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Sustainability Evaluation for Pesticide Application in Oil Palm Plantation Integrated with Industry 4.0 Technology

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Pesticide application in oil palm plantation has been a crucial and labour-intensive operation. Rapid technological development for spray machine such as tractor and drone could improve the sustainability of the operation. This paper evaluates the sustainability performance of 3 types of pesticide spraying technologies, namely drone, tractor and knapsack. A total of 3 different modes of drone power source was considered, including grid, gasoline generator and solar panel. The sustainability performance was evaluated based on return on investment (ROI), carbon footprint from operation, and exposure time to pesticide. The result shows that spray drone powered by gasoline generator has the highest overall sustainability index of (0.834), with the ROI of (34), carbon footprint of 270.7 kg CO_2/d and a total of 720 h/y exposure time to pesticide.

1. Introduction

Pesticides are common chemicals utilised for crop protection by killing pests. Spraying pesticides is an essential aspect of modern farming and it plays a significant role in enhancing agriculture efficiency. The use of pesticides has significantly increased over the years in the agricultural sector, including the oil palm industry. With the increasing sustainability awareness, the operation of pesticide application is a critical component for sustainable oil palm production. The operation should be conducted optimally with high efficiency, and safety of the environment and farmers. Study shows that pesticide is a concern for potential health effects, even for the proximity exposure in a large-scale system (Maggi et al., 2021). There are various pesticide application methods among agriculture crops, which include band application, broadcast application, direct spray and foliar application. Generally, oil palm plantation would apply broadcast (disperse in a wide range) or band (parallel row) application, depending on the available technology/equipment and the coverage size. Knapsack is a popular and common tool used by oil palm farmers for pesticide application. Study shows that approximately 75 % of smallholder farmers employed knapsack sprayers for agriculture production in the past decades (Franke et al., 2010). Pesticide application with a knapsack is a labour intensive and inefficient process. It also arises health concerns for farmers due to the long close contact time with pesticides. Exposure to pesticides has been correlated to adverse health effects such as reducing the birth rate and cancer, leading to more fatalities (Damalas and Koutroubas, 2017).
The rapid introduction of advanced technologies is swiftly changing the mode of industrial development towards digitalisation and automation to improve process efficiency and profit (Eppinger et al., 2021). A study was conducted to compare the cost and return of investment (ROI) of various pesticide application technologies in oil palm plantations including knapsack, spray tractors and spray drones (Lim et al., 2021). Wachenheim et al.

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(2021) showed that unmanned aerial vehicles have great potential for precision agriculture and should be adopted by more farmers. A review of drone technology was given for farm monitoring and pesticide spraying suggests that costing, battery limitation and end-user readiness are a few issues to be addressed (Hafeez et al., 2011). A low-cost agriculture robot was developed for spray fertilizers and pesticide application which could operate in autonomous mode for reduced labour dependency (Ghafar et al., 2021). Despite the improvement in efficiency, spray tractors, robots, and drones require additional energy sources that would increase their carbon footprint. The impact would be significant considering palm oil is the major vegetable oil for food, energy and chemicals with huge plantation area globally. Apart from improved efficiency, an adaptation of drone technology also could minimise the contact time of operators to pesticides via remote operation. Farmers are only exposed to pesticides while handling the drone during the preparation, filing and cleaning stage. The contact time would be significantly lower, enhancing the social sustainability of the process.

This paper aims to perform a sustainability analysis and comparison of knapsacks, tractors and drones for pesticide application in oil palm plantations based on the economy, environment and social aspects. The analysis includes the return of investment (ROI), carbon emission, and exposure time to pesticides for safety considerations. Due to the limited access to electricity in some oil palm plantation sites for drone application, this study includes consideration of power sources from the grid, diesel generators, and solar panels. The results would provide insight into the various technologies for pesticide application and determine the optimum sustainable technology.

