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New mechanized system for circle spraying of oil palms seedling emergence

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ABSTRACT:, A new machine system has been designed, developed and evaluated for extensive circle spraying of oil palms (*Elaeis guineensis* Jacq.) in an effort to overcome the inefficient spraying problem with the conventional spraying system. The machine system consists of a four-wheeled drive 4WD prime mover with front mounted machine attachments for the circle spraying operation. The configuration of the circle spraying attachment consists of a hexagonal curved spray boom, lifting arm, opening-tilting mechanism unit, storage tank, spray pump, solid cone nozzles, and associate hydraulic system. Field performance tests on the machine system showed an average effective field capacity of 7.89 ha per man per day and when compared to the earlier reported effective field capacity of the walking spray-operated equipment using Serena LT16 knapsack sprayer; a difference of 1.97 time for circle spraying of mature palms grove. Reduction in the human energy expenditure of 101.28 kJ man^{-1} h^{-1} or 10.68 % but an increase in the spraying cost of 1.53 USD ha^{-1} or 24.9 % were obtained with the machine system against the walking spraying-operated equipment using Serena LT16 knapsack sprayer. Justification for machine system to be cost effective could be satisfied if the present effective field capacity is increased to 1.263 time with good skilled operator or if the current R&D cost is reduced to 0.41 time. This is because the improved field capacity of new machine system could not rationalize its current R&D cost. Admittedly, the machine system has great potential to overcome the limitations with the current employed machine/equipment in the circle spraying operation of oil palms in the plantation.

Keywords: chemical spraying, oil palm cultivation, agricultural machinery, mechanization

Introduction

Good weed control around palms (*Elaeis guineensis* Jacq.) not only aims to reduce nutrients competition between the palms and surrounding weeds but could also facilitate effective fertilising, harvesting, and in-field fresh fruit bunch (FFB), and loose fruit collection-transportation operations in the plantations (Turner and Gillbanks, 1974). The circle for weed control around the base of planted palm tree is usually 1.0 m radius at the time of planting and is gradually expanded to 2.0 m by the time the palm has reached 18 to 24 months. However, precaution to avoid contact of the translocated chemicals with the palm foliage is required when spraying immature palms of less than two years old (Orme, 2001).

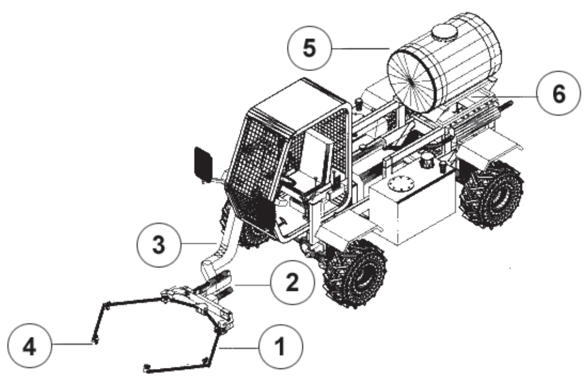
Currently, walking spraying hand lever-operated knapsack sprayer, Controlled Droplet Applicator (CDA) knapsack sprayer and 'Serena' knapsack sprayer are the commonly used equipment for weed control in the oil palm plantations. The walking spraying hand lever-operated knapsack sprayer has a tank of 18 L capacity and requires 450 L volume of water for a hectare spray area. The dry cell battery powered CDA knapsack sprayer has a tank of 10 L capacity and requires only 25 L volume of water for a hectare spray. Despite the reduction in the water requirement, this sprayer consumes high battery power and thus gives higher downtime to replace the battery. The spray penetration produced is poor due to gravity flow and none pressurized of the liquid in the system. The walking spraying rechargeable battery-powered "Serena" knapsack sprayer has a tank capacity of 16 L and requires 50 L volume of water for a hectare spray (Orme, 2001). For all the three systems, the field capacity for the spraying is still low since the operator while carrying the tank on his back has to walk from palm to palm do the spraying on each available palms within the specified spraying area. He also has to make frequent trips to the nearby refilling point in the field to refill the empty sprayer tank while at times he has to carrying water from a remote source to the refilling point for the preparation of the spray mixture. Pebrian et al. (2010) indicated that circle spraying using walking type Serena knapsack sprayer was the second most critical field operation among the twelve important field operations in the oil palm cultivation in Malaysia.

