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Nitrogen and potassium fertiliser requirement optimisation for high-density planting in Oil palm (*Elaeis guineensis*) under Coastal environment of Peninsula Malaysia

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Abstract Fertilisation is crucial to sustaining optimum vegetative growth and yield performance of oil palm in high-density planting (HDP). In this study, the fresh fruit bunch yield was significantly improved by increasing the application of nitrogen up to 6 kg of ammonium sulphate palm^{-1} year^{-1}. Nonetheless, the yield performance was less responsive to potassium fertiliser mainly due to the high potassium reserve in the coastal clay soil of Peninsula Malaysia. No significant interaction effects were observed between nitrogen and potassium on the yield performance. Conclusively, considering the palm vegetative growth, FFB yield, and economic benefits, the optimum N and K rates for high-density planting in oil palm under the coastal environment of Peninsula Malaysia were 4 kg of ammonium sulphate palm^{-1} year^{-1} and 1 kg of muriate of potash palm^{-1} year^{-1} respectively.

Keywords: Agronomy, Balanced fertilisation, Nutrient management, Oil palm, Plantation management

Introduction

Oil palm is one of the most important tropical crops, grown for oil. Palm oil derived from oil palm fruits is primarily used in the food industry and for the production of non-food commodities, such as biodiesel, cosmetics, and cleaning products. Malaysia is one of the leading producers of palm oil with a total oil palm planted area of 5.87 million ha, thus contributing to a total crude palm oil production of 19.14 million tons in 2020 (Nordin *et al.*, 2021). Nonetheless, the average productivity of oil palm in Malaysia has stagnated for decades as the national fresh fruit bunch (FFB) yield performance had fluctuated between 15.9 to 22 tons ha^{-1} (Latif, *et al*., 2003; Ezechi and Muda, 2019).

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One of the initiatives to improve oil palm productivity is by increasing the density of oil palms planted in a fixed area. Oil palm is commonly planted at a density of 136–148 palms ha^{-1}, whereas the field stands in high density planting is greater than 160 palms ha^{-1}. High-density planting (HDP) during the early years of harvesting followed by thinning in the later years could maximise oil palm yield. Palat *et al.* (2012) reported that HDP at 180 palm ha^{-1} followed by 33% thinning at year 8 permits an increment of cumulative fresh fruit bunch yield by at least 15%.

The high yield potential of HDP is greatly associated with plant nutrient management especially the inputs of nitrogen and potassium. Nitrogen is a building block of amino acids, nucleic acids, and chlorophyll. Additionally, potassium plays a major role in enzyme activation, stomata opening, and protein synthesis (Tiemann *et al*., 2018). According to Corley and Tinker (2015), oil palms have high nitrogen and potassium nutrient demand for growth in which the average annual growth demand for matured oil palms in Malaysia is 1.32 kg of nitrogen and 1.68 kg of potassium. These nutrient demands are normally fulfilled by the application of chemical fertiliser.

The fertilisation requirement of crop is highly dependent on soil types. The coastal clay soils which have been developed from marine and riverine clay are normally found on the western coastal belt of Peninsular Malaysia. Coastal clay soils including the Selangor and Briah soil series are relatively fertile and suitable for oil palm cultivation (Pushparajah and Amin, 1977). Fertiliser optimisation under these soils is crucial to save input costs and reduce the negative environmental impacts caused by over fertilisation. Therefore, this study aimed to determine the optimum nitrogen and potassium fertilisers for HDP in oil palm under coastal environment of Peninsula Malaysia.

