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Analysis of Weed Communities in Solar Farms Located in Tropical Areas—The Case of Malaysia

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Abstract: Weed management in large-scale solar photovoltaic (LSS-PV) farms has become a great concern to the solar industry due to scarcity of labour and the ever-increasing price of pesticides, which opens up possibilities for integrated farming, also known as agrivoltaics. Improper weed control may have multiple negative impacts such as permanent shading of the module surface, pest housing which damages communication cables, and even bush fires. The shaded PV modules can be heated up to extreme temperatures, causing costly burn-out damage. Critical information on the types of weeds on solar farms, especially in Malaysia, has not been established to support the concept of weed management. Thus, with this study, detailed composition of the weed community was obtained via quadrat sampling between solar PV modules, near ground equipment, near perimeter fencing, and directly underneath the PV modules. Weed-control measures via high-quality weedmat installation under solar PV arrays have been implemented where this approach can be considered effective on solar farms based on the existing PV structure height and equipment constraints plus the increasing cost for labour and agricultural inputs. This work underlines the proposed Agrivoltaic for Large Scale Solar (Agrivoltaic4LSS) program to complement the solar industry in Malaysia towards an agrivoltaic, eco-friendly approach to weed management.

Keywords: weed identification; Agrivoltaic4LSS; tropical climate; large-scale solar; sustainable cities

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1. Introduction

Malaysia is committed to its target of becoming a carbon-neutral nation by as early as 2050 through a strategic approach to accelerating the growth of the green economy, boosting energy sustainability, and transforming the water sector as the core of the country's socio-economy. Photovoltaic (PV) has been identified as one of the most dependable, developed, and cost-competitive sustainable energy technologies with the potential to reduce carbon dioxide (CO_2) emissions by up to 4.9 gigatonnes (Gt) by 2050 [1]. According to the International Renewable Energy Agency (IRENA), the worldwide PV installed capacities will reach roughly 4837 Gigawatts (GW) in Asia, 1728 GW in North America, and 891 GW in Europe by 2050. It indicates that the total PV installed capacity in 2050 at the global level will be almost 18 times higher than in 2018. In 2050, overall, utility-scale solar

PV will account for 60% of total PV capacity globally, with rooftop PV accounting for the remaining 40% [1,2]. In local areas, PV installations assist in the production of electricity, reducing the need for fossil fuels [2]. The commissioned large-scale solar (LSS) farms in Malaysia are shown in Figure 1. Based on the Malaysia Energy Statistic Handbook 2020 as of 31 December 2019 [3], PV generating capacity reaches 948.6 MWp (3.3% energy mix) covering the Feed-in-Tariff (FiT), LSS, and Net Energy Metering (NEM) initiatives.

Figure 1. Typical LSS sites in Peninsular Malaysia [4].

Currently, combining agricultural activities with solar PV energy production is a critical topic being discussed worldwide. An opportunity to resolve these issues lies in the integration and co-development with primary activities of land-based solar PV farms, commonly known as agrivoltaic or multi-output systems. In 1981, the technique of using the same land area for food and PV power was conceived by Goetzberger and Zastrow [5]. Akira Nagashima, in 2004, advanced matters by introducing a new concept in the co-production of food and power [6]. The light saturation point of a certain crop is the amount of solar radiation required to reach its maximum photosynthesis rate; further irradiation intensity does not boost photosynthesis. Dupraz et al. [7] originally coined the term 'agrivoltaics' by combining 'agriculture' and 'photovoltaics' to represent an entirely new academic and commercial discipline of raising crops under PV installations based on the principle of shared sunlight [8]. The same system is known as "agrophotovoltaics" in Germany [9], "solar sharing" in India [10], "solar PV agriculture" in Malaysia [11], and "PV agriculture" in China [12]. Agrivoltaic systems offer threefold benefits: production of crops, generation of electricity, and reduction in water consumption [13]. There is an improved water balance in agrivoltaic facilities along with the use of the same water for PV-surface cleaning and irrigation. The agrivoltaic concept tends to optimize both the plants' yield and DC electricity in a cost-effective way by using land areas for agriculture and solar PV power generation simultaneously. Moreover, agrivoltaic systems can not only mitigate carbon emissions but also solve land scarcity, particularly in urban areas [14].

