beneficial for balanced nutrition of plants. The micronutrients support the biological functions of plant as their deficiency leads to stunted growth and delayed maturity. Table 1.1 shows the essential plant nutrients which is classified into mineral or non-mineral, and primary or secondary nutrient. All the nutrients are supplied to the plant either in the elemental form or fertilizer form.

The most common fertilizers used are urea, ammonium sulphate, calcium ammonium nitrate, phosphate rock, super phosphate, ammonium phosphate, potassium chloride, potassium sulphate, nitrogen (N)-phosphorus (P)-potassium (K), NP and PK compound fertilizers (Food and Agriculture Organization, 2004). Also, chemical fertilizers are being widely used for more than 90% of fertilizer consumed by all type of farming system in Malaysia (Food and Agriculture Organization, 2004). However, inappropriate application of chemical fertilizers and pesticides in Malaysia is growing concern by the government due to the impacts on the environmental damages and food safety issues. In contrast, organic fertilizer has many limitations as such it contains low nutrient concentration, large volumes to transport, often inconsistent quality and the organic material needs to be decomposed to release nutrients. Thus, chemical fertilizers are preferable to provide an optimal nutrient balance and consistent nutrient demand

Table 1.1 Essential plant nutrients and their chemical symbol (University of Tennessee, 2012)

Plant nutrient	**Symbol**	**Classifications**
Carbon	C	Non-mineral
Hydrogen	H	Non-mineral
Oxygen	O	Non-mineral
Nitrogen	N	Mineral, primary macronutrient
Phosphorus	P	Mineral, primary macronutrient
Potassium	K	Mineral, primary macronutrient
Calcium	Ca	Mineral, secondary macronutrient
Magnesium	Mg	Mineral, secondary macronutrient
Sulphur	S	Mineral, secondary macronutrient
Zinc	Zn	Mineral, micronutrient
Chlorine	Cl	Mineral, micronutrient
Boron	B	Mineral, micronutrient
Molybdenum	Mo	Mineral, micronutrient
Copper	Cu	Mineral, micronutrient
Iron	Fe	Mineral, micronutrient
Manganese	Mn	Mineral, micronutrient
Cobalt	Co	Mineral, micronutrient
Nickel	Ni	Mineral, micronutrient

The amount of fertilizer supply affects the plant growth which leads to maximum yield, plant deficiency, or causes toxicity. The relationship between plant growth and the fertilizer supply are illustrated in Figure 1.3. Every plant needs sufficient nutrient to sustain from deficiency. Thus, optimum level of nutrients is required to be supplied to achieve maximum yield, healthy plant growth, sustainable environment and cost efficient. However, the fact that common practices by farmers to supply excess fertilizer that leads to toxicity. The conventional method is varying in fertilizer supply, higher cost and causes higher possibilities for toxicity to the plant, human and environment. Overall concept of the plant growth relationship with the nutrient supply are supported by "Liebig's Law of the Minimum" which stated that increasing the quantity of abundant nutrients did not increase plant growth but increased the quantity of limiting nutrient (Centre for Rural Agricultural Training and Entrepreneurship Handbook, 2019). It means that the plant growth will be completely unhealthy if one of the plant nutrients is deficient even though the other nutrient available are abundant. Other than that, the plant's growth rate, size and overall health are depending on the amount of essential nutrient received in which the concept is a general model of limiting factors for all organisms including the limiting effects of excess chemical nutrients and other environmental factors (Allaby, 2010).

