UNIVERSITI PUTRA MALAYSIA

FIELD PERFORMANCE EVALUATION ON DYE-SENSITIZED SOLAR CELL MINI GREENHOUSE IN THE TROPICS

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By

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

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Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Master of Science

FIELD PERFORMMANCE EVALUATION ON DYE-SENSITIZED SOLAR CELL MINI GREENHOUSE IN THE TROPICS

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February 2021

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Faculty : Engineering

In many countries modern solar greenhouses that were developed by incorporating solar Photovoltaic (PV) (crystalline silicon based) into the agricultural greenhouses are currently being implemented. With this development, farmers will be able to generate income from both agricultural activity output and electrical generation. However, the most challenges manifested by PV greenhouses are to strike a balance between PV roofs and plants since conventional PV (Si based) is opaque to sunlight. The distribution of sunshades by PV panels above the greenhouse follows a linear correlation with the cover ratio. Therefore, semi-transparent DSSC; third generation of solar PV cells is the perfect choice in greenhouse application due to its unique characteristics such as various colour and transparency, versatility in scaling and low fabrication cost. In addition, DSSC's specific colour (determined by the dye) can serve as a plant growth regulator or photoselective shading that adsorbs and manipulates the greenhouse spectral irradiation. The Dynamic Dye-sensitized solar cell Mini Greenhouse (DDMG) has been developed and fabricated to maximize the use of light (PAR wavelength) that is important to the plant photosynthesis process, while the other wavelengths are used to generate electricity. The field test was carried out to determine DDMG's performance by means of examining Misai Kucing's sustainability within this prototype. To assess the effects and contributing factors, microclimate parameters such as temperature, relative humidity (RH), Vapour Pressure Deficit (VPD) and Photosynthetic Photon Flux Density (PPFD) were measured. To determine the feasibility of the DDMG, the experimental data were compared with the glass greenhouse as control. From the experiment and findings, it is observed that the performance of DDMG is related to internal microclimate greenhouse which is consequently affect the sustainability and growth of Misai Kucing cultivated in this prototype. From this analysis, semi-transparent shading of the DSSC reduces air temperature by 1.47°C and raises relative humidity by 10.91%. Moreover, the average VPD (1.07 kPa) for DSSC

greenhouse is an ideal for greenhouse. Unlike un-shaded greenhouse (control), the VPD is 1.63 kPa while maximum PPFD ranging from 1363.6 to 1798.4 µmolm-2s-1 which can cause plant stress. From an agronomic perspective, Misai Kucing cultivated under red DSSC shading tends to be slightly higher in branch number, size of leaves and total dry weight but slightly lower in plant height and stem diameter when compared with control greenhouse. Aside from the above, manipulation of spectral irradiation under red DSSC shading has been successfully achieved and demonstrated using a spectrometer. The results showed that spectral irradiance such as UV, blue and green were filtered out except red light (600-826nm) was transmitted through DSSC photo-selective shading. The DSSC modules generate a DC voltage, electric power, Fill Factor (FF) and efficiency with a maximum recording DC current of 0.119A, 2.081W, 1.148, and 2.907% respectively. This study enhances farming technology and creates knowledge gaps (by providing field measurement) and perspectives for policy makers and stakeholders in agro-PV industry for better decision making.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia
sebagai memenuhi keperluan untuk ijazah Master Sains