In agronomy, weeds are one of the most important competitors for minerals, water, and nutrients in the soil with other desirable crops, and thus result in a huge reduction in crop yield [15–18]. Weed identification is the first stage of weed management to aid in a fundamental understanding of the life cycle and biology of the weeds. Proper weed identification plays a significant role in obtaining appropriate recommendations for weed control options [19]. More specifically, the types of weeds can reveal information about the field, its management, and the best means of direct control. Correct weed identification, therefore, can help select the right herbicide needed to control the particular weed effectively [19]. Thus, it is possible to eradicate new weeds before they are established. Weed identification also contributes to the timing of the application of the herbicide. In this way, it will directly bring about cost savings if there is a lower-priced herbicide [19]. With the aid of weed identification, precision agriculture is attainable to protect crops by performing site-specific and suitable herbicide spraying of weeds in a timely manner [20]. Fast and automatic weed identification is vital in order to achieve accurate solutions and various methods have been adopted by different studies. Tang et al. [21] used soybean seedlings and three types of weeds as study subjects. They then proposed a weed identification model as a function of K-means feature learning that was also combined with a convolutional neural network (CNN) to gain higher accuracy in identification rather than depending on the human experience.

Improper weed management, as shown in Figure 2, has been a major issue in ground-mounted LSS in Malaysia. The weeds grow at a high density, which creates housing for vertebrate pests, i.e., rodents, rats, snakes, and other reptiles [22,23]. These conditions not only create risk to the farmworkers but also damage the electrical cables, especially communication cables for data logging, as depicted in Figure 3. Even more alarming, the damaged cables and equipment can cause short circuits or fire [24]. These serious problems caused by improper weed management come with high repair costs. In addition, improper weed management can also lead to the weeds permanently shading the surface of solar PV. The shadows on the solar panels become fixed because the weeds grow close to the top surface of the panels. As shown in Figure 4, tall weeds growing around the installation can create permanent shading on the PV surface with an exponential growth trend of surface cover during rainy seasons. This permanent shading can cause power loss in a PV system as well as hotspot heating.

Figure 2. Improper weed management on LSS farms.

Figure 3. Pest damage to solar PV arrays [25].

Figure 4. Actual snapshots of various weeds leading to permanent shading of the PV.

As shown in Figure 5, the performance of the whole PV panel will be negatively affected even though only a small section of the solar panel is shaded. This is because PV panels are composed of a number of PV cells that are wired in series; that is to say, the power output of the whole system in series is dropped to the level of current passing through the weakest cell when the power output of a single cell is significantly reduced due to weed permanent shading [26]. Beyond that, when a shaded cell generates much less current than the unshaded ones, due to the series connection of the cells in the modules, the same current must flow through all the cells. Therefore, the more serious situation is that the shaded cells can heat up to such extreme temperatures that the PV module can become burnt out and permanently damaged [27]. The arrow in Figure 5 indicates the effects of reduction in current flow due to the partly shaded solar PV Module.