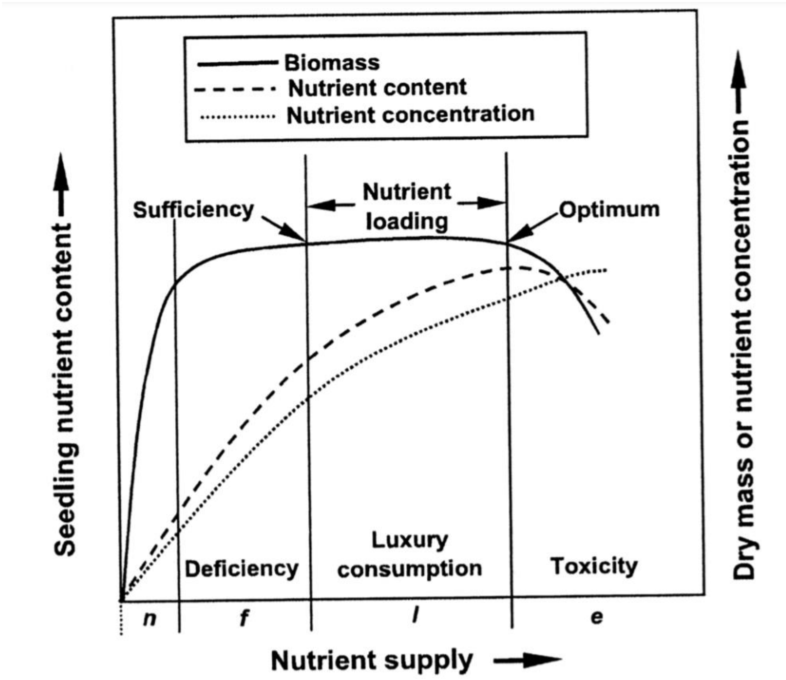

Figure 1.3 Plant growth relationship with the nutrients supply (Imo, 2011)

Excess fertilizer can cause toxicity and cause bad environmental impacts. Thus, fertigation system can precisely supply fertilizers and overcome the excessive fertilizer wash out (Pérez-Castro, 2017). Efficient system is needed in order to manage a proper plant nutrient requirement, fertigation cost, water usage and fertigation system. The system is including the management of fertilizer requirement, water needed, cost, time, labour, and environmental impacts. The fertigation management application provides agricultural users with a computer-aided approach to obtain optimized parameters related to the fertigation process which is a friendly and easy to-be-use interface.

Prior to this, there is several computer-aided software in the market that can assume the fertilizer recommendation to make up the right amount of nutrients and selects the least costly combination of fertilizer sources in open field, tunnel, and greenhouse. Recently, the computer-aided software with information system and large amount of data led to increase production, producing quality food with more environmentally practices and saving money (Saiz-Rubio and Rovira-Mas, 2020). More importantly, the key to agriculture is agricultural production because of the significant increased price of their essential raw materials and the trends is expected to continue in future (Food and Agriculture Organization of the United Nations, 2012).

1.2 Problem Statement

Fertilizer consumption is increasing every year due to the demands in agriculture production. In fact, the fertilizer is needed by every plant for growth as every plant has its own nutrient uptake at different levels of growth stages. Conventionally, farmers and small holders formulate the fertilizer requirement by experimental work, previous experiences, or suggestion from other farmers. The conventional method of determining fertilizer formulation may vary, time-consuming, higher cost, nutrients excess that affects the plants yields, health and causes more high environmental impacts. Ministry of Energy, Green Technology and Water (KeTTHA) has emphasized the environmental protection since year 2009 through the promotion and support of high impact green technology research.

According to Centre of Education and Training in Renewable Energy, Energy Efficiency and Green Technology of Malaysia (2018), compost fertilizer application is one of the green technology solutions for agriculture and forestry sector. Also, the compost fertilizers are expected to enhance nutrient quality, plant irrigation management and improved planting practise by using rainwater to water plants.

Nevertheless, the organic fertilizers are not readily available to plant as it requires six weeks or more for the organic raw material sources to be broken down into organic form by soil bacteria (Centre of Education and Training in Renewable Energy, Energy Efficiency and Green Technology of Malaysia, 2018). Besides, they are relatively low in nutrient content, absence of major plant nutrients and need large volume of organic fertilizers to provide enough nutrient for plant growth (Gupta and Hussain, 2014). Despite this, large volume and long-term application of compost may result in the accumulation of salt, nutrients, heavy metals and adversely affect the plant growth as well as the soil organisms and water quality.