PENILAIAN PRESTASI TERHADAP RUMAH HIJAU MINI SEL SOLAR PEWARNA SENSITIZER DI TROPIK

Oleh

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Di pelbagai negara, rumah hijau solar moden yang dibangunkan dengan memasukkan Solar Fotovoltan (PV) (berasaskan kristal silikon) ke dalam rumah hijau pertanian sedang dilaksanakan. Melalui perkembangan ini, petani akan dapat menjana pendapatan dari kesemua hasil aktiviti pertanian dan juga penjanaan elektrik. Walau bagaimanapun, cabaran tertinggi ditunjukkan oleh rumah hijau PV adalah untuk mencapai keseimbangan antara bumbung PV dan tumbuhan kerana PV konvensional (berasaskan Si) adalah bersifat legap. Taburan cahaya matahari oleh panel PV di atas rumah hijau adalah mengikut korelasi linear dengan nisbah penutupan. Oleh itu, DSSC yang separa telus; sel PV solar generasi ketiga adalah pilihan yang tepat dalam aplikasi rumah hijau kerana ciri-ciri uniknya seperti terdiri daripada pelbagai warna dan ketelusan, fleksibiliti dalam penskalaan dan kos pembuatan yang rendah. Di samping itu, warna spesifik DSSC (ditentukan oleh pewarna) dapat berfungsi sebagai pengawalatur pertumbuhan tanaman atau pemilihan cahaya yang menyerap dan seterusnya memanipulasi penyinaran spektrum rumah hijau. Rumah Hijau Mini sel solar Pewarna Peka Dinamik (DDMG) telah dimajukan dan dibina untuk memaksimumkan penggunaan cahaya (panjang gelombang Radiasi Aktif Fotosintesis, PAR) yang penting untuk proses fotosintesis tumbuhan, sementara panjang gelombang yang lain digunakan untuk menghasilkan elektrik. Kajian lapangan dilakukan untuk menentukan prestasi DDMG dengan memeriksa kelestarian Misai Kucing dalam prototaip ini. Untuk menilai kesan dan faktor penyumbang, parameter mikroklimat diukur seperti suhu, kelembapan relatif (RH), Kekurangan Tekanan Wap (VPD) dan Kepadatan Fluks Fotosintetik (PPFD). Untuk menentukan kemungkinan DDMG, data eksperimen dibandingkan dengan rumah kaca (sebagai kawalan / rujukan). Dari eksperimen dan penemuan, diperhatikan bahawa prestasi DDMG berkaitan dengan rumah hijau mikroklimat dalaman yang akibatnya mempengaruhi kelestarian dan pertumbuhan Misai Kucing yang ditanam dalam prototaip ini. Daripada analisis ini, teduhan separa telus DSSC mengurangkan

suhu udara sebanyak 1.47 ° C dan meningkatkan kelembapan relatif sebanyak 10.91%. Lebih-lebih lagi, purata VPD (1.07 kPa) untuk rumah hijau DSSC adalah ideal untuk rumah hijau. Tidak seperti rumah hijau (kawalan) yang tiada teduhan, VPD adalah 1.63 kPa sementara PPFD maksimum antara 1363.6 hingga 1798.4 µmolm-2s-1 yang boleh menyebabkan tumbuhan stres. Dari perspektif agronomi, Misai Kucing yang ditanam di bawah naungan merah DSSC cenderung sedikit lebih tinggi pada jumlah cabang, bilangan daun dan jumlah kering daun tetapi sedikit lebih rendah pada ketinggian tanaman dan diameter batang jika dibandingkan dengan rumah hijau yang tiada teduhan (kawalan) Selain daripada perkara di atas, manipulasi penyinaran spektrum di bawah teduhan DSSC merah telah berjaya dicapai dan ditunjukkan dengan menggunakan spektrometer. Hasil kajian menunjukkan bahawa sinar spektrum seperti UV, biru dan hijau disaring kecuali cahaya merah (600-826nm) disebarkan melalui teduhan selektif foto DSSC. Modul DSSC menghasilkan voltan DC, kuasa elektrik, Faktor Pengisian (FF) dan kecekapan dengan arus DC rakaman maksimum masing-masing 0.119A, 2.081W, 1.148, dan 2.907%. Kajian ini meningkatkan teknologi pertanian dan mewujudkan jurang pengetahuan (dengan menyediakan pengukuran lapangan) dan perspektif untuk pembuat dasar dan pihak berkepentingan dalam industri agro-PV untuk membuat keputusan yang lebih baik.

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Last but not least, I beseech ALLAH to make all that I have assembled and written beneficial to other people who have read it and to benefit me and the Muslims as a whole with it.