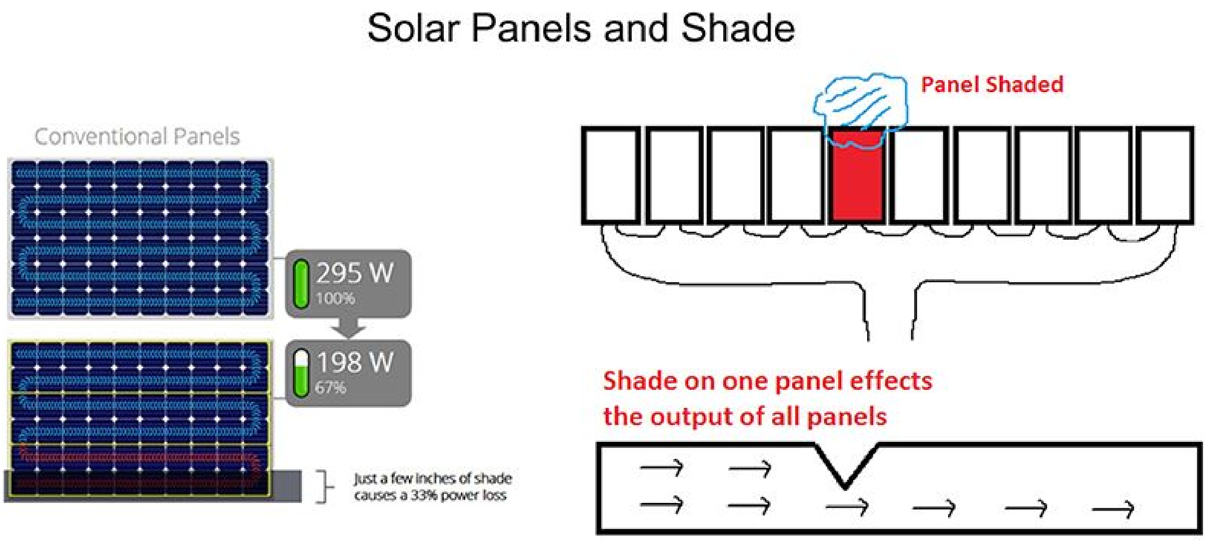

Figure 5. Shading effect on the performance of the solar panels [27].

There are several weed-control methods applied on LSS farms, such as mowing, spraying herbicide, grazing sheep/goats, and covering the area with weed-control sheets. However, controlling weeds incurs additional operation and maintenance expenses for solar PV systems, and the long-term costs and benefits should be assessed.

In Malaysia, weed management strongly relies on herbicides [28]. Early detection and proper management of weed infestations is crucial. Unmanned Aerial Vehicle (UAV) or satellite imagery can be used to map weeds on solar farms. A UAV equipped with a multispectral camera can be used in weed mapping using a deep neural network (DNN) and *normalized difference vegetation index* (NDVI), which significantly helps in discriminating between crops and weeds by segmenting out vegetation in the input images [29]. Mohidem et al. [30] also mentioned that UAVs could help weed detection and sustainable weed management. They suggested the use of artificial intelligence (AI) to integrate with the UAV for accurate weed detection. Thus, UAVs have the potential to detect and map weeds on solar farms. Even though some areas are covered by solar panels, the map can show weed infestations visible outside the coverage of the solar panels.

Most of the weed or grass mapping using GIS were produced in agricultural and open areas. For example, Gašparović et al. [31] used GIS and UAVs for mapping weeds in crops. They found that they could more than 80% accurately classify the weeds. At the same time, Alexandridis et al. [32] found that weeds mapped using UAVs could be classified with up to 90% accuracy. Hyperspectral UAV also showed a high potential for pasture measuring in grazing areas. It can be used to predict biomass from pastures [33]. However, all these studies investigated weed mapping in agricultural and open areas where UAVs can easily fly overhead. Therefore, UAVs have a high potential for monitoring solar farms, for example, for defects in the solar panels. According to [34], thermal and red-blue-green UAVs can provide fast and reliable detection methods. A similar project with Gammill et al. [35] used a thermal UAV to monitor a solar farm based on the solar panels' temperature. In our project, we are focusing on the weeds and grasses under the solar panels. Thus, for safety reasons, UAVs might not be suitable because of the shade induced on the solar panel surface. Nevertheless, UAV and satellite imagery were used for aerial data collection due to the available data and spatial resolution. Alternatively, ground sensing could be used to monitor weeds and grasses under solar panels.

The critical information on the types of weed in solar PV farms, especially in Malaysia, has not been established to support agrivoltaic weed management. In this paper, detailed information on weeds via quadrat sampling with sample spot locations between PV modules, near ground equipment, along perimeter fencing, and directly underneath the PV modules was obtained.