Ultimately, there is need to design and develop a completely machine system that is capable of performing circle spraying operation in the oil palm plantation in Malaysia. The machine should be completely mechanized, self-contained, continuous once-over-operation, simple in construction and operation, flexible to use, economical, reliable and sustainable.

Materials and Methods

The newly developed mechanized system for circle spraying of oil palm consists of a universal prototype 4WD prime mover and a prototype circle spraying attachment (Figure 1). The configuration of the circle spraying attachment consists of the hexagonal curved spray boom, opening-tilting mechanism unit, lifting arm, solid cone nozzles, storage tank, spray pump, and associate hydraulic system as in Figure 2. The universal prime mover, which is to be used as carrier for circle spraying attachment was equipped with a 51 kW @

Figure 1 – Prototype prime mover with circle spraying attachment for spraying the palm circle.



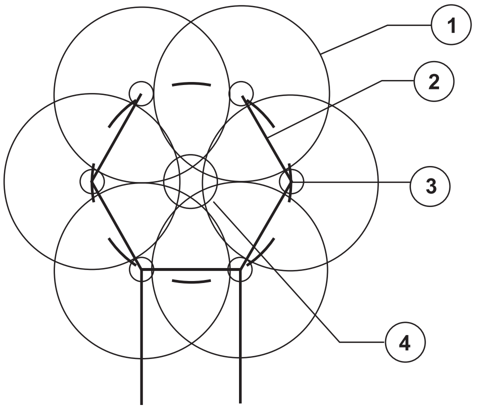
1. Hexagonal curved spray boom
2. Opening-tilting mechanism unit
3. lifting arm
4. Solid cone nozzles
5.Storage tank
6.Spray pump

Figure 2 – Design concept of the prototype 4WD universal prime mover with circle spraying attachment.

2,600 rpm water-cooled Kubota V-3300 diesel engine that directly couple to a Sauer Danfoss Series 40 main pump with a displacement of 46 cm^3 rev^{-1} at continuous pressure of 21 MPa. The Sauer Danfoss Series 40 main pump runs two units of Eaton Char-Lynn Series 2000 hydraulic motors with a displacement of 245 cm^3 rev^{-1} at continuous pressure of 20.5 MPa in the closed loop system to enable the prime mover to be propelled either in series or parallel drive modes. The hydraulic power in the open loop system was available to run the respective hydraulic cylinders and motors in the steering system of the prime mover and its machine attachments. This hydraulic power for circle spraying attachments was run by a Ronzio-6 gear pump with displacement of 11 cm^3 rev^{-1} at 30000 kPa continuous pressure that are connected in-tandem to the Sauer Danfoss Series 40 main pump. Computations were made to determine the required actual flow rate for the relevant actuators in the hydraulic systems of the circle spraying attachments. The calculated flow rate of the whole relevant actuators in the hydraulic systems of the circle spraying attachments was found to be 28.6 L min^{-1}. The computed flow rate of the available actuators within the hydraulic system was enough to run the operational steps of the circle spraying attachment, which include tilting the hexagonal curved spray boom, opening-closing the spray boom arms and raising the lifting arm and hexagonal curved spray boom.

The hexagonal curved spray boom for circle spraying comes with two sizes; the boom side 0.725-m long for immature palms, which are younger than two years; and the boom side 0.975-m long for mature palms, which are older than five years. Both of these hexagonal curved booms have been designed to accommodate a circle spraying radius of 1.0 m and 1.75 m from the centre of palms base as recommended by Turner and Gillbanks (1974) and at the nozzle height position of 0.60 m from the ground for immature and mature palms, respectively. The hexagonal curved boom was purposely adopted in the design concept of spray boom since it is easier to fabricate with the nozzle arrangement still within the circumferential of the spray coverage. One end of the lifting arm is pivoted to the support stanchion on the prime power chassis having two side-by side hydraulic cylinders positioned for its up-down movements. The other overhang end of the lifting arm holds the opening-tilting mechanism unit from which the hexagonal curved spray boom is fitted. Two separate miniature hydraulic cylinders are used on the opening-tilting mechanisms for the respective movements by the hexagonal curved spray boom. With such combinations, the two sizes hexagonal curved spray boom could be at wide open for 1.10 m and 1.40 m, respectively and both could be fully tilted at 45 degrees below the horizon.