2. Methodology

Figure 1 shows factors considered in this study to evaluate various technologies for pesticide application in the oil palm plantation, including knapsack, tractor and drone. The economic aspect is evaluated based on ROI, which is adapted from the previous study in (Lim et al., 2021). Eqs.(1) to (3) show the ROI of each technology, i, ROI_i is determined based the cost difference of existing, C and new technology, I_i over a given year of operation, Y, and the capital investment cost, $CAPEX_i$. The annual operating cost, $OPEX_i$ is calculated based on the operating cost of energy, e_i, labour cost, l_i, maintenance cost, m_i, and the quantity of equipment, n_i, as shown in Eq.(4). The carbon footprint, $Carbon_i$ is determined based on the operational energy requirement, ER_i and the respective carbon emission factor, EM_i in Eq.(5), while the total exposure time to pesticide, $Exposure_i$ is based on the individual contact time, ICT_i and the number of farmers operating in the site, F_i as shown in Eq(6).

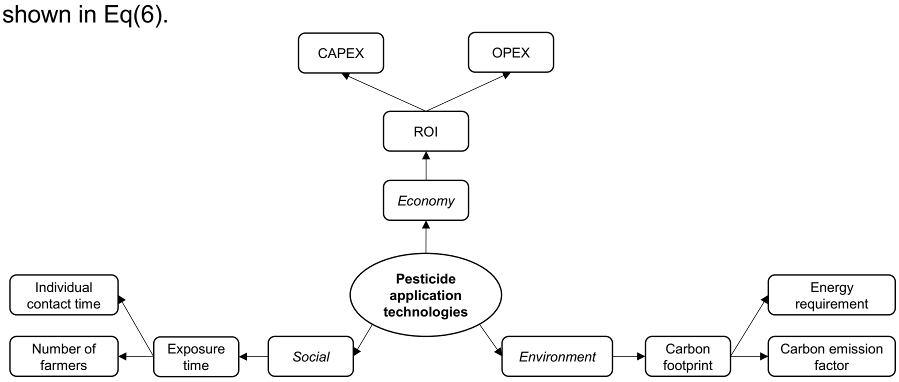

Figure 1: Consideration factors for sustainable pesticide application technologies

$$ROI_i = \frac{Saving\ from\ cost\ reduction}{Capital\ investment\ cost} = \frac{C - I_i}{CAPEX_i} \quad \forall\ i \in I \tag{1}$$

$$C = OPEX \times Y + CAPEX \tag{2}$$

$$I_i = OPEX_i \times Y + CAPEX_i \quad \forall\ i \in I \tag{3}$$

$$OPEX_i = (e_i + l_i + m_i) \times n_i \quad \forall\ i \in I \tag{4}$$

$$Carbon_i = ER_i \times EM_i \quad \forall\ i \in I \tag{5}$$

$$Exposure_i = ICT_i \times F_i \quad \forall\ i \in I \tag{6}$$

Upon identification of the ROI_i, $Carbon_i$ and $Exposure_i$ for each technology, the overall sustainability index, SI_i of the technology is determined based on Eq.(7). The individual performance indices for ROI, carbon footprint and exposure time in Eqs.(8) to (10) are determined with respect to the best and worst solutions among the technologies in comparison. The best technology would give a score of 1; while the worst option gives 0. Note that the index of carbon footprint and exposure time are inversed as lower values represent better performance. The proposed method assumes equal contribution from the economy, environment and social aspects toward the overall sustainability of the technology.

$$SI_i = \frac{I\_ROI_i + I\_Carbon_i + I\_Exposure_i}{3} \qquad \forall\ i \in I \qquad (7)$$

$$I\_ROI_i = \frac{ROI_i - ROI_{min}}{ROI_{max} - ROI_{min}} \qquad \forall\ i \in I \qquad (8)$$

$$I\_Carbon_i = \frac{Carbon_{max} - Carbon_i}{Carbon_{max} - Carbon_{min}} \qquad \forall\ i \in I \qquad (9)$$

$$I\_Exposure_i = \frac{Exposure_{max} - Exposure_i}{Exposure_{max} - Exposure_{min}} \qquad \forall\ i \in I \qquad (10)$$