2. Materials and Methods

The studied solar PV farm site in Puchong, Selangor (2°59′20″ N, 101°43′30″ E), shown in Figure 6, has a generating capacity of 2MWac and covers 5 acres of flat land beside a commercial area. It has been in operation since February 2015 under the Feed-in-Tariff scheme (21-year contract for renewable-energy generation). The average ambient temperature, average relative humidity, and average wind speed of this site were 27.8 °C, 82%, and 0.05 m/s, respectively, during the research period.

Figure 6. Snapshots of 2MWp Puchong solar farm in Selangor.

The methodology for weed sampling is based on field observations at spot areas, as shown in Figure 7, focusing on the solar farm infrastructure and ground conditions, namely: (**a**) A pathway between Solar Modules/strings; (**b**) Perimeter Fencing; (**c**) Directly under Solar PV Modules; (**d**) Near PV Inverters and earth poles.

Figure 7. Spot ground conditions at the solar farm in Puchong.

A total of 108 sampling points were established within our study area using a systematic study design. Sampling points were located at a minimum distance of 15 m apart from each other as shown in Figure 8. At each sampling point, weeds were sampled using a quadrat survey method. From each quadrat survey, we determined and measured (i) vegetation height—mean of readings (cm) from four corners at each established quadrat; (ii) vegetation coverage—taken using the smartphone application Canopeo [36] (Oklahoma State University); (iii) total number of species—number of species counted within the 1 m^2 quadrat; (iv) species density—total abundance of each recorded species within the 1 m^2 quadrat. The method used for the quadrat survey was adapted from a previous study [37].

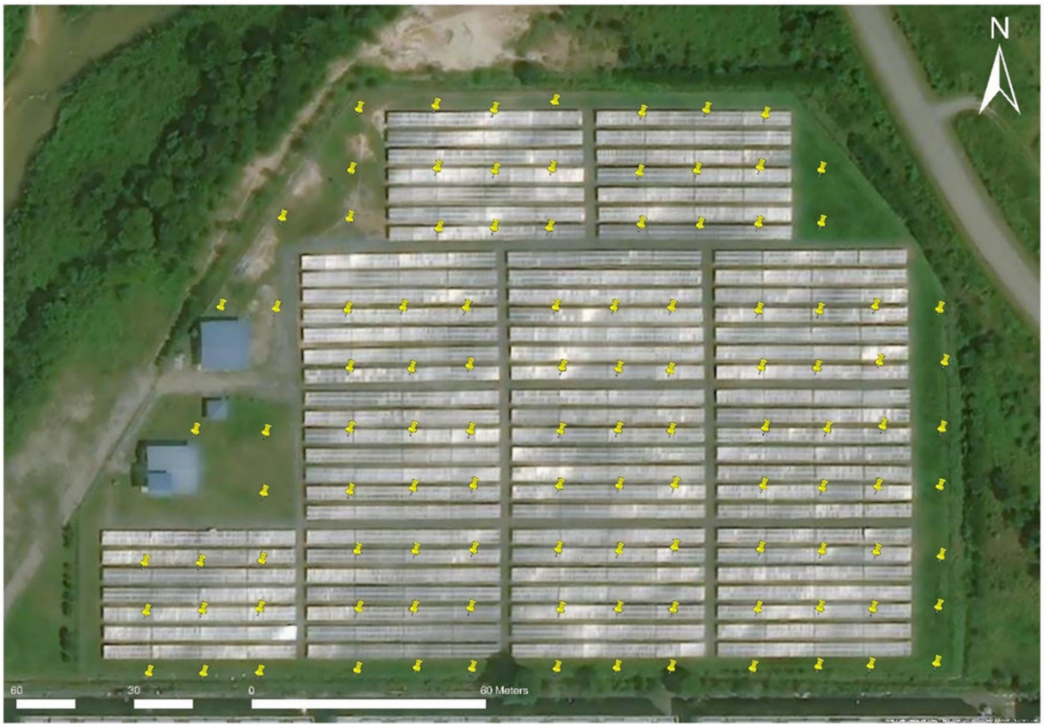

Figure 8. Quadrat sampling approach with 108 sampling points at the Puchong site.