The sprayer runs on a ST Series FS-600 polyethylene cylindrical tank with 600 L capacity that is mounted behind the prime mover. A 12 volt DC Shurflo 8000 Series pump with 6.80 L min^{-1} maximum flow and 10.30 bar maximum operating pressure are used to provide the required spraying pressure to a total of 6 units of ST Spray Nozzle FCX02 solid cone yellow nozzles with spray swaths of 1.20 m and spraying angles of 80 degree. A total of six nozzles in the an hexagonal arrangement shown in Figure 3 were required to provide a spray coverage with 1.0 cm and 1.75 m radius based on the theoretical spray swath (spray diameter) and spray angle of the chosen nozzle. Spray swath (spray diameter) refers to the area sprayed by each nozzle in the hexagonal curved spray boom. Spray coverage refers to the area sprayed by the total of six nozzles in the hexagonal curved spray boom. Each of the nozzles was position at all the corners of the hexagonal curved spray boom. A multilayer plastic hose having internal diameter of 10 mm and 2.0 mm thickness was used to deliver the spray liquid from the tank to the respective nozzles.



1. Theoretical nozzle spray diameter 3. Nozzle
2. Hexagonal curved spray boom 4. Expected palm trunk diameter

Figure 3 - Spray coverage and the individual spray swath.

This spray boom design was able to distribute the spray liquid onto the targeted weed area around a palm with the circle spraying diameter of about 2.0 m from the boom with 0.725 m side length (i.e boom A) for immature palms and about 3.50 m from the boom with 0.975 cm side length (i.e boom B) for mature palms. Solid cone nozzle was chosen for the sprayer since the nozzle type known to produce uniform, round, medium-to-large sized droplets and medium-to-large flow rates for full spray pattern coverage. According to the nozzle manufacturer, such spray characteristics are ideal to deliver spot spraying to the tall and dense weeds which commonly exist around the base of planted palm trees.

The prime mover with the circle spraying attachments were tested using clean water only in the laboratory for their nozzle spray angles, spray swath, flow rates and spray distribution. The use of clean water followed the procedure of boom sprayer nozzle performance test reported by Dean (2008). In the conducted test, the prime mover with circle spraying attachment was immobile and all the windows and doors in the laboratory to reduce occurrence of spray drift. The spray boom was rigidly set at 0.60 m height from the ground level and the nozzles were numbered from 1 to 3 in a clockwise direction starting from the front most nozzles on the right hexagonal curved spray boom arm and from 6 to 4 in an anti-clockwise direction starting from the front most nozzles on the left hexagonal curved spray boom arm. A 1.0 L catch container was placed below each available nozzle on the circle spraying attachment. The flow rate spray delivered by the respective nozzles was computed based on the volume collected by catch container for 15 seconds spraying duration. The spray swath at each individual nozzle was computed using the geometry of the measured sprayed angle and the predetermined height of the sprayed water.

Brief laboratory tests were also conducted on the prime mover with circle spraying attachment to check on the uniformity of their spray pattern during operation. A total of 49 petri disks in 0.3 m square grids were used to cover the 1.80 × 1.80 m^2 floor area with the test using 72.5 cm side length hexagonal curved spray boom while a total of 64 petri disks in 0.45 m square grids were used to cover the 3.60 × 3.60 m^2 floor area with the test using the boom side 0.975-m long. These grid sizes were arbitrarily selected to cover the actual spray swath areas in chemical field spraying on immature and mature palms. Under both situations, the hexagonal curved spray booms were positioned at 0.6 m height above the center point of the catchment's area. Spraying durations of 3 and 6 seconds were set in the test for the boom side 0.725-m and the 0.975-m long. The complete test was replicated three times and the individual Petri disks after each test were weighted to determine for the amount of collected spray. Surfer 7 software was used to produce the contour maps of the spray distribution for each circle spraying attachments.

Field performances evaluations on the prime mover with circle spraying attachments were conducted on 30 ha gazette test area in Labu, Negeri Sembilan, Malaysia (2°46′2″ N and 101°48′42″ E). The area has an undulating terrain with heavy undergrowths on the surface while the available machine paths have scattered patches of exposed surfaces due to the formation of gullies. The adopted planting density is 127 palms per hectare with 12 to 15 palms per planting row. The variety planted within the area is Dura × Pisifera with plant age of almost 21 years which is being categorized as mature palms. A detailed time and motion study on the circle spraying operation using the machine system was conducted continuously for three days with the days taken as replications in this field evaluation test. Only one machine operator was involved throughout the test to minimize the effects of man-machine interaction variations with multiple operators on the machine field performance.

