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COSTS EVALUATION OF AUTOPILOT TRACTOR-MOUNTED REAL-TIME SENSORS FOR PLANT AND SOIL MONITORING OPERATION IN OIL PALM CULTIVATION

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ABSTRACT

As a major input of capital investment in mechanised agricultural operations, farm machinery cost is important to be evaluated before making decisions for its further adoption. This study aimed to evaluate the total costs of an autopilot tractor-mounted real-time plant Nitrogen (N) sensor and autopilot tractor-mounted real-time soil electrical conductivity (EC) sensor for plant and soil monitoring operation in oil palm cultivation. The estimated total cost for operating an autopilot tractor-mounted real-time plant N sensor was RM5.51 ha^{-1} or 45.00% lower than that of the current practice in immature palm fertilising operations. Whilst, the estimated total cost for operating an autopilot tractor-mounted real-time soil EC sensor was RM6.90 ha^{-1} or 31.14% cheaper than that of the current practice. Considering the average oil palm estate area of 960 ha in Malaysia and the frequency of operation per year, the break-even areas (BEA) for economic justification of owning an autopilot tractor-mounted real-time plant N sensor was five estates, and an autopilot tractor-mounted real-time soil EC sensor was two estates. Despite securing higher total cost saving offered by each machine system was a challenge, however, the machine's capability of optimising site-specific crop management (SSCM) for managing efficient inputs is a key benefit of this technology.

Keywords: autopilot tractor, machinery cost, oil palm, plant and soil sensors.

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INTRODUCTION

The need for speedy, practical sensing and monitoring methods in crop cultivation has extended the role of farm machinery not only as a farm power but also must be compatible with various sensors platforms to be mounted on it. Nowadays, sensing and monitoring play a pivotal role to turn the function of farm machinery to be data-rich sensing and monitoring system, besides field work support. As such, the process of sensing and monitoring by farm machinery has become a key farm operation like other common farm operations such as ploughing, planting, crop maintenance and harvesting. This is consistent with Wolfert *et al.* (2017), who stated that smart machines with crop sensors have been advancing their functions to be intelligent data-rich sensing and monitoring systems on farms.

Many important benefits have been offered by the role of sensing and monitoring technology in the crop production process. Besides empowering real-time sensing and monitoring of large plant populations in the field, Buja *et al*. (2021) also stated that the presence of the technology has enabled detection of the plant conditions with high sensitivity and specificity, overcoming the limits of traditional diagnosis procedures and the requirement of skilled scientists. Lakhiar *et al.* (2018) added that the achievements of intelligent sensor technology for monitoring crops and soils have yielded significant benefits through using limited resources with minimum human intervention. Sensing and monitoring operations are also important to ensure

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optimised site-specific crop management (SSCM) for making better farm management decisions. Li *et al.* (2019) revealed that SSCM is a popular approach that helps farmers in making decisions on the precise application of crop inputs according to the variability appearing throughout the field. Its role helps farmers to quantify crop and soil needs in advance and is very helpful in ensuring that farm inputs can be used very efficiently. This is supported by Vrochidou *et al.* (2022), whereby crop monitoring can steer profitable decisions if properly accomplished. Moreover, recent advances in data analysis and management have made agricultural data becoming an important decision-making factor for farmers.

Although these technologies have exhibited promising field performance, nevertheless its economic performance is necessary to be considered since the ultimate goal of machine use is profit. Profit can only be achieved when the machine spends minimum cost to gain maximum profit. Hunt and Wilson (2016) emphasised that a machine system is profitable only when the machine is able to add value to the products and processes beyond the cost of operation. Siemens and Bowers (2008) mentioned that keeping machine costs as low as possible is the best way to reach profit goals. Therefore, it can be concluded that profit should be the intention of agricultural enterprises in employing farm machinery to support the daily fieldwork. This is a consequence of farm machinery, which always portrays a major input of capital investment in mechanised agricultural operations. On that account, the economic success of mechanised agricultural operations very much depends on the profit collected from the adoption of farm machinery.

Several studies on the costs of owning and operating farm machinery have been reported by numerous researchers such as Lips (2017) who investigated life-cycle costs of a tractor in Switzerland. Hanna *et al*. (2018) discussed machinery costs in their study related to the evaluation of the row cover establishment system for cantaloupe and summer squash. Ernst *et al.* (2020) examined machinery and equipment costs typical to a small vegetable farm. Samsudin *et al.* (2017) explored farm machinery costs in Malaysian oil palm plantations. However, these studies highlighted the costs of operating conventional farm machinery and tractor with their implements.