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

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Date: 14 October 2021

Declaration by graduate student

I hereby confirm that:

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- this thesis has not been submitted previously or concurrently for any other degree at any other institutions;
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Declaration by Members of Supervisory Committee

This is to confirm that:

- the research conducted and the writing of this thesis was under our supervision;
- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) are adhered to.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AM 0	Air mass 0 spectrum (standard)
AM 1.5	Air mass 1.5 spectrum (global)
a-Si	Amorphous Silicone
AVP	Average Vapour Pressure
BIPV	Building Integrated Photovoltaic
CdTe	Cadmium Telluride
CFD	Computation Fluid Dynamic
DDMG	Dynamic Dye-sensitized solar cell Mini Greenhouse
DSSC	Dye-Sensitized Solar Cell
EPP1	Entry Point Project 1
ETP	Economic Transformation Program
EW	East-West
FiT	Feed in Tariff
FR	Far-Red
GDP	Gross Domestic Product
HAVs	Hybrid Agri-Voltaic showcase
HCP	Herbal Cultivation Parks
HVH	High Value Herbal
HVHc	High Value Herbal crops
LSSPV	Large Scale Solar Photovoltaic
NEM	Net Energy Metering
NIR	Near Infrared
NKEA	National Key Economic Area
NPV	Net Present Value

NRS	Netted Rain Shelter
NS	Netted Structure
NS	North-South
OPV	Organic Photovoltaic
OTTV	Overall Thermal Transfer Value
PAR	Photosynthetic Active Radiation
PE	Poly-Ethylene
PPFD	Photosynthetically Photon Flux Density
PV	Photovoltaic
PVC	Poly-Vinyl-Chloride
PVP	Photovoltaic Panels
R & D	Research and Development
RE	Renewable Energy
REA	Renewable Energy Act
RH	Relative Humidity
RIE	Radiation Interception Efficiency
ROI	Return-On-Investment
RSS	Rain Shelter Structure
SHS	Shading House Structure
Si-PV	Silicon Photovoltaic
STPV	Semi-Transparent Photovoltaic
SVP	Saturation Vapour Pressure
UV	Ultraviolet
VPD	Vapour Pressure Deficit

CHAPTER 1

INTRODUCTION

1.1 Overview

Due to the increasing population and energy consumption of the world, researchers and scientist are leaded to use alternative sources (such as solar, biomass, wind energy and etc.) to provide adequate amounts of food and energy technology. Additionally, climate change and limited water supplies have revealed that cultivation in protected greenhouse have become a favoured method of improving the agriculture sector. Greenhouse production is carried out in favourable climates condition while minimizing operating costs (Bot et al., 2005). Meanwhile, an important contribution to the efficient operation of modern greenhouses is energy supply. Hassanien, Li and Dong Lin (2016) conducted a survey of electrical energy consumption greenhouses at different countries. They estimated that in one year about 0.1 to 528 $kWhm^{-2}$/year electrical power was consumed per unit greenhouse area.

Most contemporary greenhouses typically depend on the fossil fuels and/or the use of electrical energy, whereby this traditional combustion of energy has been considered a major cause of greenhouse gas emissions. Kuang et al. (2016) reported that, about 90% of CO2 emissions come from fossil fuels, which greatly contributes to global warming and environmental degradation. Hence, renewable energy exploration is highly desirable in maintaining current greenhouse production (Wang et al., 2017).

The renewable energy in Malaysia is very striking for sustainable energy development. Renewable energy is energy derived from natural resources that are replenished unceasingly without harming the environment. In Malaysia, the most abundant renewable energy resources are the solar, biomass, and hydro energy. Figure 1.0 demonstrates usable renewable energy resources in Malaysia.