Since it a newly developed machine system, the selected operator had to undergo proper on-the-job training in handling the machine system for the field operation prior to the actual field test. The measured parameters in the circle spraying operations included time for spraying individual palm, traveling between palm locations, and lastly, cornering at headlands. The total time for circle spraying was calculated as the sum of time spent for spraying individual palm, traveling between palm locations, and cornering at headlands. Time for spraying individual palms tree refers to the total time at the instant when the machine system stops beside the palm for the spraying operation until it starts to move to the next palm tree for the next spraying operation. Time for traveling between palm tree location refers to the total time taken when the machine starts to move to the next individual palm tree after completing the earlier spraying operation until it stops close to the individual palm tree for the next spraying operation. Time for cornering at headlands is taken when the machine starts to move out from the first machine path until it enters to the next machine path while turning at the field headland. Duncan's Multiple Range Test (DMRT) was conducted to compare the differences of the breakdown of average time for the circle spraying operations with the machine system.

Measurements on the heart rates of the machine operator while conducting the circle spraying operation with the machine system for each day of operation were recorded using a Polar S810M Heart Rate Monitor (Polar Electro, Oulu, Finland). This equipment comprised of a wrist receiver and a polar heart rate transmitter. Immediately after the field test, the stored data in the wrist receiver of the subject were downloaded into a computer at the laboratory for post processing. Mean increase in heart rate of the machine operator was computed by subtracting the recorded average heart rate of the subject with his or her initial resting heart rate. Energy expenditure of the machine operator per hour was computed by dividing the recorded human energy expenditure of the machine operator with the recorded time of the completion operation in a day.

Field capacity of an operation per hour was computed by dividing the total completed assigned area by the machine operator with the recorded time of the completion operation in a day. Measurements on volume of the fuel and the duration of time used by the machine system were taken after the completion of the circle spraying operation for each day of operation to compute for the fuel consumption of the machine system. The volume of fuel used by the machine system was recorded by measuring the amount of fuel to fill back the fuel tank of the machine system to its full capacity. Measurements on the diameter of the eradicated-weeds area around the treated palms one week after the completion of the circle spraying operation were made to quantify the effectiveness of the circle spraying operation using the machine system. A total of 20 palms within the area covered on the third day of spraying operation were randomly selected for this purpose.

Comparisons on both the obtained machine system effective field capacity and the machine operator's physiological impact were made against the published data by Pebrian et al. (2010) on the semi mechanized system using the walking spraying rechargeable battery powered Serena LT 16 knapsack sprayer for circle spraying of palms.

The estimated economic life of the machine systems was computed based on the economic life of 16000 hours for a 4WD tractors in ASAE Standard EP 497.5 FEB2006 (ASABE, 2006a) divided by the total operating hours of the individual machine system in a year. The proposed economic life was considered since the prime mover itself acts a as multipurpose carried for conducting other field operations in oil palm cultivation such as seedling transplanting, fertilizer application, in-field fresh fruit bunch collection-transportation and etc. The actual total annual operating hours of the prime mover with circle spraying attachment for spraying operation was expected to be 2,038 h based on the operation frequency of four times a year, average oil palm plantation estate size of 1,005 ha, and machine system field capacity of 7.89 ha^{-1} per day. The machine system was assumed to have salvage values of 10 % of its initial purchase price (Kepner et al., 1982). Tax, shelter, and insurance are 2 % of the total initial costs of the machine systems in accordance to ASAE Standard EP 496.3 FEB2006 (ASABE, 2006a). An interest rate on the higher extreme value of 10 % was assumed under the present economic scenario in Malaysia. Repair and maintenance factors *RF1* of 0.003 and *RF2* of 2.0 were assumed for the machine systems based on the value of repair and maintenance factors for the 4WD tractors in ASAE Standard EP 497.5 FEB2006 (ASABE, 2006b). Lubricant costs of the machine systems were estimated to be 15 % of their fuel costs based from Kepner et al. (1982). The daily standard wage for a tractor operator in an oil palm plantation is 1.46 USD h^{-1} based from the personal communications made with two plantation managers in the Selangor and Pahang states.