Meanwhile, the past studies on the use of autopilot tractors for farm operations were limited to field performance evaluation of the machines, for example, as conveyed by Azmi *et al*. (2020; 2022), Mohammad *et al*. (2021), Santos *et al.* (2018) and Zhang *et al*. (2018). In particular, Azmi *et al.* (2020; 2022) and Mohammad *et al*. (2021) specifically initiated an evaluation to explore the field performance of autopilot tractor-mounted real-time plant N sensor and autopilot tractor-mounted real-time soil electrical conductivity (EC) sensors for plant and soil monitoring operation in oil palm cultivation. Their findings concluded that the machine systems show great potential to accelerate the implementation of precision agriculture technology, especially for sensing and monitoring operations in oil palm cultivation to suit the progression of the Fourth Industrial Revolution (IR 4.0) era.

Since their studies did not look at the costs of machine systems, hence, there is a gap of knowledge that may lead to hesitance for its further adoption in oil palm cultivation. This is because of the differences between oil palm and the crops grown in the countries of origin of this technology, *i.e.,* winter wheat, oilseed rape, maize and barley. Furthermore, the agronomic practices of the said crops and geographical conditions are also dissimilar to that of the oil palm. All these differences would affect the costs of operating the machine. This is coherent with Siemens and Bowers (2008), who mentioned that the repair cost of a particular machine varies across geographic parts of the country due to differences in soil, crops, climate and operations.

Therefore, this study aimed to evaluate the costs of autopilot tractor-mounted real-time sensors for monitoring plant N and autopilot tractor-mounted real-time sensors for sensing soil EC in oil palm cultivation. Autopilot tractor was used as the prime mover for the operations since it is one of the agricultural machines that continuously evolve with the ongoing trend in precision control of steering system. Understanding the actual costs of the machine systems is a starting point in the decision-making for greater acceptance of the use of machine systems for plant and soil monitoring operations in oil palm cultivation.

MATERIALS AND METHODS

Costs Parameters

The cost evaluation involved two principle items of the machine systems, *i.e.* the autopilot tractor-mounted real-time plant N sensor (*Figure 1*), and the autopilot tractor-mounted real-time soil EC sensor (*Figure 2*). Costs of the autopilot tractor-mounted real-time plant N sensor were established from the costs data of the New Holland TD5.75 tractor, Trimble® EZ-Pilot® steering system, Trimble® FmX® 2050 Plus Application and Yara N-sensor ALS. Whereas the cost for the autopilot tractor-mounted real-time soil EC sensor involved the costs of the New Holland TD5.75 tractor, Trimble® EZ-Pilot® steering system, Trimble® FmX® 2050 Plus Application and Veris 3100 soil EC sensor.

The data and required assumptions for cost calculation are presented in *Table 1.* The initial price

Figure 1. Autopilot tractor-mounted real-time plant N sensor.

Figure 2. Autopilot tractor- mounted real-time soil EC sensor.

of all machine components was recorded from the bill of sale from the local machine suppliers in 2018. The values of economic life and hours of annual use of farm machinery in Malaysian oil palm plantations were based on a study by Samsudin *et al.* (2018). The salvage value was 10% of the initial price of the machine. Taxes, shelter, insurance and interest (TSII) cost was 13% of the value of the machine (Siemens and Bowers, 2008). The repair and maintenance factors (RF1 of 0.07 and RF2 of 2.0) were as quoted from repair and maintenance factors for two-wheel-drive (2WD) tractors according to the ASABE (2011). As the autopilot tractor used in this study was a medium-power tractor and operated in 2WD mode, hence, determining the fuel consumption of the tractor was referred to the reported data of 2WD tractor (Damanauskas and Januleviciu, 2015). Diesel market prices and labour wages were based on the economic situation in the country during the study.

The field capacity of machine systems was measured through a field evaluation at Kempas Estate in Jasin district of Melaka state, Malaysia which is located on the coordinates of N 02^{0}15.414” and E 102^{0}27.718”. A plot size of 4.5 ha in the estate was used for this evaluation. To fulfil the statistical principles, the plot was divided into three (3) sub-plots by which each sub-plot size was 1.5 ha and denoted as a replication. We believed that the size was adequate for evaluating the field capacity of farm machinery. Normally, the sub-plot size of 1 ha is sufficient for a replication of this evaluation. With three sub-plots, hence, three replications were made