Materials and methods

Experimental design and treatments

The trial was initiated on six years old palms (Tenera palm- SD Premium) planted at 180 palms per hectare in Seri Intan Estate, Perak (3° 58.2084’ N 100° 59.1504’ E) for five years. The soil of the experimental site was Selangor Series (Typic Endoaquepts). The trial was laid out in a 3×3 factorial experiment arranged in a randomised complete block with three replications. Each plot consists of 36 palms with 16 recording palms. The treatments include three levels of nitrogen (2, 4, and 6 kg of ammonium sulphate $palm^{-1}$ $year^{-1}$) and three levels of potassium (1, 2, and 3 kg of muriate of potash $palm^{-1}$ $year^{-1}$). The standard rate of phosphate fertiliser (2.30 kg of rock phosphate $palm^{-1}$ $year^{-1}$)

was applied to all palms, while boron was applied at 0.1 kg palm^{-1} year^{-1} on a corrective basis. All fertilisers were broadcast onto the frond compost heap. Upkeep and maintenance of the trial site were performed as per standard oil palm agricultural practices.

Soil sampling and analysis

Soil analysis was conducted annually. Soil samples were collected from every recording palm in a plot using a screw auger at the depth of 0 to 15 cm and 15 to 30 cm from the frond stacking area. Soil samples taken from a plot were bulked into a composite sample/depth/plot. Thereaafter, soil samples were air-dried, ground, sieved (2 mm), and subjected to soil chemical analysis for pH, organic carbon, total N, cation exchange capacity (CEC), and exchangeable cations (K, Mg, and Ca).

Vegetative growth measurements and foliar nutrient analysis

Vegetative measurements including palm height, rachis length, and petiole cross-section area were recorded annually. Palm height was measured from the ground surface to the base of frond 41, while rachis length was measured from the base of rudimentary leaflets to the tip of the rachis. In addition, the width and depth of the petiole at the point of insertion of the lowest rudimentary leaflet were measured to obtain the petiole cross-section area. Foliar samples of frond 17 were collected from every recording palm in a plot. The foliar samples were bulked into a composite sample/plot, air-dried at 80°C for 5 hours, and subjected to standard chemical analyses for N, K, Mg and Ca.

Fresh fruit bunch (FFB) yield recording

The fresh fruit bunches (FFBs) were harvested at 10 to 12 days intervals. Every bunch was weighed together with loose fruits using a Salter balance mounted on a tripod. The FFB yield per hectare was obtained by multiplying the total bunch weight per palm with the stand per hectare. Meanwhile, the FFB yield recorded in the first two years was excluded from statistical analysis to reduce the experimental error due to the residual effects of fertiliser regime.

Economic analysis

The gross profit was calculated by multiplying the average fresh fruit bunch (FFB) yield with the average oil extraction rate (OER) and crude palm oil (CPO) price. On the other side, the total expenses were contributed by the fertiliser cost per hectare, fertiliser application cost, and other variable costs (FFB harvesting and transportation). The benefit-cost ratio was determined by dividing the gross profit by the total expenses.

Statistical analysis

All data were analysed using SAS JMP 14 (SAS Institute, 2018). Post hoc analyses were performed using the Tukey test and significant differences between treatment means were assessed at $P < 0.05$.

Results

Soil chemical properties

The main effects of ammonium sulphate (AS) and muriate of potash (MOP) on soil pH and cation exchange capacity (CEC) were summarised in Table 1. Mean depicted the status of soil total nitrogen, exchangeable potassium, magnesium, and calcium (Table 2 and 3). Soil pH decreased significantly with increasing application of AS five years after treatment at two soil depths at the frond stacking area. In contrast, the application of MOP did not affect the soil pH significantly. Furthermore, The CEC decreased as the application of AS increased. For instance, a 16% reduction of CEC at 0 to 15 cm of frond stacking area was noted when applied with 6 kg of AS palm^{-1} year^{-1} (Table 1). The application of AS increased soil total nitrogen at two soil depths up to 15% over five years. In addition, the application of MOP increased the soil exchangeable potassium significantly. The highest soil exchangeable potassium (1.41 cmol kg^{-1}) was noted when applied with 3 kg of MOP palm^{-1} year^{-1} (Table 2). Soil exchangeable calcium and magnesium decreased with the increasing application of AS. Specifically, soil exchangeable calcium and magnesium decreased by 222% and 195% five years after the application of 6 kg AS palm^{-1} year^{-1}. Furthermore, the soil exchange of calcium and magnesium decreased at all treatments of MOP.