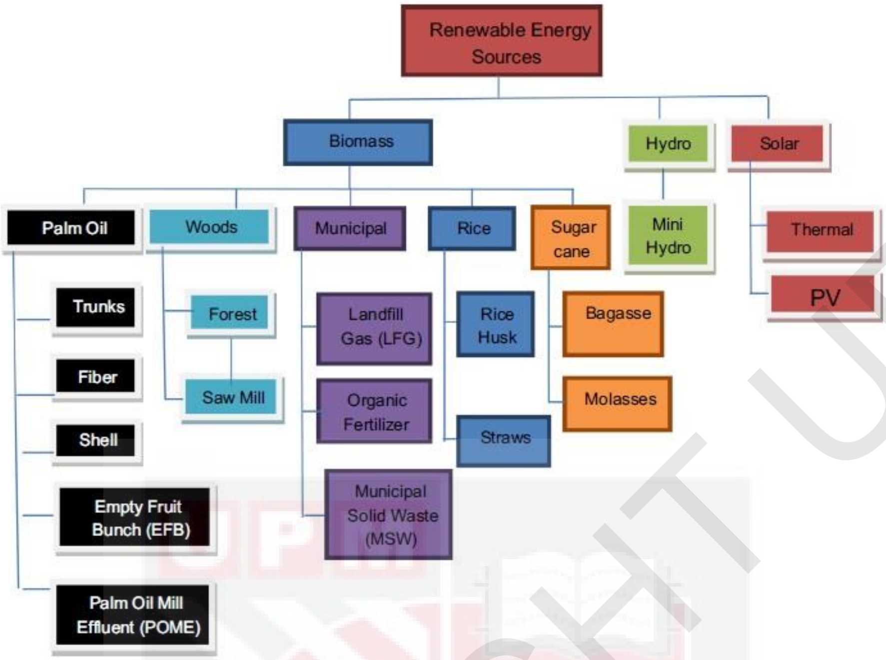

Figure 1.0: Malaysia's renewable energy potential for continuous energy supply (Petinrin & Shaaban, 2015).

Malaysia Government has planned to increase energy mix of the country from 2% to 20% in 2025. In helping to improve renewable energy (RE), photovoltaic (PV) or so-called solar energy plays a major role to increase the energy mix of Malaysia. Via an implementation scheme or program such as Feed in Tariff (FiT), Small Renewable Energy Program, Malaysia Building Integrated Photovoltaic Project, Large Scale Solar Photovoltaic (LSSPV), and Net Energy Metering (NEM), the Government of Malaysia has therefore taken numerous efforts to boost the percentage of renewables in the total fuel mix. Between those program as mentioned above, the cumulative value of RE by the FiT program are expected to achieved up to 11.5 GW by 2050 where major outcomes; 9GW is expected from solar PV as illustrates in Figure 1.1.

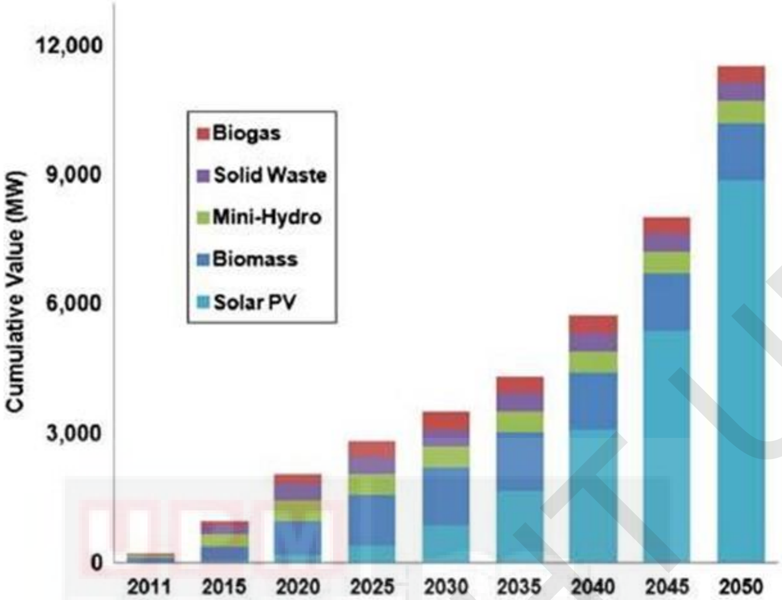

Figure 1.1: Renewable energy cumulative in Malaysia 2011 to 2050 (Muhammad-Sukki et al., 2014)**.**

Renewable energy sources such as solar energy can be an important role in Malaysia since Malaysia is located near to equatorial region where gets abundance of sunshine throughout the year. Moreover, such RE not beneficial to the environment like avoiding carbon emission; it also improve economics of RE technology and lower the cost of energy by avoiding fuel cost (Petinrin & Shaaban, 2015).

1.2 Research background

As fossil fuels experience dramatic decreases and their consumption contributes to spike in the global average temperature, the energy crisis is a main issue worldwide. As a result, discovering clean and sustainable energy resources is crucial. Solar energy technology is constantly moving forward, among renewable energy sources, to meet the challenges of growth, maintenance and deployment costs (Fadaeenejad et al., 2014).

