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Early Performance Results of Polyhalite on Newly Planted Oil Palms

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ABSTRACT

In oil palm plantations, the application of secondary nutrients, especially calcium and sulfur is often negligible due to the focus on merely primary nutrients and magnesium. Calcium is responsible for proper plant cell division and for strengthening cell walls while sulfur improves the oil synthesis rate in oil palm. Polyhalite ($K_2SO_4 \cdot MgSO_4 \cdot 2CaSO_4 \cdot 2H_2O$) is a natural marine evaporite mineral produced by successive marine evaporation events throughout history. Its huge potential as a potassium fertiliser, due to its very low quantities of chlorine but richness in potassium, calcium, and magnesium, has attracted its use in various crops to achieve higher yields and better-quality crops. In addition to potassium, magnesium fertilisation can increase crop yield and quality. Previous studies focus on applying Polyhalite in cash crops and are less prominent in the oil palm. Therefore, this study aims to evaluate the vegetative growth performance of Polyhalite on oil palm aged one-year-old in addition to the conventional programme. Results showed that applying 0.3 kg ERP + 0.3 kg AgCOTE 18/6/8/2+ME + 0.3 kg Polyhalite into planting holes during transplanting the oil palm seedlings in the field is most cost-efficient while delivering the same vegetative growth compared to the conventional practices.

Keywords: Economic, low carbon, nutrient use efficiency, polysulphate, sustainable

INTRODUCTION

The labour shortage has been an issue in the oil palm industry for years and has remained uncertain till now. Fewer local people are willing to work in oil palm estates as general workers because they cannot tolerate with the tough working environment in the estate (Azahar, 2022), leading to higher demand for foreign workers to cope with the labour

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requirement. The ratio of workers to plantation area is one worker to 10 hectares of oil palm area (Jasni & Othman, 2017). However, foreign workers coming to Malaysia are mainly employed in the manufacturing and service sectors due to the nature of the working environment, leading to a labour shortage of approximately 40,000 workers in the country's oil palm industry (Evanson, 2024). For instance, the export earnings for Malaysia would reduce to RM10 billion if the number of foreign workers were reduced by 30% (Mamat, 2010). Therefore, the big player in each organisation should look into another approach to deal with the labour shortage issue.

One of the solutions to reduce the impact of the labour shortage issue is to reduce labour requirements through reducing fertiliser application rounds. Thus, controlled-release fertiliser (CRF) is introduced to the market by developing controlled release of nutrients for oil palm seedlings and first-year oil palms. During the immature stage, heavy pest and disease control are required due to the higher vulnerability of the trees. The application of CRF for the first year of oil palm is 1 -2 times per year, depending on the release period of the fertiliser used. Compared to the conventional fertiliser programme of 4 -5 application rounds per year (Goh et al., 2013; SK Specialties, 2020), the reduction in the application rounds can save on labour and handling. In addition, the controlled release system can reduce the losses of fertiliser, reduce the amounts of fertiliser used and minimise environmental pollution (Bah et al., 2014; Jariwala et al., 2022), because the gradual nutrient release from CRF around the root zone can maximise nutrient absorption. Using CRF also enhances economic benefit by 5.21-11.44% (Lyu et al., 2021). Thus, the CRF application can save on labour while at the same time improving the efficiency of nutrient uptake, and this is such a win-win situation for the oil palm industry.

In contrast, the high cost of CRF has turned it into a barrier in the oil palm industry. Price of CRF is usually triple of the price of the compound fertiliser due to its complex coating processing (Govil et al., 2024; Monsouri et al., 2023). As a mature oil palm is a heavy fertiliser feeder which requires at least 10.75 kg/tree/year to sustain 30 mt fruit bunches per hectare (Ng et al., 1999), application of CRF is only applicable during the nursery stage and replanting stage due to insufficient nutrient supply for its aggressive growth. Besides that, polymer-coated CRF poses potential microplastic pollution, which tends to release tiny plastic particles into the environment when the polymer coatings break down in the soil (Stan, 2025).