The collected field data were analyzed using GenStat Ver. 12 (VSN International Ltd., Hemel Hempstead, UK) and Similarity percentage analysis (SIMPER)—Primer-e Ver. 6 (Primer-e Ltd., Ivybridge, UK). These two applications are commonly used in some fields. For example, Egbadzor [38] adopted GenStat Ver. 12 to analyze the diversity of baobab in the Volta Region of Ghana, including its germination and growth data. SIMPER was used by Achieng et al. [39] for identifying fish species mostly attributed to variation in assemblages among rivers of Lake Victoria Basin in Kenya.

3. Results and Discussion

The weed community characterisation in terms of number of weed species, abundance of weeds, vegetation coverage, and vegetation height are shown in Table 1.

Table 1. Summary statistics of vegetation coverage, vegetation height, number of weed species, and abundance of weeds collected from the field [40–44].

Parameter	Number of Weed Species	Abundance of Weeds	Vegetation Coverage (%)	Vegetation Height (cm)
Mean	9.083	141.9	31.25	29.34
Median	9	104	27.93	24.75
Minimum	3	9	1.72	4.5
Maximum	16	608	84.3	148.5
Lower quartile	7	75.5	17.69	14.25
Upper quartile	11	198	44.94	34
Standard deviation	2.782	108.6	18.03	24.85
Coefficient of variation	30.63	76.53	57.68	84.68

The top ten weed species contributions (abundance at sample points) based on weed species which grow naturally in the sample solar farm location are shown in Table 2, with sample pictures in Figures A1–A10 in Appendix A.

Table 2. Top ten identified weed species on the solar farm in Puchong with Similarity Percentages and Species Contributions.

Species	Av.Abund	Av.Sim	Sim/SD	Contrib%	Cum.%
Ageratum conyzoides	6.68	14.25	1.30	43.05	43.05
Lindernia crustacea	2.45	3.13	0.61	9.46	52.51
Eleusine indica	1.97	3.08	0.66	9.31	61.82
Echinochloa colona	1.77	2.66	0.61	8.03	69.85
Phyllantus amarus	1.54	1.93	0.55	5.84	75.69
Paspalum scrobiculatum	0.84	1.22	0.42	3.69	79.39
Fimbristylis globulosa	1.53	1.18	0.33	3.57	82.96
Oldenlandia corymbosa	0.82	0.80	0.38	2.40	85.36
Mimosa pudica	0.43	0.73	0.45	2.19	87.55
Brachiaria mutica	0.84	0.65	0.35	1.96	89.51

Note: Av.Abund—average abundance, Av.Sim—average similarity, Sim/SD—average similarity divided by standard deviation, Contrib%—percentage of species contribution to weed community, Cum.%—cumulative percentage of species contribution to weed community.

A total of 64 weed species as described in Table 3 was classified by habit and comprise Climbers/Creepers (14 species), Ferns (4 species), Grasses (12 species), Herbs (23 species), Sedges (3 species), Shrubs (6 species), and Trees (1 species).

Table 3. Descriptions of weeds identified at Puchong site [45–53].