TABLE 1. COSTS DATA FOR COST ANALYSIS OF THE MACHINES SYSTEMS

Parameter	Value
Initial price of New Holland TD5.75 tractor	RM133 287.00
Initial price of Trimble ® EZ-Pilot assisted steering system	RM39 899.00
Initial price of Trimble ® TMX@2050 display system	RM34 085.00
Initial price of Yara N-sensor ALS	RM339 000.00
Initial price of Veris 3100 Soil EC	RM49 766.00
Estimated economic life of the machine[1]	10 years
Salvage value of the machine[2]	10% of machine purchase price
Tax, shelter, insurance and interest[2]	13%
Factor repair and maintenance[3]	RF1 = 0.007; RF2 = 2.000
Current local diesel market price[4]	RM2.18 L
Fuel consumption[5]	1.15 L hr^{-1}
Hours of annual use of farm machinery in oil palm plantation[1]	2 000 hr
Labour wage per day[6]	RM57.69

Note:
[1] Samsudin *et al*. (2018).
[2] Siemens and Bowers (2008).
[3] Based on conditions of a tractor is run in 2WD driving system (ASABE, 2011).
[4] Based on weekly local fuel price during the study.
[5] Based on medium-power of 2WD tractor (Damanauskas and Januleviciu, 2015).
[6] Based on monthly minimum wage of RM1500 for plantation worker on an average 26 working days commitment in a month, and 8 working hr commitment in a day under the local current economic scenario (Sime Darby, 2022).

to obtain an unbiased and consistent measurement, and at the same time minimise measures of variation that might occur as field variability in the study area. The average field capacity of the machine systems was calculated by dividing the areas completed by the hours of operation.

The total costs of the machines were determined based on the sum of fixed (ownership) costs and operating costs (variable costs). Categorising costs was made based on Siemens and Bowers (2008) and Hunt and Wilson (2016). Fixed costs consist of depreciation, taxes, shelter, insurance and interest. Operating costs comprise fuel and lubricant costs, repair costs and labour costs. The flow chart of cost calculation is shown in *Figure 3*. The analysis of the total costs of machine systems involved the entire costs spent on the field operation only. Costs of professional services for further imagery processing analysis from the sensors reading were included in the calculation of the cost.

Costs Calculation Method

As mentioned earlier, the total costs were obtained by adding fixed costs to the operating costs of each machine. Fixed costs include depreciation and taxes, shelter, insurance and interest (TSII) of the machine systems. The depreciation costs were computed by using Equation (1) as proposed by Siemens and Bowers (2008):

$$D = ((P\text{-}S))/L \qquad (1)$$

where D is the depreciation costs of the machine system (RM yr^{-1}), P is the total initial price of the machine system (RM), S is the salvage value for the machine system (RM) and L is the expected economic life for the machine system (yr).

Taxes, shelter, insurance and interest (TSII) costs were assumed to be 13% of the total initial price of the machine system (Siemens and Bowers, 2008). Thus, the TSII costs were computed by using Equation (2) as suggested by Siemens and Bowers (2008):

$$TSII = (13\%\ X\ P) \qquad (2)$$

where TSII is taxes, shelter, interest and insurance costs of the machine system (RM yr^{-1}) and P is the total initial price of the machine system (RM).

Operating costs included repair and maintenance costs, fuel cost and labour costs (Siemens and Bowers, 2008). For repair and maintenance, the costs were computed by using Equation (3) as mentioned by the ASABE (2006):

$$R\&M = (RF1)\ P\ [h/1000]^{RF2} \qquad (3)$$

where $R\&M$ is the accumulated repair and maintenance costs of the machine system (RM yr^{-1}), P is the total initial price of the machine system (RM), $RF1$ and $RF2$ are repair and maintenance factors (for this machine, RF1 = 0.007 and RF2= 2.0 were designated), and h is the hours of annual use (hr).

The fuel cost of the machine system was computed by multiplying the average fuel consumption of 1.15 L hr^{-1} of the medium-power tractor running in a dual-wheel 2WD driving system (Damanauskas and Januleviciu, 2015) by the current local diesel market price of RM2.18 L^{-1}.