3. Case study

This section discusses the comparison of 5 technologies for pesticide applications in oil palm plantations including drones, tractors and knapsacks. The introduction of drones in oil palm plantations causes the need for an electrical power source on the plantation site. Accessibility to electricity from the grid could be challenging for plantation sites in rural areas. This study considered 3 different power sources for drone application, grid (T1), gasoline power generator (T2) and solar panel (T3). T2 represents the solution for a mature and portable technology; while T3 considered the green and renewable approach. T4 represents the usage of spray tractors in pesticide application, which is a mature alternative technology to knapsack. T5 represents the traditional approach of pesticide application using a knapsack and the basis of comparison. The comparisons were performed based on the pesticide application cycle of 90 d/y for a total of 5 y of operation in a 22,760 ha of oil palm plantation site. It was estimated that a total of 4 units of drones, 4 units of tractors or 127 units of knapsacks are needed to perform the operation.

Table 1 shows the information included for CAPEX and OPEX calculations. The majority of the cost consideration for T1, T2 and T3 are similar, with the exception of CAPEX and OPEX for power generation. CAPEX for power generation for T1 is assumed to be negligible considering that the electric grid is pre-existed within the plantation site. T2 considered the CAPEX of the gasoline power generator of 1,200 USD/unit; while T3 considered the CAPEX of 8 solar panels with 3 kW of 9,225 USD/unit. Note that there is no additional CAPEX for power generation for both T4 and T5. OPEX for energy was estimated differently for each technology. T1 was estimated based on the electricity tariff (based on Malaysia) of 0.11 USD/kWh, T2 was estimated based on the gasoline consumption for the generator at 0.486 USD/L, T3 was estimated to have negligible cost considering 100 % from solar panels, T4 was estimated based on the diesel consumption for the tractor at 0.55 USD/L and T5 does not have power requirement.

Table 1: Cost data for pesticide application technologies

	Pesticide application technology				
	T1	T2	T3	T4	T5
Coverage (ha/d·unit)	80	80	80	48	1
Number of units	4	4	4	4	127
CAPEX:					
Equipment price (USD/unit)	15,000	15,000	15,000	13,000	50
Power source (USD/unit)	-	1,200	9,225	-	-
OPEX:					
Labour (USD/ha)	0.84	0.84	0.84	0.84	26.78
Operating cost for energy (USD/ha)	0.06	0.28	-	3.03	-
Battery (USD/y·unit)	2,400	2,400	2,400		

The carbon footprint considered in this work was limited to the carbon emissions from the energy generation (the main contributor) for the pesticide application operations. The carbon emission from T1 was taken to be 622 gCO_2/kWh and estimated at 517.5 $kgCO_2$/d based on the battery capacity and charging cycle requirement

(World Benchmarking Alliance, 2022). The carbon emissions from T2 and T4 were estimated based on the carbon footprint of hydrocarbon production (well-to tank) at 0.95 $kgCO_2/L$ (Jhang et al., 2020), and the engine emission of gasoline and diesel at 2.01 $kgCO_2/L$ and 2.33 $kgCO_2/L$ (Energy Information Administration, 2022). T3 and T5 were assumed to have 0 carbon emission as the energy sources are coming from solar power and manual labour. In the social safety aspect, total personnel exposure time to pesticides during the pesticide application was considered. The Individual Contact Time (ICT) to the pesticide for a drone is significantly lower as compared to tractors and knapsacks due to remote operation. The ICT for T1 to T3 was estimated to be 1 h/d while for T4 and T5 were estimated to be 8 h/d based on the standard operating hours with close contact of pesticide at the tractor or knapsack.

Table 2 summarises the calculated ROI, carbon footprint and exposure time for each of the technology. The results show that investment in drones for pesticide application is generally better than tractors and knapsacks. T1 has the highest ROI at 39.9 among the drone technologies due to the low capital cost considered in this study. The facility to charge the drone using electricity from the grid was assumed to be pre-existing at the site. Consequently, T1 would not be the solution for rural oil palm plantations without grid access. The construction of a grid facility was not included in this paper due to the high capital cost and would not be a feasible solution for oil palm plantation stakeholders. In a comparison between a gasoline generator and a solar-powered drone, the latter option shows lower ROI despite the free energy source from solar. This shows the high capital cost of the solar panel remains a barrier to implementation. The actual ROI of T3 would be lower with consideration of the operating and maintenance cost of the solar panel, which is highly dependent on the model and operating condition. For a 3 kW solar panel system, the average operating and maintenance costs could be up to 100 USD/y (Walker et al., 2020). Despite the lower efficiency, the ROI of a tractor is outperforming the solar-powered drone due to the same reason. Note that T5 is considered the existing technology, and it has 0 value in the ROI calculation.