Habit	Family	Scientific Name	Common Name	Local Name
Climber	Asteraceae	*Mikania micrantha*	Mile-a-minute	Ulam tikus
Creeper	Asteraceae	*Tridax procumbens*	Coat buttons	Kanching baju
	Convovulaceae	*Ipomoea triloba*	Little bell morning glory	Kangkung bulu

Table 3. *Cont.*

Habit	Family	Scientific Name	Common Name	Local Name
		Merremia umbellata	Greater Malayan bindweed	Ulan tapak pelanduk
	Cucurbitaceae	*Cucumis maderaspatanus*	Madras pea pumpkin	-
		Gymnopetalum scabrum	-	-
		Scopellaria marginata	-	Timun tikus
	Fabaceae	*Alysicarpus vaginalis*	Alyce clover	-
		Calopogonium mucunoides	Calopo	Kacang asu
		Desmodium heterophyllum	Spanish clover	Rumput sisik naga
		Desmodium trifolium	Tick clover	Sisik naga
		Mimosa pudica	Touch-me-not	Semalu
	Passifloraceae	*Passiflora foetida*	Stinking passionflower	Timun padang
		Passiflora suberosa	Devil's pumpkin	-
Fern	Gleicheniaceae	*Dicranopteris linearis*	Tropical bracken	Resam
	Lycopodiaceae	*Lycopodiella cernua*	Staghorn club moss	Paku serani
	Nephrolepidaceae	*Nephrolepis biserrata*	Giant sword fern	Paku larat
	Schizaeaceae	*Lygodium microphyllum*	Climbing maidenhair fern	Ribu-ribu
Grass	Poaceae	*Axonopus compressus*	Cow grass	Rumput parit
		Brachiaria mutica	Para grass	Suket babang
		Cynodon dactylon	Bermuda grass	Rumput minyak
		Dactyloctenium aegyptium	Egyptian crowfoot grass	Rumput jari mesir
		Echinochloa colona	Bird rice	Padi burung
		Eleusine indica	Goose grass	Suket wululang
		Eragrotis tenella	Bug's egg grass	Rumput telur kutu
		Imperata cylindrica	Sword grass	Lalang
		Paspalum scrobiculatum	Bull Paspalum	Rumput ketih belalang
		Pennisetum purpureum	Napier grass	Rumput gajah
		Sacciolepis indica	Glenwood grass	Rumput bidis
		Sporobolus indicus	Common drop-seed	Suket sadan
Herb	Acanthaceae	*Asystasia gangetica*	Chinese violet	Rumput Israel
	Asteraceae	*Ageratum conyzoides*	Billy goat weed	Rumput tahi ayam
		Eclipta prostata	False daisy	Urang-aring
		Emilia sonchifolia	Sow thistle	Bayam terkukur
		Erigeron sumatrensis	Fleabane	Sawi bulan
	Cleomaceae	*Cleome rutidosperma*	Yellow cleome	Maman ungu
	Euphorbiaceae	*Croton hirtus*	Hairy croton	-
		Euphorbia hirta	Hairy spurge	Ara tanah
		Phyllantus amarus	Lagoon spurge	Dukung anak
	Fabaceae	*Indigofera hirsuta*	Hairy indigo	Kacang babi

Table 3. *Cont.*

Habit	Family	Scientific Name	Common Name	Local Name
	Lamiaceae	*Plectranthus monostachyus*	Monkey's potato	-
	Linderniaceae	*Lindernia crustacea*	Malaysian false pimpernel	Akar kerak nasi
	Loganiaceae	*Spigelia anthelmia*	Pinkroot	-
	Onagraceae	*Ludwigia hyssopifolia*	Seedbox	Inai pasir
	Polygalaceae	*Polygala paniculata*	Root beer plant	Akar wangi
		Salomonia cantoniensis	Common Salomonia	Rumput buak
	Rubiaceae	*Borreria laevicaulis*	Purple-leaved button weed	Kerekah batu
		Borreria latifolia	Broadleaf-button weed	Rumput setawar
		Borreria setidens	Toothed button weed	Kemangi jantan
		Oldenlandia corymbosa	Old world diamond-flower	Siku-siku
	Scrophulariaceae	*Scoparia dulcis*	Macao tea	Pokok delis
	Solanaceae	*Physalis minima*	Bladder cherry	Letup-letup
	Verbenaceae	*Stachytarpheta jamaicensis*	Light blue snake-weed	Jolok cacing
Sedge	Cyperaceae	*Cyperus brevifolius*	Shortlead spike sedge	-
		Cyperus digitatus	Digitate Cyperus	Rumput bunga satuan
		Fimbristylis globulosa	Globular Fimbristylis	Rumput sandang
Shrub	Asteraceae	*Bidens alba*	Butterfly needles	Subang puteri
		Chromolaena odorata	Siam weed	Pokok kapal terbang
	Malvaceae	*Waltheria indica*	Boaterbush	-
	Melastomaceae	*Clidemia hirta*	Hairy clidemia	Senduduk bulu
		Melastoma malabathricum	Straits rhododendron	Senduduk
	Solanaceae	*Solanum* cf. *coagulans*	-	-
Tree	Moraceae	*Ficus hispida*	River fig	Ara nasi