Results and Discussion

Generally, spray swath increased with increasing spray angle and spray flow rates (Table 1). With the hexagonal curved spray boom, smaller spray swaths were observed at the nozzles number 1 and 6 since the spray angles and flow rates at these two locations were minimized. These phenomena occurred because the nozzles were located at the far end of the spraying line in the spray booms and there was a drop in the pressure as the liquid flows to the end most point in the spray line. The measured nozzle spraying characteristics data from the hexagonal curved spray boom were later used to determine the application rate and spraying time duration for circle spraying operation with the prime mover.

Figure 4 and Figure 5 show the respective typical contour maps of spray patterns uniformity for the hexagonal curved spray boom A and the hexagonal curved spray boom B of the circle spraying attachment as the results from the laboratory test. Square count method was used to calculate the unsprayed areas in the respective

Table 1 – Nozzles spraying characteristics of the hexagonal curved spray boom.

Nozzles Number	Spray angle, degree	Spray swath	Flow rate
		cm	L min^{-1}
2	80[a]	100.69[a]	0.980[a]
5	79.33[a]	100.69[a]	0.976[a]
3	78.67[a]	98.34[a]	0.966[a]
4	78.33[a]	97.17[a]	0.960[a]
6	73.33[b]	89.39[b]	0.707[b]
1	70[c]	84.02[c]	0.693[b]

Means in a given column having suffices with the same letters are treated not different ($p < 0.05$).

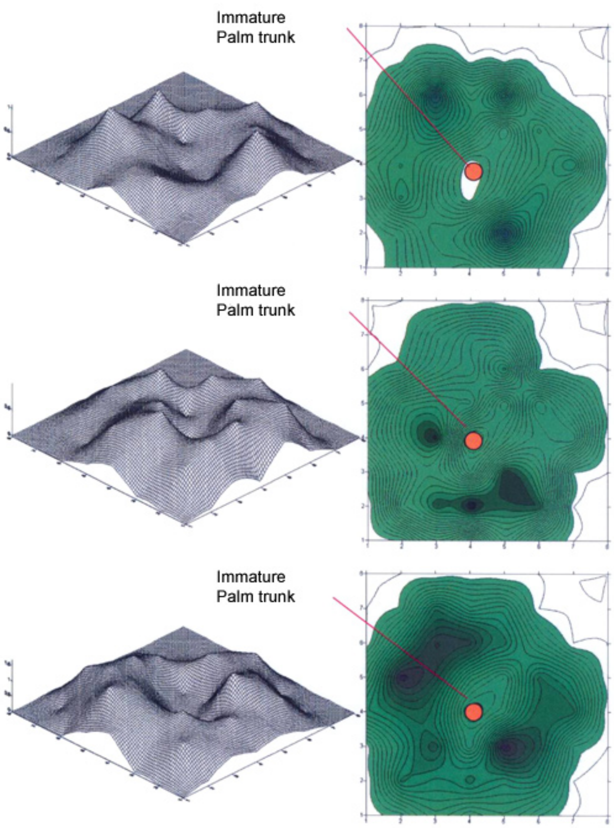


Figure 4 – Pattern of uniformity of spray distribution with the hexagonal curved spray boom having side length of 72.50 cm (i.e boom A).

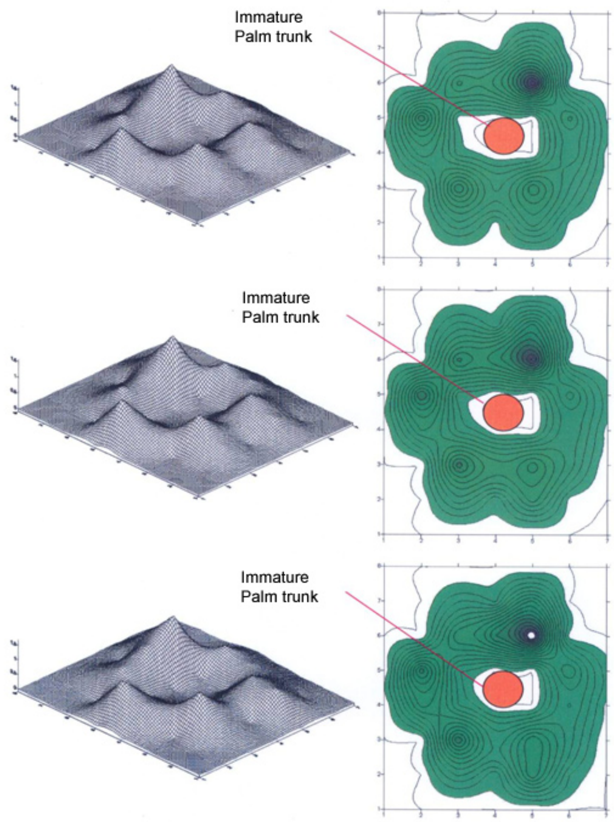


Figure 5 – Pattern of uniformity of spray distribution with the hexagonal curved spray boom having side length of 97.50 cm (i.e boom B).