Table 2: Performance comparison for different pesticide application technologies

Technology	ROI (USD/USD)	Carbon footprint ($kgCO_2/d$)	Exposure time (h/y)
Drone powered by grid (T1)	39.9	517.5	720
Drone powered by gasoline generator (T2)	34.0	270.7	720
Drone power by solar (T3)	17.5	0.0	720
Tractor (T4)	23.9	778.7	5,760
Knapsack (T5)	0.0	0.0	91,440

In terms of carbon footprint, this work only considers the footprint contributed from the energy usage for pesticide application operation at the oil palm plantation site. T3 and T5 have zero footprint to power the equipment used in pesticide applications as they are using solar and labour energy. Interestingly, the result shows that utilising a gasoline generator to charge the drone for the same operation has the lowest carbon footprint, followed by using electricity from the grid and a spray tractor with a diesel engine. Note that the carbon footprint from the grid is highly dependent on the source of power generation. In this case, the data is based on the emissions in Malaysia where the electricity is mostly generated by coal power plants. In the social safety aspect, the comparison shows that drone operation (T1 to T3) is significantly better as compared to T4 and T5. Due to the reduction of close contact time with pesticides in the remote operation, the concentration of the pesticide could be increased for higher efficiency operation and performance. Research on the optimum dosage of pesticides can be performed without the consideration of health concerns. In the comparison between spray tractor and knapsack, the ICT for both technologies are identical at 8 h/d. T5 has a significantly higher impact in the safety concern due to the involvement of a higher number of operators which increases the collective exposure time to pesticides for the same operation.

The results indicate each of the proposed technology performs well in different aspects of sustainability. Figure 2 shows the comparison of the performance indices for T1 to T5. The factor of ROI in T1, T2, T3, T4, and T5 were calculated to be (1), (0.852), (0.439), (0.600) and (0). The factor of the carbon footprint was calculated to be (0.332), (0.651), (1), (0), and (1), and the factor of exposure time to pesticides was calculated to be (1), (1), (1), (0) and (0). T1 with the highest ROI does not perform well in carbon footprint, while T3 and T5 with the lowest carbon footprint have low economic potential. An ideal solution for sustainable technology should have a high ROI, low carbon footprint and low safety risk of exposure time pesticides.

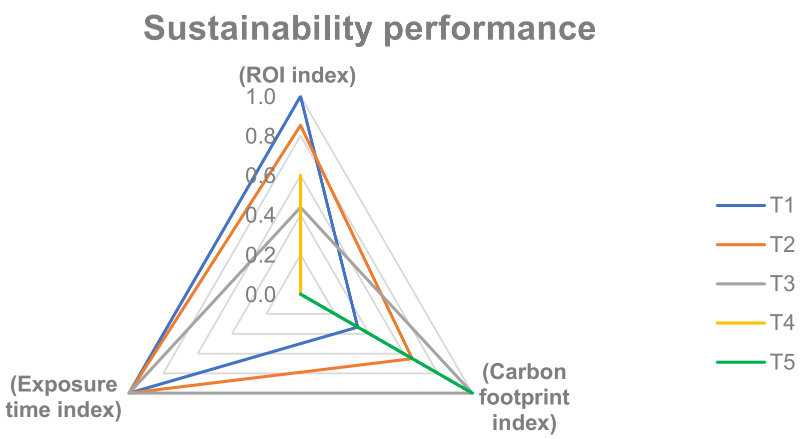

Figure 2: Sustainability performance for, T1: spray drone powered by grid, T2: spray drone powered by gasoline generator, T3: spray drone powered by solar, T4: spray tractor powered by diesel, and T5: manual knapsack