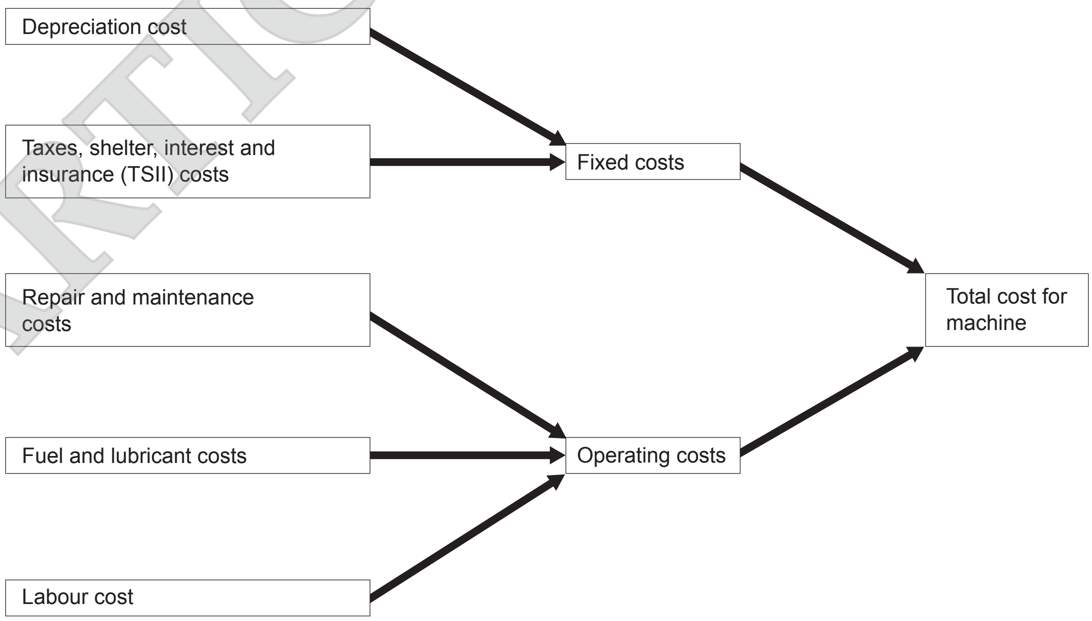

Figure 3. Flow chart of machine system costs calculation.

Labour costs consisted of labour wages for machine operation on the field and local professional services costs for further imagery processing analysis. The labour cost for machine operation was computed by dividing labour wage per day by working hours commitment in a day. Having a labour wage of RM57.69 day^{-1} and 8 working hours commitment in a day, thus, the computed labour cost of each machine system was RM7.21 hr^{-1}.

The total cost for operating machine system was calculated by using Equation (4) according to Siemens and Bowers (2008).

$$T = [(D+TSII+ R\&M)/h] + Fn+ Lb \quad (4)$$

where T is the total cost of operating the machine system (RM hr^{-1}), D is the depreciation cost of the machine system (RM yr^{-1}), $TSII$ is taxes, shelter, interest and insurance costs of the machine system (RM yr^{-1}), $R\&M$ is accumulated repair and maintenance costs of the machine system (RM hr^{-1}), h is hours of annual use of the machine system (hr), Fn is fuel cost of the machine system (RM hr^{-1}) and Lb is labour cost (RM hr^{-1}).

The calculated total cost of the machine system on RM hr^{-1} basis was then converted into RM ha^{-1}. It was obtained by dividing the calculated total cost in RM per hr^{-1} by the average effective field capacity in hectares per hour. The measured average effective field capacity of 14.07 ha hr^{-1} of autopilot tractor-mounted-real time plant N sensor and 5.13 ha hr^{-1} of autopilot tractor-mounted real-time soil EC sensor was used in the calculation.

Since both machine systems are relatively new technology to be adopted for oil palm cultivation and the machine price is also relatively expensive, consequently, it is necessary to calculate the BEA in hectares per year. The BEA is necessary to justify ownership of the machine system. Equation (5) by Siemens and Bowers (2008) was used for the BEA calculation.

$$BEA=(D+TSII)/(CR-OC) \quad (5)$$

where BEA is the break-even point area (ha yr^{-1}), D is the depreciation cost of the machine system (RM yr^{-1}), $TSII$ is taxes, shelter, interest and insurance cost of the machine system, (RM yr^{-1}), CR is custom charge (RM ha^{-1}) and OC is operating cost (RM ha^{-1}). In this case, the customs charge was assumed to be the same as the current practice cost. The computed operating cost in RM ha^{-1} is converted into RM ha^{-1}.

Actual hours of annual use of the machine system in order to suit the computed BEA was calculated by Equation (6).

$$H=BEA/EFC \quad (6)$$

where H is the actual hours of annual use of the machine system (hr yr^{-1}), BEA is break-even areas (ha yr^{-1}) and EFC is the effective field capacity of the machine (ha ha^{-1}).