spray contour maps. Any square with equal and greater than half sprayed area was counted as a full sprayed area while any sprayed area less than half square was consider as an unsprayed area. Generally, the sprayers were able to distribute the spray droplets throughout the targeted area. Higher spray distribution was found exactly below the each nozzle positions as indicated in the produced wireframe map. Overall, the hexagonal curved spray boom A gave an average total spraying swath of about 2.1 m. This measured average total spraying swath was about 87 % of the earlier predicted spraying swath. However, the average total spraying swath was adequate to fulfill the recommended spraying diameters of 1.5 m to 2.0 m for chemical spraying on immature palms (Janick and Paull, 2008). Almost the entire targeted area was successfully sprayed with this spray boom. With the current boom size, the sprayer could be categorized under low spray volume application rate sprayer since the measured application rates were in the range of 16.32 to 125 L ha^{-1}. There was no unsprayed area within the total spray coverage but the oversprayed area ranged from 0.21 to 0.48 m^2 within the total spray coverage.

Overall, the hexagonal curved spray boom B had an average total spraying swath of about 3.15 m. This measured average total spraying swath is about 95.34 % of the earlier predicted spraying swath. Again, the average total spraying swath was adequate to fulfill the recommended spraying diameters of 2 m up to not more than about 4 m for chemical spraying on mature palms (Janick and Paull, 2008). With the current boom size, the sprayer could be again categorized under low spray volume application rate sprayer since the measured application rates were in the range of 10.66 to 26.70 L ha^{-1}. The small unsprayed area ranged from 0.75 to 0.90 m^2 at the center of the spay coverage while the oversprayed area ranged from 0.20 to 0.26 m^2 within the spray coverage. The coefficient of variation in the deposits were 74.3 % and 56 % for the nozzles in the hexagonal curved spray boom with 72.50 cm side length boom A and the hexagonal curved spray boom B, respectively. This coefficient of variation was even higher than that of 5 % to 17 % for static boom as well as of 6 % to 37 % for moving (at 6 to 26 km h^{-1}) boom as reported by Womac et al. (2001) and Lardoux et al. (2007). The side length of spray boom and nozzles overlap influenced the coefficient of variation in the deposits. The hexagonal curved spray boom with 72.50 cm side length gave a higher coefficient of variation since it had a smaller side length, which enabled to create a higher overlap between the individual nozzles on the spray boom.

Table 2 – Effective field capacity of machine system for circle spraying operation.

Days operation	Effective field capacity	Effective field capacity
	ha ha^{-1}	ha man^{-1} per day
1	0.83	6.64
2	0.97	7.76
3	1.16	9.28
Average	0.98	7.89

The average effective field capacity for circle spraying operation with the machine system was found to be 0.98 ha man^{-1} h^{-1} which was equaled to 7.89 ha man^{-1} per day with eight committed working hours per day (Table 2). Circle spraying operation under the semi-mechanized system using rechargeable battery-powered Serena LT16 knapsack sprayer as reported by Orme (2001) claimed to have an average effective field capacity of 4 ha per man per day which was about 1.97 time lower than the proposed mechanized system. The effective field capacity of the machine system increases with the consecutive days of operations (Table 2). This trend occurred because the machine operator had acquired the skill to the new spraying technique with the days of operations. The effective field capacity was also being affected by the field conditions, especially the areas around the palm trunk. Uneven field conditions around the palm trunk due to the presence of the anthills and gullies had slowed down the performances of circle spraying operation with the machine system.

The machine operator took considerably amount of time to direct the hexagonal curved spray boom to envelope the palm trunk and adjust the hexagonal spray boom to the recommended spray height position. In addition, the performance of the machine system was much affected at the headlands where the area width was normally restricted and the terrain surface conditions were not favorable for machine movements. Thus, the machine operator seemed to take longer time for cornering at the headland upon entering into the next machine paths for new spraying operation.