Vegetative growth

Result showed the main effects of ammonium sulphate (AS) and muriate of potash (MOP) on vegetative growth five years after treatment (Table 4). The palm height, rachis length, and petiole cross-section area increased with the application of AS and MOP. The application of 4 kg of AS and 2 kg of MOP palm^{-1} year^{-1} resulted in the highest vegetative growth.

Table 1. Main effects of ammonium sulphate and muriate of potash on soil pH and cation exchange capacity at frond stacking area at two soil depths five years after treatment

Main Effects		pH		CEC (cmol kg^{-1} soil)	
		Soil Depth (cm)			
		0-15	15-30	0-15	15-30
Ammonium sulphate (kg palm^{-1} year^{-1})	2	3.7 ^{a} (-8)	3.73 ^{a} (-5)	27.90 (-8)	26.80 (-13)
	4	3.51 ^{b} (-13)	3.50 ^{b} (-13)	25.10 (-13)	25.58 (-12)
	6	3.42 ^{b} (-13)	3.40 ^{b} (-13)	26.60 (-17)	26.76 (-14)
	p-value	0.0001	0.0003	0.0607	0.4734
Muriate of potash (kg palm^{-1} year^{-1})	1	3.52 (-12)	3.50 (-13)	25.80 (-14)	24.4 ^{b} (-18)
	2	3.67 (-9)	3.67 (-9)	27.52 (-11)	28.1 ^{a} (-9)
	3	3.53 (-12)	3.54 (-9)	26.29 (-12)	26.6 ^{ab} (-13)
	p-value	0.5601	0.4784	0.2832	0.0153
	CV (%)	2.53	3.28	8.76	8.96

Notes:
[1]() represents the percentage change between pre-and post-treatment,
[2]Mean values with the same letter within a column are not significantly different at $p<0.05$ by Tukey Test,
[3]CV- Coefficient of variation

Table 2. Main effects of ammonium sulphate and muriate of potash on soil total nitrogen and exchangeable potassium at frond stacking area at two soil depths five years after treatment

Main Effects		N (%)		Exchangeable K (cmol kg^{-1} soil)	
		Soil Depth (cm)			
		0-15	15-30	0-15	15-30
Ammonium sulphate (kg palm^{-1} year^{-1})	2	0.41 (15)	0.40 (5)	0.92 (-37)	0.93 (-26)
	4	0.40 (14)	0.40 (15)	0.97 (-36)	0.95 (-29)
	6	0.42 (11)	0.39 (8)	1.00 (-24)	0.93 (-21)
	p-value	0.6237	0.8664	0.8176	0.9784
Muriate of potash (kg palm^{-1} year^{-1})	1	0.40 (12)	0.38 (8)	0.62 ^{b} (-56)	0.63 ^{b} (-52)
	2	0.43 (16)	0.42 (13)	0.85 ^{b} (-36)	0.87 ^{b} (-28)
	3	0.40 (15)	0.39 (6)	1.41 ^{a} (-8)	1.31 ^{a} (4)
	p-value	0.4473	0.3137	0.0254	0.0114
	CV (%)	11.62	14.06	28.42	35.09

Notes:
[1]() represents the percentage change between pre-and post-treatment,
[2]Mean values with the same letter within a column are not significantly different at $p<0.05$ by Tukey Test,
[3]CV- Coefficient of variation

Table 3. Main effects of ammonium sulphate and muriate of potash on exchangeable potassium and magnesium at frond stacking area at two soil depths five years after treatment