Finally, the number of adjacent estates that should be served by the machine in order to justify the ownership was calculated by Equation (7).

$$N=BEA/(FR \times SP) \quad (7)$$

where N is the number of estates served by the machine system (dimensionless), BEA is the break-even areas of the machine system (ha yr^{-1}), FR is the frequency of operation per year (dimensionless) and SP is the average oil palm estate size in Malaysia in 2019 (ha). The common frequency of operation of 3 rounds yr^{-1} with respect to the current fertilising practice (Hasan *et al.*, 2021) and an average plantation size of 960 ha in 2019 in Malaysia (DOSM, 2022) were taken into consideration.

RESULTS AND DISCUSSION

Total Costs for Operating Machine System

The cost of operating an autopilot tractor-mounted real-time plant N sensor was estimated to be RM77.46 hr^{-1} (*Table 2*). The TSII's cost accounted for 45.84% of the total cost and was the highest cost breakdown for the autopilot tractor-mounted real-time plant N sensor, followed by depreciation cost, repair and maintenance cost, and labour cost. Fuel cost was the lowest cost breakdown, accounting for 3.24% of the total cost of the machine system.

The estimated cost of the autopilot tractor-mounted-real time plant N sensor was higher as compared to the cost of other machines in oil palm cultivation. For example, the cost of this machine system was 76.59% and 77.17% greater than the costs

TABLE 2. BREAKDOWN OF ESTIMATED COSTS OF AUTOPILOT TRACTOR-MOUNTED REAL-TIME PLANT N SENSOR

Cost component	Cost[1]	Percent from total cost
Depreciation (RM hr^{-1})	24.58	31.73
Taxes, shelter, interest and insurance (TSII) (RM hr^{-1})	35.51	45.84
Repairs and Maintenance (RM hr^{-1})	7.65	9.88
Fuel cost (RM hr^{-1})	2.51	3.24
Labour cost (RM hr^{-1})	7.21	9.31
Total cost (RM hr^{-1})	77.46	100.00
Total cost (RM ha^{-1})	5.51	

Note: 1 RM = 0.24018 USD (exchange rate during the study).

of the 6WD 4WS oil palm fruit fresh bunch (FFB) transporting machine (RM18.13 hr^{-1}) and the mini tractor with grabber (RM17.68 hr^{-1}) as stated by Shuib *et al.*, 2020. The cost was also 69.97% higher than that of the 4WD prime mover for oil palm circle spraying (RM25.11 hr^{-1}) by Pebrian and Yahya (2012). The higher initial price of the component of the autopilot tractor-mounted real-time plant leads to the higher cost of this machine. As indicated in the formula of cost calculation, the initial price of the machine is one of the cost components in computing fixed costs. The more the initial price of the machine, the higher the fixed costs. Thus, this affects the total cost of operating the machine. With additional professional services costs of RM30 hr^{-1} (ERI's Salary Expert Database, 2022) for further imagery processing analysis, the total cost would be RM107.46 hr^{-1}. With an average effective field capacity of 14.07 ha hr^{-1}, hence, the estimated total cost for operating the system is equivalent to RM7.64 ha^{-1}.

The estimated cost of the autopilot tractor-mounted real-time soil EC sensor was RM35.52 hr^{-1} (*Table 3*). A similar trend also appeared in the cost breakdown of the autopilot tractor-mounted real-time soil EC sensor. The TSII cost was the highest cost breakdown (38.03%), followed by depreciation cost, repair and maintenance cost, and labour cost, while fuel cost was the lowest cost breakdown (7.09%). The cost of TSII was higher than others, as its percentage in the cost formula was also high, accounting for 13.00% of the initial price of the machine system. The percentage was purposely used or the TSII cost calculation since the initial price of both machines was quite expensive. Therefore, adopting such a percentage for the TSII cost calculation could protect the machines against breakdown and damage risks that may occur when operating on rough fields, which are commonly found in oil palm plantations.

The cost of autopilot tractor-mounted real-time soil EC sensor was also higher than that of the costs of the existing earlier-mentioned machines in oil palm plantations. The cost of the machine system was 48.81% and 29.10% more expensive than that of the 6WD 4WS oil palm FFB harvesting-transporting machine (RM18.13 hr^{-1}) reported by Shuib *et al.* (2020), and 4WD oil palm circle spraying machine (RM25.11 hr^{-1}) by Pebrian and Yahya (2012), respectively. Again, the high initial price of equipment of the autopilot tractor-mounted real-time plant N sensor contributed to the high cost of this machine. By adding professional services costs of RM30 hr^{-1} (ERI's Salary Expert Database, 2022) for further imagery processing analysis, hence, the total cost would be RM65.42 hr^{-1}. With the machine's average effective field capacity of 5.13 ha hr^{-1}, the total cost is equivalent to RM12.75 ha^{-1}.