On first day of operation, the machine system operates at a much lower effective field capacity due to the poor man-machine interactions. The field conditions around the palm trunk on that day was dominantly surrounded by anthills and gullies that had given the machine operator much difficulty in driving the machine system to the targeted palm and positioning the hexagonal curved spray boom around the palm. These conditions became worst at the headlands where some areas were not accessible for the machine system to make cornering. Under such situations, there was a lot of time lost for the operator to play with both the steering wheel and forward-reserve control lever in maneuvering the machine system for cornering. The third day of operation showed the highest effective field capacity of the machine system. On this day, the operator had acquired both the experience and skill to operate the machine system besides having terrain surfaces with minimum anthills and gullies and better machine accessibility at the headlands. Such terrain topography and field layout represents the typical terrain and field conditions for the oil palm plantation in Malaysia. Even though such conditions are not ideal for any machine operation, any mechanized system is still acceptable as long as the terrain slope is not greater than 18 degrees and the introduced system could alleviate the total dependence of human labor in conducting the field operation.

Table 3 – Breakdown of average time in circle spraying operation.

No	Task	Time range	Mean time	Proportion
		s	s	%
1	Spraying individual palm	8 to 43	11.45^{c}	20.12^{c}
2	Traveling between palm locations	9 to 111	16.64^{b}	29.25^{b}
3	Cornering at headlands	17 to 67	28.80^{a}	50.62^{a}

Means in a given column having suffices with the same letters are not different ($p < 0.05$).

There were differences ($p < 0.05$) in the mean time of tasks for the machine system (Table 3). Cornering at the headland task had the highest mean time as compared to the rest of the tasks within the circle spraying operation using the machine system. Spraying individual palm was the lowest time consuming task within the circle spraying operation. Time for spraying individual palm was much influenced by the field conditions around the palm trunk and the operator skill in placing the hexagonal curved spray boom exactly at the center of the palm. Precise placement of the hexagonal curved spray boom was not only dependent on field condition around the palm trunk, but also on the operator's expertise in operating the machine system. The placement was considered to be precise only if the center of hexagonal curved spray boom coincides with the center of the palm trunk and the height of the hexagonal curved spray boom is at 0.60 m above the terrain surface. Occasionally, the operator had to spend extra time to position the spray boom to meet these requirements due to uneven terrain topography in the plantation estate.

The time spent for traveling between palms was very much dependent on skill of the machine operator to direct the machine system to the targeted palm in the field where circle spraying need to be done. The measured average fuel consumption of the prime mover with circle spraying attachment was 3.14 L h^{-1} (Table 4). The measured fuel consumption on the first day was much higher than the rest days of operation. Due to the terrain conditions as earlier explained, the machine operator had to operate the machine system at higher engine throttle at most times which later caused it to consume more fuel than the rest of the tested days.

The measured spray swath around the randomly selected palms within the tested field area (ranged from

2.7 m to 3.5 m (Table 5), which was within the range mentioned by Janick and Paull (2008) for mature palms. The spraying swath was very much dependent on the operator's ability in adjusting the height position of the hexagonal curved spray boom during the spraying operation. Much difficulty in the adjusting the boom height of the machine system was experienced on sloping or uneven terrain. Setting the sprayer's boom at higher height would result with bigger spray swath while setting it at lower height would result with smaller spray swath.

From results of the operator's physiological impact, circle spraying operation by the prime mover with circle spraying attachment was 11% time less exhausting on basis of the measured of the human energy expenditure, 68% time less demanding on the basis of the measured mean increase in heart rate and 178% less dawdling on the basis of the measured average field capacity than the operation by the Serena LT16 knapsack sprayer. The energy expenditure of machine operator was 947.64 kJ $man^{-1} h^{-1}$ or a reduction of 101.28 kJ $man^{-1} h^{-1}$ or 10.68 % was obtained for circle spraying operation as compared to the circle spraying operation with Serena LT16 knapsack sprayer. Obviously, circle spraying operation with machine system was not only be able to give the better field performances but also able to give better operator comfort as compared to the operation with Serena LT16 knapsack sprayer.

The total cost for circle spraying operation by the machine system was 6.03 USD h^{-1} (Table 6). With a known average effective field capacity of 0.98 ha h^{-1}, the total cost for circle spraying operation with the machine system is equal to 6.15 USD ha^{-1}. Fuel consumption cost shows the highest percentage cost breakdown with a value of 26.79 % of the total operation cost. Tax, shelter and insurance cost show the lowest percentage cost breakdown with a value of 3.08 % of the total operation cost for circle spraying with the machine system. Even though tax, shelter and insurance cost normally constitute as minor costs in the total operation cost of the machinery, should not to be left out in the cost analysis of any machinery.