Meanwhile, Malaysia is situated in the tropical climate-experiencing equatorial zone, which receives sun all year long (Ahmad et al., 2013). Electric power generation has become the most economically viable green resource through solar technology, or also known as PV technology, particularly in tropical countries (Effendy Ya'acob et al., 2013). Nevertheless, the major limitation of this technology, through the energy absorbed by the solar cells, is poor energy conversion efficiency relative to other alternative resources. In addition, its current usage is still restricted by the physical nature of non-transparent solar cells (first generation of solar cell; mono-crystalline silicon), and special arrangements and locations are required for field deployment.

While with some drawbacks, solar power is growing greatly for the present and future prospects. Since 2011 solar energy was being described as a new basis of contribution to economic development under the Economic Transformation Program (ETP) (PEMANDU, 2011). In addition, a strong emphasis is given to grow the share of renewables in the energy mix for achieving green growth for sustainability and resilience in the 11th Malaysian Plan (2016-2020). It is in line with the rapidly dropping price of PV technologies that will bring PV to grid parity with fossil-fuel generated electricity. As a result, the PV market is expected to rise very rapidly up to 2020 at a rate of 25 % per year. It converts into a global total installed capacity of 560 GW, with annual production of sales of 113 GW and RM 918 billion in 2020. This demand growth is anticipated to continue over the next few years, with solar energy generation is expected to increase to 25 % of global energy production in 2050 (Economic Planning Unit, 2015).

The agriculture industry contributes significantly to Malaysia's economic growth by improving farmers' income, providing rural jobs, and ensuring national food security. According to the 11th Malaysia Report (2016-2020), the agricultural industry provided RM455 billion to Gross Domestic Products (GDP), with yearly growth of 2.4%. In 2011 within National Key Economic Area (NKEA), herbal plants has been recognised as High Value Herbs (HVH) which has economical potential as illustrated in Figure 1.2 (phase 1 & phase 2; 10 plants). The targeted HVH are typically selected related to present market potential, active pharmacological research and higher demand in Malaysia's vast biodiversity (Othman et al., 2016). Among 10 plants as listed in NKEA, *Orthosiphon stamineus* or local known as Misai Kucing is used in this study based on their strong medicinal properties and sustainability of this plant when cultivating under solar PV farms which previously done by (Othman et al., 2017).

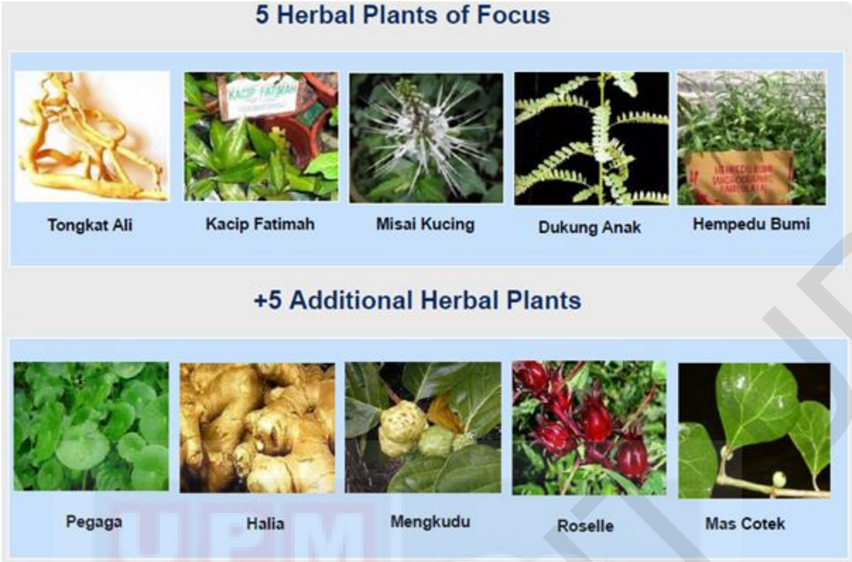

Figure 1.2: Herbal as High Value Herbal crops (HVHc) which selected for EPP1 program.