However, the computed cost of autopilot tractor-mounted real-time plant N sensor in oil palm cultivation was much lower than that of the similar machine system used in potatoes, grain and oilseed rape cultivation in European countries that cost €25 ha^{-1} (or equal to RM112.90 ha^{-1}) as reported by Koerhunis (2017). The cost of RM7.64 ha^{-1} for operating the machine in oil palm cultivation, including professional services costs was about 0.07 times lower than that of the cost as stated by Koerhunis (2017). One of the factors contributing to significant cost reductions is that the machine system was not equipped with the fertiliser spreader for the operation in oil palm cultivation. In this study, we used Yara N-sensor ALS only for monitoring plant N requirement on oil palm trees without fertiliser spreader for concurrently applying N. Ideally, the machine system should be completed with a fertiliser spreader for applying variable rate fertilizer application (VRA) on-the-go while sensing the crop. In his study, Koerhunis (2017) incorporated a fertiliser spreader into the system for allowing on-the-go VRA. Adding the spreader into the system increased overall costs. This is why the cost of the machine system in potatoes, grain and oilseed rape cultivation was much higher than that of the oil palm. Apart from that, the differences in cropping systems between oil palm and potatoes, cereals and rapeseed along with disparities in the topographical conditions and current economic situation between Malaysia and European regions may make the cost of the machine's systems not the same.

A comparison was also made between the cost of soil EC mapping calculated by this study and the reported cost from the same operation on a vegetable farm in Queensland, Australia. The Queensland Department of Agriculture and Fisheries (2020) reported that the EC mapping cost on a vegetable farm in that region ranges from USD17 ha^{-1} to USD35 ha^{-1} (RM75.83 ha^{-1} to RM156.14 ha^{-1}). Therefore, the soil EC mapping cost of RM12.75 ha^{-1} in oil palm cultivation, including professional services costs was about 0.082 times lower than that of the maximum costs of RM156.14 ha^{-1} in

TABLE 3. BREAKDOWN OF ESTIMATED COSTS OF AUTOPILOT TRACTOR-MOUNTED REAL-TIME SOIL EC SENSOR

Cost component	Cost[1]	Percent from total cost
Depreciation (RM hr^{-1})	9.33	26.34
Taxes, shelter, interest and insurance (TSII) (RM hr^{-1})	13.47	38.03
Repairs and Maintenance (RM hr^{-1})	2.90	8.19
Fuel cost (RM hr^{-1})	2.51	7.09
Labour cost (RM hr^{-1})	7.21	20.36
Total cost (RM hr^{-1})	35.42	100.00
Total cost (RM ha^{-1})	6.90	

Note: 1 RM = 0.24018 USD (exchange rate during the study).

Queensland. The main contributing factor for the significant cost differences is that number of probes installed on the equipment used for sensing soil EC was also different. The current sensing operation in the oil palm field used a tractor as a ground vehicle and a sensor with a soil EC probe only, therefore, only a soil EC map was obtained. But, for the operation in Queensland's vegetable farm, the machine was also equipped with a pH probe in addition to the EC probe, thus, producing a pH map as an additional output aside from the EC map.

For oil palm cultivation itself, the cost of the autopilot tractor-mounted real-time plant N and soil EC sensors were compared to that of the current practice. The current practice refers to the inspection of the plant nutrient prior to the immature palms fertilising operation. We used the immature palm fertilising operation for the cost comparisons because this operation is nearly similar to the functions of machine systems. In fact, the nature of the operation is almost analogous to the machine system operation even though currently this operation is performed manually. This is because the tasks in the current practice also involve observation of plant nutrient requirements, but it only emphasizes the qualitative appearance of N in immature palms. Nevertheless, it still meets the requirement for a comparative study with the machine system. Other than that, the machine system is only suitable for sensing N on immature palms trees as stated by Mohammad *et al.* (2021). The cost of the current practice was found to be RM7.21 hr^{-1}. It was computed by dividing the RM1500 monthly minimum wage of plantation workers (Sime Darby, 2022) by 26 working days in a month and eight working hours in a day. This computed cost was equal to RM10.02 ha^{-1}, which is obtained by dividing the cost of RM7.21 hr^{-1} by the average field capacity of the current practice of 0.72 ha hr^{-1} (Pebrian *et al.*, 2014).