The Serena LT16 knapsack sprayer has a single nozzle having flow rate of 0.315 L min^{-1} and volume application rate of 50 L ha^{-1}. This sprayer has estimated market price of USD 243 per unit and estimated economic life of five years. The sprayer tank has to be refilled twice for every hectare of sprayed area. Whilst, the prime mover with circle spraying attachment has six nozzles on its boom with a total flow rate of 5.280 L min^{-1} and volume application rate of 114 L ha^{-1}. Having 600 L tank capacity, the machine system has the ability to spray more than 5 ha without any refilling to its tank. Thus, a downtime saving for refilling the water of ten times was obtained from the prime mover with circle spraying attachment over the Serena LT16 knapsack sprayer.

A spraying cost increment per hectare of 24.9 % or an additional cost of USD 1.53 ha^{-1} was obtained from the prime mover with circle spraying attachment over the Serena LT16 knapsack sprayer (Table 7). Higher total cost of the prime mover with circle spraying

Table 4 – Fuel consumption of the machine system in circle spraying operation.

Days	Fuel consumptions
	L h^{-1}
1	3.17
2	3.15
3	3.13
Average	3.14

Table 5 – Spraying swath of the sprayed area by the prime mover with circle spraying attachment.

Palm tree no.	Spray swath
	m
1	3.5
2	3.4
3	3.2
4	3.0
5	3.1
6	3.0
7	3.1
8	3.0
9	2.7
10	3.0
11	2.7
12	2.7
95 % CI	3.03 ± 0.26

Table 6 – Costs breakdown in circle spraying operation.

Cost component	Cost	Percent. from total cost	Rank based on the highest cost
		%	
Depreciation cost, USD h^{-1}	0.84	13.99	4
Interest on investment cost, USD h^{-1}	0.51	8.53	5
Tax, shelter and insurance cost, USD h^{-1}	0.18	3.08	7
Repair and maintenance cost, USD h^{-1}	1.16	19.35	3
Fuel consumption cost, USD h^{-1}	1.61	26.79	1
Lubricants costs, USD h^{-1}	0.25	4.03	6
Operators cost, USD h^{-1}	1.47	24.23	2
Total spraying operation cost, USD h^{-1}	6.03	100	

Table 7 – Comparisons on costs and effective field capacity between the prime mover with circle spraying attachment and commonly used equipment.

Parameter	Prime mover with circle spraying attachment	Serena LT16 knapsack sprayer	Differences
Effective field capacity, ha per day	7.89	4	1.97 times
Cost, USD ha^{-1}	6.15	4.61	+ 24.90 %

attachment since its initial market price is much higher than the Serena LT16 knapsack sprayer. The market price of prime mover with circle spraying attachment is about 78 times of the Serena LT16 knapsack sprayer market price, while the improvements on effective field capacity by using the machine system are only about 1.97 time. The effective field capacity of the prime mover with circle spraying attachment could not justify its high initial cost in order for the machine system to be economical feasible over the Serena LT16 knapsack sprayer. The operating cost of the prime mover with circle spraying attachment for the circle spraying operation could be made comparable with the current operating cost with Serena LT16 knapsack sprayer by either increasing the effective field capacity or reducing the initial cost of the machine system. Increasing the effective field capacity of the machine system to a value equal or greater than 1.33 ha h^{-1} (i.e 26.3 % increased) or reducing the initial cost of the machine system to USD7714.28 (or 0.41 times reduction) would qualify the machine system to be cost effective over the Serena LT16 knapsack sprayer for circle spraying operation. A compromise between these two mentioned values could made the machine system to be economically feasible since the present effective field capacity could be further improved as the machine operator attained the required operational skill and the present initial cost of the machine system could be further reduced under mass production.

Conclusions

The obtained total spraying swath was adequate to fulfill the recommended spraying diameters for chemical spraying on both immature and mature palms. Generally, the introduced mechanized system machine has great potential to overcome the limitations faced by the current machine/equipment for circle spraying operations in the oil palm plantation in Malaysia. However, plumbing components on the hexagonal curved spray boom need to be re-examined in order to reduce the reduction in flow rate from nozzles 6 and1 which was found to be the prime cause for the high spray coefficient of variation.

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