Main Effects		Exchangeable Ca (cmol kg^{-1} soil)		Exchangeable Mg (cmol kg^{-1} soil)	
		--------------------------Soil Depth (cm)--------------------------			
		0-15	15-30	0-15	15-30
Ammonium sulphate (kg $palm^{-1}$ $year^{-1}$)	2	1.67 (-129)	1.58 (-67)	0.32 ^{a} (-66)	0.32 (-28)
	4	1.52 (-76)	1.52 (-85)	0.26 ^{ab} (-104)	0.26 (-82)
	6	1.31 (-222)	1.39 (-143)	0.22 ^{b} (-195)	0.23 (-115)
	p-value	0.4509	0.8172	0.0438	0.1645
Muriate of potash (kg $palm^{-1}$ $year^{-1}$)	1	1.32 (-136)	1.29 (-180)	0.21 ^{b} (-71)	0.20 ^{b} (-110)
	2	1.46 (-124)	1.75 (-37)	0.32 ^{a} (-91)	0.35 ^{a} (-26)
	3	1.73 (-152)	1.45 (-95)	0.27 ^{ab} (-174)	0.26 ^{ab} (-100)
	p-value	0.3705	0.3503	0.0254	0.0114
	CV (%)	40.09	43.57	28.42	35.09

Notes:
[1]() represents the percentage change between pre-and post-treatment,
[2]Mean values with the same letter within a column are not significantly different at p<0.05 by Tukey Test,
[3]CV- Coefficient of variation

Table 4. Main effects of ammonium sulphate and muriate of potash on vegetative growth five years after treatments

Main effects		Palm Height (m)	Rachis Length (m)	Petiole Cross Section Area (cm^2)
Ammonium sulphate (kg $palm^{-1}$	2	4.35	6.53	47.19
	4	4.53	6.69	48.40
	6	4.49	6.52	46.94
	p-value	0.0624	0.0647	0.4176
Muriate of potash (kg $palm^{-1}$	1	4.37	6.54	46.62
	2	4.56	6.62	48.45
	3	4.43	6.58	47.46
	p-value	0.0741	0.6234	0.3081
	CV (%)	3.59	2.54	5.12

Note:
[1]CV- Coefficient of variation

Foliar nutrient level

Result showed the main effects of ammonium sulphate (AS) and muriate of potash (MOP) on foliar nitrogen, potassium, magnesium, and calcium levels five years after treatment (Table 5). The foliar N level increased significantly with the application of AS. The foliar N level was the highest (2.55%) when 6 kg of AS was applied per palm per year. On the other hand, the foliar K, Mg, and Ca levels were not affected significantly by the application of both AS and MOP fertilisers.

Table 5. Main effects of ammonium sulphate and muriate of potash on foliar nutrient levels (N, K, Mg, and Ca) five years after treatment

Main effects		N (%)	K (%)	Mg (%)	Ca (%)
Ammonium sulphate (kg palm^{-1} year^{-1})	2	2.45 [b]	1	0.25	0.41
	4	2.49 [ab]	1.01	0.24	0.41
	6	2.55 [a]	0.98	0.25	0.41
	p-value	0.01	0.3588	0.6001	0.922
Muriate of potash (kg palm^{-1} year^{-1})	1	2.48	0.98	0.25	0.43
	2	2.52	1	0.25	0.41
	3	2.49	1	0.23	0.39
	p-value	0.3185	0.5636	0.089	0.2363
	CV (%)	2.48	4.64	8.66	11.51

Notes:
[1]Mean values with the same letter within a column are not significantly different at $p<0.05$ by Tukey Test,
[2]CV- Coefficient of variation

Yield performance

Result presented the main effects of ammonium sulphate (AS) and muriate of potash (MOP) on the average FFB yield components over three years (Table 6). The application of AS increased the average FFB yield significantly, whereas the average bunch number and bunch weight were not affected. On the other hand, the FFB yield, number of bunches produced per palm, and the average bunch weight per palm were not affected by increasing MOP application. In contrast, the application of MOP at 1 kg palm^{-1} year^{-1} gave the highest yield though the effect was not significant.