Therefore, the use of chemical fertilizers is now considered a necessary agricultural technology (Savci, 2012). The main chemical fertilizer imports to Malaysia in 2013 is muriate of potash, followed by rock phosphate, ammonium sulphate and magnesium sulphate (Fertilizer Industry Association of Malaysia, 2015). However, some of the fertilizers in Malaysia are imported from other countries such as China, Germany, Russia, and Canada to meet the future demands. Moreover, fertilizer prices are projected to rise 2.2 percent in 2020, after an expected 0.6 percent loss in 2019 (World Bank, 2018). Thus, a proper fertilizer formulation needs to be developed for efficient fertilizer use, irrigation water level controls, cost effective and environmental protection for maximum plant growth.

Prior to the disadvantages of conventional method of fertilizer usage, there is numerous computer-aided approach in the market to make easier the user’s task (Hopkin et al., 2014) but only a few of them offer the possibility to calculate the optimal fertilizer by taking account of the nutrient uptakes by plants and computing the total fertilizer cost. Although there is some computer-aided software in the market, the focus is only applicable to the plants that the software’s countries are built-in. This software is lacking on the tropical plants data which have its own nutrients requirement, soil types, climatic conditions, and different cost aspect such as the fertilizer market prices. Therefore, an efficient method for fertilizer formulation needs to be studied. Also, the efficient use of water and fertilizers is a major aim of all agricultural systems should be designed in terms of saving money and time that led to more profitable production.

1.3 Research Objectives

The main objective of the study is to develop a systematic methodology to design fertilizer formulation for tropical plants using a computer-aided approach. In order to achieve the main objectives, the sub-objectives of the study are identified as follow:

1. To establish the plant nutrient and fertilizer management database.
2. To develop a fertilizer design methodology using a computer-aided approach.
3. To verify the performance of designed fertilizer formulation by analyzing the plant growth and yield of two selected plants.

1.4 Research Scopes

The scope of this research is divided into three categories. Firstly, the plant database consists of nutrient requirement for 18 plants that are suitable for tropical weather. While for the fertilizer database listed the locally available fertilizer sources and fertilizer prices which obtained from selected local markets during the study period. The prices are illustrated in RM/kg. The nutrient requirement in fertilizer formulation includes macronutrients and micronutrients such as N, P, K, Ca, Mg, S, B, Fe, Mo, Cu, Mn, and Zn. In designing a fertilizer design methodology using a computer-aided approach, the fertilizer formulation design is to minimize the cost of fertilizer which is subjected to the nutrient requirements by plants using linear programming (LP). The optimization problem is coded and solved using MATLAB®.

Lastly, the performance of designed fertilizer formulation is verified using two plants from different plant families. The selected case studies are formulation of fertilizer for eggplant and tomato. The case studies are conducted at N29, School of Chemical and Energy Engineering, Faculty of Engineering, Universiti Teknologi Malaysia, 81310 Johor Bahru, Johor, Malaysia for 2 years. The plants are planted in a greenhouse using fully water-soluble fertilizers and fertigation system set up. The medium is the mixture of cocopeat and rice husk ash in the volume ratio of cocopeat: rice husk ash by 7: 3. Study conducted by Awang et al. (2009) proves that a mixture of 70% cocopeat and 30% rice husk ash improves the growth and development of cockscomb. Moreover, there are many studies use the medium of cocopeat and rice husk ash in the ratio of 7:3, which are studies by Mohammud et al. (2016), Rusmana and Yuwati (2016), Yi (2012) and Roseli et al. (2011).