Comparisons of Economic Performance with Current Practice

Comparisons of economic performance between the autopilot with the current practices are shown in *Table 4*. The autopilot tractor-mounted real time plant N sensor and autopilot tractor-mounted real time soil EC sensor offered 94.88% and 85.22% larger average field capacities, respectively than the current practice. Thus, it indicates that the machine systems gave a better performance in the field rather than the current practice. In spite of that, the cost of a machine system in RM per hour for plant and soil sensing operations was also 93.29% and 88.99% higher than the current practice. Especially, an additional cost of 21.41% was incurred by the autopilot tractor-mounted real-time soil EC sensor. This is due to the high average effective field capacity given by the machine system cannot justify the added cost of professional services for further image analysis of the sensor data captured by the machine. However, 23.75% of machine costs for plant sensing were saved by the machine as compared with the current practice. The much higher average effective field capacity offered by the autopilot tractor-mounted real-time plant N sensor rationalises this cost saving against the current practice, although there is an additional cost for professional services as mentioned earlier. Saving more cost can be attained when the owners or operators of the machine systems are well-trained in the imagery analysis to save cost on professional services. Mastering imagery analysis skills is not that challenging. It is just like learning another software. Once the owners or operators become familiar with the analysis, the cost of professional services is no longer necessary. Conclusively, professional services cost can be considered as a temporary cost for the machine systems.

The computed BEA of autopilot tractor-mounted real time plant N sensor was approximately 13 672 ha yr^{-1} (*Table 5*), and economically justifiable to serve at least five oil palm estates based on the average estate size of 960 ha in 2019 in Malaysia (DOSM, 2022). Whilst, the BEA of autopilot tractor-mounted real time soil EC sensor of about 6032 ha yr^{-1} was economically justifiable for at least two oil palm estates.

In general, the BEA is used for evaluating the economics of the machine system. There is no gain or no profit at the BEA. Conclusively, it would be uneconomic to own the machine system if the total working area does not meet the computed BEA. In the case of the oil palm plantations having areas less than the computed BEA, they are not recommended to own the machine systems. If the computed BEA is achieved, the profits of owning the machine systems depend on the quantity of work. The plantation managers can also use the BEA to compare the cost of operating the machine systems with other alternatives.

From the above discussions, it is admitted that securing higher total cost savings offered by machine systems was a challenge. Nonetheless, the machine systems have proved its benefits from the physiological cost of work and labour-saving aspects. Physiological cost benefit of the machine system was mentioned by Azmi *et al.* (2020), who claimed that driving autopilot tractor-mounted soil EC sensor with automated steering had successfully reduced human energy expenditure of the operator by up to 70.67% when compared to that of the manual steering mode. Based on a field testing in an oil palm plantation, Mohammad *et al*. (2021) added that the machine system has also efficaciously demonstrated its ability to rapidly detect N in real-time with acceptable accuracy and create a spatial variability map of plant N status. Related to labour-saving, the machine systems benefit was reflected by their high

TABLE 4. COMPARISONS OF THE ECONOMIC PERFORMANCE BETWEEN THE MACHINES SYSTEMS AND THE CURRENT PRACTICE

Description	Current practice (I)	Autopilot tractor-mounted real-time plant N sensor (II)	Autopilot tractor-mounted real-time soil EC sensor (III)	Difference Percent (%)	
				II vs. I	III vs. I
Average effective field capacity (ha hr^{-1})	0.72[2]	14.07	5.13	94.88(+)	85.22(+)
Total cost (RM hr^{-1})[1]	7.21[2]	107.46[3]	65.42[3]	93.29 (+)	88.99(+)
Total cost (RM ha^{-1})[1]	10.02[2]	7.64[3]	12.75[3]	23.75 (-)	21.41 (+)

Note: [1] 1 RM = 0.24018 USD (exchange rate during the study).
[2] Based on reported data of immature oil palm fertilising operation by Pebrian *et al*. (2014).
[3] Including professional services cost of RM30 hr^{-1} for further for further imagery processing analysis (ERI's Salary Expert Database, 2022).

TABLE 5. ECONOMIC JUSTIFICATION FOR THE MACHINES SYSTEMS OWNERSHIP

Machine system	Break-even areas (ha yr^{-1})	Hours of annual use (hr yr^{-1})	Numbers of adjacent estates served by machine system for ownership justification of the machine[1,2] (dimensionless)
Autopilot tractor-mounted real-time plant N sensor	13672	972	5
Autopilot tractor-mounted real-time soil EC sensor	6032	1176	2

Note: 1 - Based on an average plantation size of 960 ha in 2019 in Malaysia (DOSM, 2022).
2 -Based on the frequency of fertilising operation per year by Hasan et al. (2021).

effective field capacity. The recorded average field capacity indicated that both the autopilot tractor-mounted real-time plant N sensor and autopilot tractor-mounted real-time soil EC sensor are able to offer land-to-labour ratios of 14:1 and 5.35:1, respectively. These ratios are 19.58 and 7.43 times higher than that of 0.72:1 of the current practice based on a study by Pebrian *et al.* (2014).