Based on the plant surveys conducted in 108 quadrats, 64 weed species were identified. The weed community was largely dominated by herbs and grasses, most notably *Ageratum conyzoides*, with a contribution to the community composition of 43.05%. *Lindernia crustacea* (herb) and *Eleusine indica* (grass) made up > 9% of the weed community composition. None of the dominant weed species are thought to cause detrimental impacts on the PV plant (i.e., a partial shading effect). Nonetheless, the surveys also identified six species of weeds which likely contribute to PV permanent shading cases, namely one species of climber (*Mikania micrantha*) and five species of creepers (*Ipomoea triloba, Merremia umbellate, Cucumis maderaspatanus, Gymnopetalum scabrum,* and *Scopellaria marginata*). Such perennial climbers are considered common in tropical regions. A hot and humid tropical climate may help such plants grow vigorously, particularly within open areas such as PV plants. For instance, the fast-growing *Mikania micrantha* has been known to be problematic and have dominant effects on understory vegetation communities [54].

Therefore, in reference to weed management strategies, these six weed species should receive more attention. Possibly, spot application of selective or narrow-spectrum herbicides as suggested by Moyo [55] could be one of the most effective ways to eradicate weeds across the PV plant. Alternatively, mechanical weed control methods (e.g., tillage, mulching) may also be used to handle these uncommonly occurring targeted weed species.

Yet, the use of mechanical options might not be as effective compared to conventional chemical approaches.

According to Tian et al. [56], programs like the U.S. economic stimulus package aim to decrease the use of fertilizers and pesticides in agriculture. Poonia et al. [57] planted crops around solar panels and sprayed pesticides prophylactically. The cost of various PV systems around the world is comparable to the economic analysis of agrivoltaic system designs [57]. The use of pesticides can also be decreased by combining them with biological control on solar farms, with the best strategy or combination of techniques designed to maximize the effectiveness of pesticide application. Many biological purification systems have been designed to treat effluent containing pesticides with the assistance of microorganisms that may consume insecticides [58]. As for the weed control measures, high-quality weed-mat installation under solar PV arrays has been practically implemented, as shown in Figure 9. This approach can be considered effective on solar farms based on the existing PV structure height and equipment constraints plus the increasing cost for labour and agricultural inputs.

Figure 9. High-quality weed mats have been used as weed control measures directly under solar PV arrays for further crop cultivation.

4. Conclusions

In this paper, some typical information on the structure of weed communities on Large-Scale Solar (LSS) farms in one sample location in Puchong, Selangor, Malaysia was described to support the practical idea of agrivoltaic weed management. Improper weed control on LSS farms could create huge financial losses and reductions in daily DC generation. This work outlines the types of weeds causing issues of pest housing, faulty cables, and health risks to solar farm workers via permanent shading, pest disturbance, and structural damage. A significant amount of information is presented in hopes of producing appropriate recommendations for weed control options. More specifically, the types of weeds can reveal the best form of direct control. Through an agrivoltaic approach to weed management, this would support a much cleaner solar PV production and an eco-friendly approach to combatting climate change.