Table 6. Main effects of ammonium sulphate and muriate of potash on the average FFB yield components over three years

Main effects		Average FFB yield components of three harvesting years		
		FFB (t ha^{-1} yr^{-1})	NOB (palm^{-1} yr^{-1})	ABW (kg palm^{-1})
Ammonium sulphate (kg palm^{-1} year^{-1})	2	30.43[b]	9.03	18.71
	4	32.19[ab]	9.61	18.61
	6	33.18[a]	9.81	18.80
	p-value	0.0345	0.1614	0.9095
Muriate of potash (kg palm^{-1} year^{-1})	1	32.28	9.56	18.75
	2	31.28	9.23	18.83
	3	32.15	9.63	18.55
	p-value	0.5284	0.5352	0.8086
	CV (%)	6.40	8.86	5.06

Notes: [1]Mean values with the same letter within a column are not significantly different at $p<0.05$ by Tukey Test,
[2]NOB represents the number of fresh fruit bunches, while ABW represents average bunch weight,
[3]CV- Coefficient of variation

The interactive effect of ammonium sulphate (AS) and muriate of potash (MOP) on the FFB yield over three years was shown in Table 7. No significant interaction effect was detected between AS and MOP on FFB yield. However, the highest FFB yield (34.63 t FFB ha-^{1} yr^{-1}) was recorded when AS was applied at the rate of 6 kg palm^{-1} year^{-1} with MOP at the rate of 3 kg palm^{-1} year^{-1}.

Table 7. Interactive effects of ammonium sulphate and muriate of potash on mean FFB yield of three harvesting years

Ammonium sulphate (kg palm^{-1} year^{-1})	**Muriate of potash (kg palm^{-1} year^{-1})**		
	1	2	3
	----------t FFB ha^{-1} yr^{-1}----------		
2	32.32	29.14	29.82
4	32.66	31.64	32.14
6	31.86	33.06	34.63
p-value		0.2582	
CV (%)		6.40	

Note:
[1]CV- Coefficient of variation

Economic analysis

Result showed the economic analysis of different fertiliser regimes (Table 8). The application of 2 kg of AS and 1 kg of MOP palm^{-1} year^{-1} showed the highest benefit-cost ratio (7.44), followed by the application of 4 kg of AS and 1 kg of MOP palm^{-1} year^{-1} (6.95). The fertiliser regime with the lowest benefit-cost ratio was the application of 6 kg of AS and 3 kg of MOP palm^{-1} year^{-1} (5.85).

Table 8. Economic analysis of different fertiliser regimes

Fertiliser rate		**Gross profit (RM)**	**Fertiliser cost per ha (RM)**	**Application cost per ha (RM)**	**Other variable costs (RM)**	**Total expenses (RM)**	**Benefit-cost ratio**
AS (kg palm^{-1} yr^{-1})	MOP (kg palm^{-1} yr^{-1})						
2	1	25,856	522	45	2908.8	3475.80	7.44
2	2	23,312	792	45	2622.6	3459.60	6.74
2	3	23,856	1,062	45	2683.8	3790.80	6.29
4	1	26,128	774	45	2939.4	3758.40	6.95
4	2	25,312	1,044	45	2847.6	3936.60	6.43
4	3	25,712	1,314	45	2892.6	4251.60	6.04
6	1	25,488	1,026	45	2867.4	3938.40	6.47
6	2	26,448	1,296	45	2975.4	4316.40	6.13
6	3	27,704	1,566	56	3116.7	4738.95	5.85

Notes:
[1]Gross profit is calculated based on an average of 20% OER and RM 4000 per ton of CPO,
[2]Fertiliser price: Ammonium sulphate RM 700 per ton; Muriate of potash RM 1,500 per ton,
[3]Application cost: RM 11.25 per round through mechanical spreader,
[4]Other variable costs: RM 90 per ton of FFB

Discussion

In this study, the increased application of ammonium sulphate (AS) improved the foliar nitrogen level significantly. Foliar nitrogen level is correlated positively to the photosynthesis capacity of C3 plants (Liang *et al*., 2020; Evans, 1989). According to Hikosaka and Terashima (1995), the carbon fixation rate in the Calvin cycle is maximised with increasing leaf N content, due to the elevated N allocation into ribulose bisphosphate carboxylase. Hence, the enhancement of photosynthesis was most likely responsible for the improvements in vegetative growth and development of the plant in this study. Additionally, a significant FFB yield response to AS application was observed, which was mainly contributed by the higher average number of bunches. This result is consistent with the report by Donough *et al.* (1996).