Given these advantages, it is believed that the machine systems could deliver the greatest revolution in leveraging the latest technology, particularly the tractor automated-steering system technology combined with plant and soil sensors for the Malaysian oil palm plantation industry. Nevertheless, the machine`s reliance on the Global Navigation Satellite System (GNSS) for the effectiveness of its navigation system and for marking sampling points limits its operation in palm oil plantations as the nature of dense oil palm trees canopy can disrupt communication between machine and GNSS. The autopilot tractor-mounted real-time soil EC sensor is therefore suitable for monitoring and mapping soil EC upon completing the land clearing and land preparation or before field planting commences. According to Bottega *et al.* (2022), understanding soil EC is important because EC values provide valuable information about variations in soil physicochemical properties such as soil texture, moisture and some nutrients that affect crop yield. On the other hand, the autopilot tractor-mounted real-time plant N sensor is capable of monitoring and mapping plant N status on the canopy of immature palm trees as the palm trees height at this growth stage is lower than the 2.74 m height of tractor-mounted sensor. Furthermore, based on close observation of the functioning of autopilot tractor alone during this study, it is also believed that this vehicle has the potential to increase the operator comfort in conducting other field operations such as herbicide spraying for *Imperata cylindrica* and other unwanted crops in immatures areas. Besides that, other related farm equipment can be attached to the autopilot tractor to facilitate land preparation and other general field maintenance tasks in immature oil palm areas.

Although the revenue in terms of dollars and cents is not that high, the machine is able to grant another revenue in terms of better working improvement through the functionality of its advanced technology. In fact, both machine systems have proved their functions of playing a pivotal role as a data-rich sensing and monitoring system in oil palm cultivation.

In the process of technology adoption, it is important to realise that the benefits of precision agriculture including plant and soil monitoring system is not barely appraised based on increased revenue, but also the economic value of information about the field. Information about different fields in an oil palm plantation through the VRA maps developed by this technology is actually an investment since it results in better cultivation management and leads to higher profits in the future. This happens as the machine system helps in guiding fertiliser and other agrochemical applications precisely. Other than that, in a wider scope, these machines are able to give better operation comfort while solving the problem of labour shortage in the oil palm plantation. The machine systems also guarantee the timeliness of operation since it has high effective field capacity. It can be said that the functionality of advanced technology in the machine system itself is a profit.

The high initial purchase price of machine systems compared to other existing machines in oil palm cultivation may be a barrier to this technology acceptance. This is usually because the machinery is still a new technology being introduced to Malaysian oil palm plantations. Nonetheless, the cost will be competitive and affordable as the machine systems become widely-used machines in the plantations later. It is hard to predict the time frame when the machine systems will become widely used. But once the various plantation management teams realize the benefits of the machines not only in terms of dollars-and-cents but also on plant and soil information data conveyed by this technology, the machine systems will then be accepted and widely adopted. In addition to this, many competitors have also offered similar technology in the local market. As a result, the purchase price of the machine systems can be significantly reduced, hence making the machine systems more economical.

CONCLUSION

This study has successfully filled the gap of knowledge of cost evaluation of autopilot tractor-mounted real-time N plant and soil EC sensors for monitoring operations in oil palm cultivation. The costs of the autopilot tractor-mounted plant N sensor and autopilot tractor-mounted soil EC sensor were RM5.51 ha^{-1} and RM6.90 ha^{-1}, respectively. Both machine systems were able to reduce the cost of the current practice by about 45.00% and 31.14 % of plant and soil sensing operations, respectively.

With an assumption of the average estate area in Malaysia is 960 ha, the BEA for owning an autopilot tractor-mounted plant N sensor was 5 estates, whereas for an autopilot tractor-mounted soil EC sensor was equal to 2 estates. The machine systems were applicable for monitoring and mapping plant N and soil EC variability from land preparation to the immature growth stage of oil palm. Although securing higher total cost savings offered by machine systems was a challenge when compared to other machines in oil palm cultivation, however, the machine systems were able to make profits from the physiological cost of work and labour-saving. More importantly, the machine systems were capable of providing valuable real-time information on soil and crop variability in oil palm fields through their advanced technology functionality.

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