As highlighted in ETP too (PEMANDU, 2011), under the initiative of upgrading capabilities for premium markets, greenhouse and fertigation control systems are among significant initiatives to ensure the plantation will be fitted with favourable and controlled-environment structure. In wide existing usages of greenhouse, as shown in Figure 1.3, limited function can be seen for only providing greater control over the growing environment of plants. In its overall system where electrical energy may be needed, it should be powered by external source in order to allow operation of specific equipment or tools for lighting and irrigation purposes.

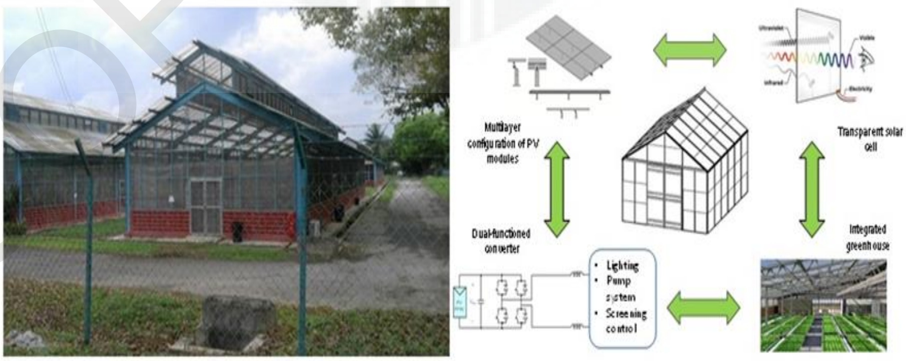

Figure 1.3: Existing greenhouse at Ladang 2, UPM (left picture); proposed integrated PV system in greenhouse (right picture).

1.3 Problem statement and justification

In several countries, modern solar greenhouses built by integrating solar PV (crystalline silicon-based) into agricultural greenhouses are currently being introduced. With this development, farmers would be get income from agriculture output and electric power generation. One of the crucial factors for plant growth and physiology due to the transmission of light (solar radiation) into the greenhouse is Photosynthetic Active Radiation (PAR). PAR is the spectral wavelength of 400 to 700 nm solar radiation allocated for the process of photosynthesis of photosynthetic organisms. The yield of crops is strongly related to this spectral band's availability.

However, the most prevalent issue with integrated PV (crystalline silicon based) greenhouse, is the mutually compatible antagonism among roof structure (PV panel) and plants, as traditional solar cells are not transparent to sunlight The placing of the solar panel on greenhouse rooftop is crucial as the roof coverage increases, impacting crop development, growth, and productivity adversely. As a result, it’s critical to strike a compromise between the two conflicting demands: minimising the shadowing impact of PV panels so that the PAR wavelengths may enter the greenhouse as much as possible, and increasing the energy production proportionate to the impenetrable panel surface. Therefore, further exploration of improving PV (crystalline silicon based) greenhouse should be undertaken to optimize the advantages of electricity production as well as the function of agriculture.

Thus, semi-transparent DSSC; third generation solar photovoltaic cells are the best choice for greenhouse applications due to their unique characteristics such as different colours and transparency (Skandalos & Karamanis, 2015). It can manipulate the spectrum of sunlight; makes the full use of photosynthesis-relevant light (PAR wavelength) by plants while also being able to use unused wavelengths to generate electricity (Emmott et al., 2015). In addition, shading by using PV modules on the greenhouse roofs has also recently been used to reduce irradiation intensity and air temperature within the greenhouses, especially in the hot and tropical regions (Ahemd et al., 2016). At present, in the tropical climate environment, there have been no publications or studies on semi-transparent DSSC greenhouse. On the other hand, under this new technology there were no attempts to cultivate medicinal plants. There is therefore a need to conduct in depth study on integrated DSSC greenhouse performance and its characteristics influence on internal greenhouse microclimate and consequently affect the plant growth. The information is crucial for optimizing electrical generation and agricultural production towards meeting food security and food safety.