Despite the positive impacts of ammonium sulphate (AS) on palm vegetative growth and yield performance, the increasing application of AS reduced the soil pH significantly. Ammonium-based nitrogen fertilisers decrease soil pH when ammonium is nitrified and NO_3^- is leached, thereby resulting in a net increase of H^+ ions that contributes to soil acidification (Goulding, 2016; Tian and Niu, 2015; Schroder *et al*., 2011). The high concentration of H^+ ion will bound and occupy the cation exchange site, leading to a reduction of the cation exchange capacity (CEC) and exchangeable basic cations. This event was observed in this study as the exchangeable calcium and magnesium in the soil reduced by 222% and 195% five years after the application of 6 kg AS palm^{-1} year^{-1}.

The application of muriate of potash (MOP) has no significant impacts on the yield in this present study. According to Goh *et al.* (1994), unmanured Selangor series coastal soil has a high exchangeable K up to 6.4 kg palm^{-1} and a low mean yield response to K fertiliser of 2.6%. Potassium available in coastal soil is sufficient to sustain the nutrient requirement of oil palm. Hence, the excess amounts of fertiliser applied are considered 'luxury consumption' in plants. A general guideline reported by Goh *et al*. (1994) showed that there will be no fertiliser response in coastal soils with exchangeable K exceeding 0.25 cmol kg^{-1}. This is proven in this study in which no yield increment was noted with higher rates of potassium fertiliser application as the inherent soils have high exchangeable K (up to 1.53 cmol kg^{-1}). Nonetheless, it was noted that the soil exchangeable K depleted drastically (up 53%) at both soil depths when 1 kg of MOP was applied. This could be attributed by a higher nutrient acquisition by palms in HDP (Truax *et al*., 2018).

The results of this study indicate that the yield response on Selangor series coastal soils was influenced by nitrogen inputs. In addition, the interactive effects of nitrogen and potassium on FFB yield were not significant in this study. This result is contrasted to previous studies in which the application of potassium was suggested to enhance the nitrogen metabolism enzyme activity, thus improving the uptake of nitrogen and increasing the yield performance (Yagi *et al.,* 2020; Hou *et al.,* 2019). Such differences could be attributed to several factors including soil fertility, plant genetic variation, and weather conditions (Sedri *et al.,* 2022). The most likely contributing factor in the present study is soil type. A small increase in potassium input may not induce significant impacts on crop performance in coastal soil with rich potassium reserves. Hence, the application of high potassium fertiliser is not economically feasible.

According to the present study, the fertiliser regime with the greatest economic benefit and palm vegetative growth for HDP under coastal environment was the application of 4 kg of AS palm^{-1} year^{-1}, with 1 kg of MOP palm^{-1} year^{-1}. The optimal nitrogen rate in HDP is marginally higher compared to normal planting density. Gurmit (1990) reported that the optimum nitrogen input for Selangor soil series under normal planting density (143 palms per hectare) is equivalent to 3.77 kg of AS. This shows that the increase of planting density does not increase the nitrogen requirement of individual palm.

In conclusion, oil palm yield in HDP under coastal environment of Peninsula Malaysia is much influenced by nitrogen inputs compared to potassium fertilisation mainly due to the high potassium reserve in coastal clay soil. The increased application of nitrogen up to 6 kg AS per palm enhanced oil palm yield significantly. The highest yield was obtained under the highest rate for both nitrogen and potassium inputs. Nonetheless, 4 kg of AS and 1 kg of MOP per palm is recommended for HDP under the coastal environment of Peninsula Malaysia to achieve optimum palm growth and economic returns.

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