1.5 Research Significance

This research involves the establishment of plant nutrient and fertilizer database for tropical plants in Malaysia. The databases will contribute towards farming industries as the local agriculture board may use this data to analyses, compare and interpret the data into a systematic reference to their decision making in a short period of time. The databases can be useful for quick reference for farmers as well as agricultural entrepreneurs at any time at their place as the database is ready accessible and follow the local market fertilizer prices.

Meanwhile, the fertilizer recommendation using a computer-aided approach can be used by many users. Many companies can use the fertilizer formulation to produce fertilizer products with the specific nutrient requirement for tropical plants and produce money. There is recommendation for the number of plots, volume of irrigation fertilizer, size of tanks, distances between or within plants depending on the area of plantation used. The industries can convince the farmer or other parties regarding the fertilizer requirement management practice that may affect the social and environmental impacts. Also, the fertilizer formulation can improve the growth rate and yield of tropical plants in terms of saving time to calculate manually, saving total fertilizer cost, and provided fertilizer requirements usage. Other than that, the computer-aided approach fertilizer formulation can allow the industry to identify the gap of improvement and weaknesses of agriculture and environmental effects at the same time.

Moreover, the optimization of fertilizer formulation is further verified for tropical plants such as eggplant and tomato. The experimental work studies the performance of plant growth and their yield. It can be used for any farmers, agriculture entrepreneurs or related agencies to recommends the ideal fertilizer formulation that saves up the fertilizer costs and compare the performance with existing data. Also, the users can monitor the performance of the growth rates and yield for their internal benchmarks and compare their performance with the existing fertilizer availability formulation. Thus, the plant nutrient and fertilizer database should be established in this research as well as the developed fertilizer design methodology using computer aided approach.

1.6 Thesis Outline

This thesis consists of five chapters. Chapter 1 gives an overview of fertilizer demands toward food sufficiency in increasing population growth and the relationship of nutrient requirement with the fertilizer applied for maximize yield. This chapter elaborates the problem statement, research objectives, scope and its significant which aims to develop a systematic methodology to design fertilizer formulation for tropical plants using a computer-aided approach as well as to verify the performance of designed fertilizer formulation by analyzing the plant growth and yield of two selected plants.

Chapter 2 summarize the comprehensive literature review and fundamental theory of plant growth and nutrient uptakes. The topic highlights are on chemical fertilizer, plant nutrients requirement and growth, deficiency symptoms and toxicity, agriculture modelling and simulation, and experimental method for fertilizer formulation design. At the end of this chapter, research gaps were highlighted to justify the research needs.

Chapter 3 is divided into two parts, first part describes the methods for designing fertilizer formulation using computational-aided methodology, while the second part of the methodology explains the experimental set up for the planting of eggplant and tomato. A flow chart in model-based fertilizer formulation design is shown in this chapter. The methods in designing fertilizer formulation are divided into two stages which are model-based fertilizer formulation and application of the model for the real case study using an experimental approach. In Stage 1, plant nutrient and fertilizer database are presented, the development of fertilizer design methodology is elaborated, optimization problem application using MATLAB® and the validation of formulated fertilizer methodology is performed. Moreover, Stage 2 explains in detail about the performance evaluation of the formulation methodology.

Chapter 4 provides the discussion of the results obtained in Stage 1 and Stage 2 based on the three objectives. The establishment of plant nutrient and fertilizer databases are addressed in Section 4.2. The model development of fertilizer formulation methodology is illustrated in Section 4.3. In Section 4.4, a developed fertilizer design methodology is then validated using computer-aided approaches which are MATLAB® and the results were validated with manual calculation using Microsoft Excel. Then, the results of the optimization problem of fertilizer formulation on the eggplant and are compared. Section 4.5 demonstrates the performance of formulated fertilizer formulation in Section 4.4 over commercial fertilizer formulation on two tropical plants which are eggplant and tomato. The performance is measured in term of plant growth measured are the plant height, size of leaves, number of fruits and weight of fruit.

Finally, Chapter 5 summarizes the conclusion of the study and the recommendation for improvement in future studies.

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