1.4 Research aim and objectives

To investigate and analyse agro-technological concept of semi-transparent DSSC (red colour) for greenhouse which to generate electricity and agriculture production, together with manipulation of the solar radiation (spectrum), for growth and physiological responses of light regulated *Orthosiphon stamineus* (Misai Kucing) plant. The study's more specific objectives were as follows:

a) To evaluate the DSSC potential as a greenhouse shading through spectral manipulation of light (solar radiation).
b) To develop the integrated semi-transparent DSSC mini greenhouse.
c) To assess DSSC mini greenhouse on microclimate by cultivating Misai Kucing in the tropical climatic condition.
d) To characterize a case study on DSSC electrical field performance in tropical climatic condition.

Therefore, the hypothesis in this study is to see if the integrated semi-transparent DSSC greenhouse is successful method of gaining electrical and agricultural production as well as stimulating specific morphological and physiological responses of Misai Kucing by using colored DSSC as photoselective shading, thus minimizing the use of plant chemical regulator.

1.5 Significance of study

A strong justification of the significance of this study can be described by the integration of semi-transparent DSSC for greenhouse which can generate both electricity and agriculture production since conventional PV greenhouse is opaque to sunlight. Furthermore, DSSC's red colour can provide as a photoselective shading that can manipulate the spectrum of sunlight to stimulate specific morphological and physiological responses of Misai Kucing, and reduce the use of plant chemical regulator.

1.6 Scope of work and limitation of the study

The scope of work and limitation of study are discussed in sub-topic 1.6.1 and 1.6.2 respectively as follows.

1.6.1 Scope of work

This study mainly focuses primarily on the performance of DSSC mini greenhouse which provides the best internal microclimate for sustenance growth of plant (in this context Misai Kucing). It also able to act as photoselective shading; whereby it can modified spectra of irradiation to specific relevant wavelength for photosynthesis process while the un-usage wavelength will be converted to electric. This work is bringing the concept of agrivoltaics which means integration of PV system and agriculture within same area. The context of the research to be completed comprises as follows:

a) Qualitative research (critical review)- Since there is no study and documentation related to the DSSC greenhouse, all the information regarding on DSSC's potential, characteristics, materials (photosensitizer), application (in building façade, bio-reactor and etc.) of past research have critically reviewed since 2017-2018. This work is vigorous in order to develop the conceptual idea and prototype development of integrated DSSC greenhouse.
b) The second scope of the research to be completed comprises on the design, fabrication and development of DSSC mini greenhouse or known as Dynamic Dye-sensitized solar cell Mini Greenhouse (DDMG).
c) Next the scope of the research was field test for system (prototype) validity. To determine performance of DDMG, there are two work scope as follows:

    i) The field test was conducted to assess DDMG's performance by studying at Misai Kucing's sustainability inside this prototype. Microclimate parameters such as temperature, RH, VPD and PPFD were evaluated to determine the impacts and contributing variables. The manipulation of spectra irradiation under red DSSC was also determined by using spectrometer. The experimental data was compared to the glass greenhouse as a reference/control to determine the viability of the DDMG.
    ii) The field test was conducted to determine electrical performance of DSSC modules in tropical climate by measuring current (I_{max}), efficiency (η), power (P) and Fill Factor (FF).

1.6.2 Limitation of study

The limitations of study are described as follows:

a) The scope of this research works only cover on prototype scale, not implemented in the real PV greenhouse sizes. Therefore, the outcomes and expected results (especially on microclimate condition inside greenhouse) must be different on this miniature scale.
b) Due to the budget & time constraint, this study only focuses on the DSSC panels which mounted on the rooftop of greenhouse (as shading) and it is supposed to apply as full covering greenhouse. This limitation may affect accuracy of the expected results and outcomes.

c) This prototype is tailored and specified to certain crops such as Misai Kucing or any shade loving plant. As a starting point, this work gives the prospective field performance.

1.7 Thesis organization

This thesis is written in an alternate format, which chapters 1-3 remaining in the traditional format. Chapters 4 to 6 represent the body of the thesis which have already published in ISI journal. Research framework & thesis organization are illustrates in Figure 1.4.