Figure 3 shows the comparison of the overall sustainability index for each of the technology with the consideration of the equal importance of ROI, carbon footprint and exposure time. In general, spray drone powered by a gasoline generator is the best option among the technologies included in this study at (0.834), followed by T3, T1, T5 and T4 at (0.813), (0.777), (0.333), and (0.200). Interestingly, the result shows that the spraying tractor is the worst option, compared to the knapsack, which is mainly affected by the high carbon footprint. Rectification of the problem, such as utilising bio-diesel, may improve the overall sustainability performance of T4. The results have provided insight into the potential of various pesticide application technologies to promote a more sustainable oil palm production. Despite that, several factors could be incorporated in future work to enhance the accuracy of the calculation model. For example, consideration of hybrid electricity usage from grid and solar panel to consider the downtime of solar panel, comparison of diesel and bio-diesel utilisation, sharing portable generator for large scale operation to reduce capital cost, and the various operation efficiency for spray drone with different pesticide concentration.

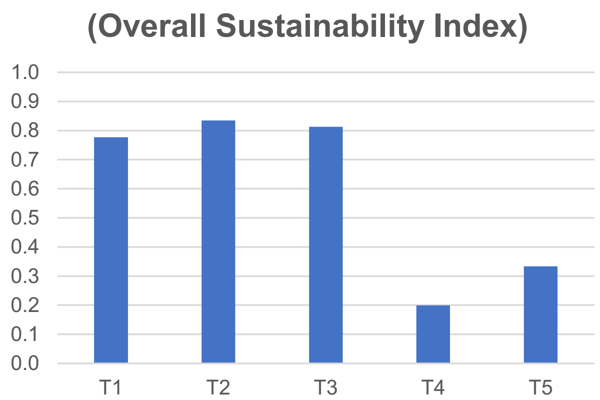

Figure 2: Overall sustainability index for, T1: spray drone powered by grid, T2: spray drone powered by gasoline generator, T3: spray drone powered by solar, T4: spray tractor powered by diesel, and T5: manual knapsack

4. Conclusions

This paper investigates the sustainability performance of pesticide application technologies for oil palm plantations. The result shows that utilising spray drones powered by electricity from the grid would generate higher ROI, subject to the site having access to power from the grid. Solar-powered drones and knapsacks represent a promising technology with a minimal carbon footprint to perform pesticide applications since all drone applications would provide safer operating conditions for farmers. Spray drones powered by gasoline generators are found to be the most sustainable technology with the highest sustainability index of (0.834). These results would assist stakeholders to compare the existing practice and IR4 technologies to move towards Industry 4.0 Revolution, where a clear and quantitative improvement of ROI, carbon emission, exposure time and overall sustainability were presented. The proposed model for sustainability analysis is limited to the carbon emission from energy usage, which could be further extended to incorporate the footprint based on life cycle analysis. Future works also could consider a time-dependence model for IR4 technologies application in pesticide application and other oil palm operations such as harvesting and monitoring.

Nomenclature

C – Total cost of existing technology, USD
$CAPEX$ – Capital cost of existing technology, USD
$CAPEX_i$ – Capital cost of new technology, i, USD
e_i– Operating cost of energy for technology, i, USD
EM_i– Carbon emission factor for technology, i, kW
ER_i– Operational energy requirement for technology, i, kW
F_i– Number farmer for technology, i
$Exposure_i$ – Total exposure time for technology, i, h
I_i– Total cost of new technology, i, USD
l_i– Labour cost of technology, i, USD
ICT_i – Individual contact time of technology, i, h
I_Carbon_i– Carbon footprint index of technology, i
$I\_Exposure_i$– Exposure index of technology, i
I_ROI_i– ROI index of technology, i
m_i– Maintenance cost of technology, i, USD
n_i– Quantity of equipment in technology, i, USD
$OPEX$ – Operating cost of existing technology, USD
$OPEX_i$ – Operating cost of technology, i, USD
ROI_i – Return on investment of technology, i
SI_i– Sustainability index of technology, i
Y – operation year, y

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