In view of meeting the increasing global energy demands and simultaneously decarbonizing the energy supply, energy generation from sustainable and eco-friendly resources has become ever more significant. Therefore, it is crucial to innovate and apply different agriculture- and eco-friendly energy technologies for sustainable agricultural farming within solar PV farm infrastructures.

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Appendix A

Figure A1. Herb Asteraceae: *Ageratum conyzoides*.

Figure A2. Herb Linderniaceae: *Lindernia crustacea*.

Figure A3. Grass Poaceae: *Eleusine indica*.

Figure A4. Grass Poaceae: *Echinochloa colona*.

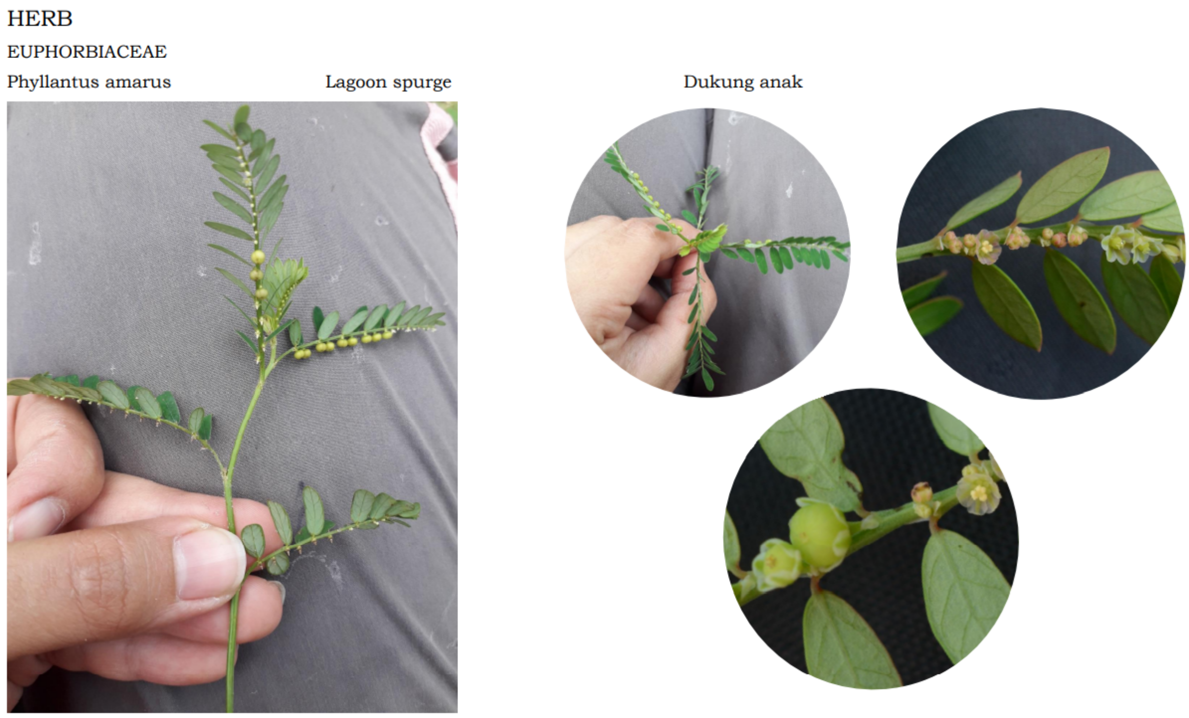

Figure A5. Herb Euphorbiaceae: *Phyllantus amarus*.

Figure A6. Grass Poaceae: *Paspalum scrobiculatum*.

Figure A7. Sedge Cyperaceae: *Fimbristylis globulosa*.

HERB

RUBIACEAE

Oldenlandia corymbosa Old world diamond-flower Siku-siku

Figure A8. Herb Rubiaceae: *Oldenlandia corymbosa*.

CREEPER

FABACEAE

Mimosa pudica Touch-me-not Semalu

Figure A9. Creeper Fabaceae: *Mimosa pudica*.

Figure A10. Grass Poaceae: *Brachiaria mutica*.

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