Thesis organization is described as follows:

a) The literature reviews in Chapter 2 pertain to the study's overall research scope with an emphasis on Solar PV technologies adaptation of DSSC material in Malaysia; since Malaysia located in an equatorial region, types of PV greenhouses, and DSSC application (as Building Integrated Photovoltaic; BIPV). Moreover, the Malaysian tropical climate and how does it affect the greenhouse microclimate also has been discussed in this chapter. Also, this chapter brings the readers an important insight on how does shading by PV (as a cooling system) effect on internal greenhouse microclimate, plant growth and quality of light. *Orthosiphon stamineus* (Misai Kucing) as High Value Herbal crops (HVHc) also has been discussed in this chapter.

b) Chapter 3 covers and discusses each procedure and methodology (as holistic) started from planning process (design phase & conceptual study/idea about DDMG, prototype development and tropical field assessment (general procedure).

c) Since neither publication nor previous studied performed regarding on DSSC greenhouse, this chapter 4 was critically reviewed on DSSC's potential as rooftop shading greenhouse in comparison with conventional PV (Si based) greenhouse. This chapter goes into further detail on the distinct features of the various DSSC colours (determined by the dye) and how this technology manipulates the irradiation spectrum by choosing the best and optimum DSSC's photosensitizer. This chapter is vital for understanding the conceptual idea where previous research has been reviewed and carefully selected where this information will related to prototype development.

d) A chapter 5 addresses practical or field performance for system and prototype (DDMG) validity by means of examining Misai Kucing's sustainability within this prototype. To assess the effects and contributing factors, microclimate parameters and light quality were measured. To determine the feasibility of DDMG, the experimental data were compared with the glass greenhouse as reference/control.

e) The electrical field performance of DSSC modules describing parameters such as current, voltage, I-V characteristics, power, efficiency and fill factor were evaluated and discussed in Chapter 6

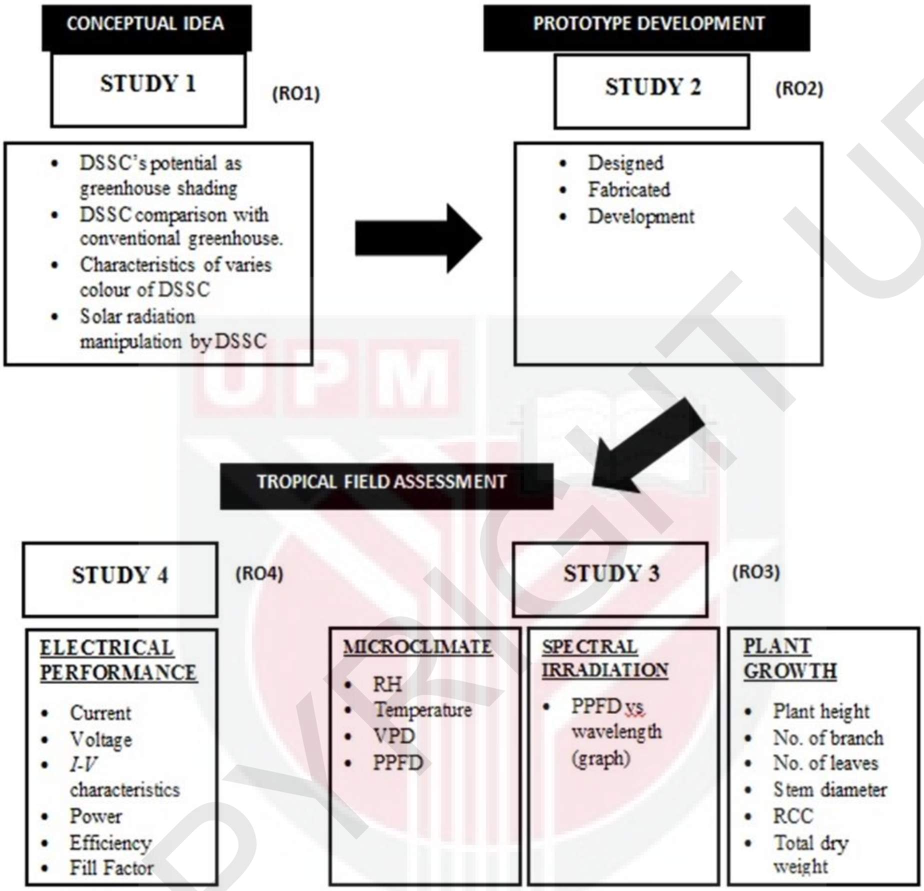

Figure 1.4: Research framework and thesis organization. (RO: Research Objective).

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