Besides CRF, Polyhalite is another potential slow-release type of fertiliser source which can be applied to the rooting zone without scorching issues. Polyhalite ($K_2SO_4 \cdot MgSO_4 \cdot 2CaSO_4 \cdot 2H_2O$), or known as Polysulphate in Malaysia, is a natural marine evaporite mineral produced by successive marine evaporation events throughout history. Its huge potential as a K fertiliser due to its very low quantities of chlorine (Cl) but rich in potassium (K), calcium (Ca), and magnesium (Mg) has attracted its use in various crops to achieve higher yield and better-quality crop. In addition to K, Mg fertilisation can increase crop yield and quality. Ca is also a necessary nutrient for oil palm and can increase root growth, while sulfur helps to improve the oil synthesis. Proper nutrient management is critical for optimising yield and ensuring sustainable cultivation. Thus, sustainable nutrient management practices incorporating these elements are essential for maintaining the long-term viability of oil palm plantations.

Polyhalite is gaining attention as a multi-nutrient fertiliser that enhances crop productivity and soil fertility. Research studies across different crops have demonstrated its potential to improve vegetative growth, yield, and nutrient uptake due to its ability to supply essential secondary nutrients (Ca, Mg, and S) alongside K makes it a promising alternative to conventional fertilisers. There are studies reporting the efficacy of Ca in increasing nutrient availability and uptake in oil palm seedlings (Rahman et al., 2007; Shamshuddin et al., 2024), resistance against basal stem rot (Bivi et al., 2016; Nur Sabrina et al., 2011), and improving physiological activity and drought resistance in oil palm seedlings (Mahyunita et al., 2019). Besides that, sulfur (S) improves soil fertility by enhancing microbial activity and organic matter decomposition, which increases nutrient cycling. Oil palm plantations with adequate S show improved soil organic carbon content and nutrient availability (Sabir et al., 2015).

Previous studies summarised the positive impact of Polyhalite application on various crops, including peanut (Gopinath et al., 2024), maize (Baez-Perez et al., 2021), soybean (Baez-Perez et al., 2021), cabbage (Jamal et al., 2010; Yermiyahu et al., 2017), alfalfa (Bernardi et al., 2018), sunflower (Aziz et al., 2023), potato (Keren-Keiserman et al., 2019), sugarcane (Bhatt et al., 2024), and wheat-based cropping systems (Singh et al., 2023), but there was no study yet reporting on its agronomic efficacy on the immature oil palm trees especially during replanting stage. Additionally, there is limited literature cited on CRF performance reflect conditions specific to tropical oil palm estates. The available commercial trials on the oil palm tree were published on the website, highlighting the economic (Nousbo, 2026) and labour-saving (SK Specialties, 2020) from using CRF. Even though CRF and Polyhalite are both slow-release in nature, their combined use on the growth of oil palm has not been systematically evaluated. Therefore, in this study, we aim to evaluate the early vegetative growth performance of Polyhalite on oil palm aged one year old in addition to the conventional programme. Control treatment without fertiliser application was not included in this study as this is a commercial trial aiming to compare the early performance of palm trees in both agronomic and economic with the incorporation of Polyhalite in addition to the estate's practice. As the estate practice involves the application of rock phosphate, reduced application was also evaluated to determine the optimum dosage and early performance result for both rock phosphate and Polyhalite during transplanting the oil palm seedlings. Besides that, the cost-effectiveness of applying Polyhalite during transplanting in the field was computed to evaluate its economic efficacy.

MATERIALS AND METHODS

The study was conducted for one year, from June 2022 to June 2023, at an oil palm estate located in Keratong, Pahang, Malaysia. The trial size of one (1) hectare was arranged in Randomised Complete Block Design (RCBD) to allocate for three (3) treatments, as shown in Table 1 and *Figure 1*, where each treatment consists of four (4) replicates. While each set of replicates consists of three (3) palms, the total data collection is thus thirty-six (36) palms. One hectare of trial plot is sufficient in an agronomic trial, as the agronomic trials often adopt 3 -4 replicates per treatment as a practical compromise between statistical rigour and resource constraints (Yan, 2021). In perennial crops such as oil palm, estate-scale designs often adopt one-hectare plots with subsampling of 20 -30 palms to measure within-plot variability while remaining operationally feasible (Verdooren, 2019). Throughout the trial period, there was no extreme drought season with two or more consecutive months of low rainfall at below 100mm/month (Table 2). The fertiliser was applied in the planting hole during transplanting, which is a one-time application. Thus, the rainfall variability towards nutrient release is assumed homogeneous across the treatments. The soil samples collected before applying fertiliser treatment confirm the low CEC and low soil nutrient level at the trial site (Table 3). During transplanting, Egyptian Rock Phosphate (ERP) was applied into the planting hole, followed by applying the CRF, AgCOTE 18/6/8/2+ME. Thereafter, the seedlings were placed into the hole and then partially covered with soil. Next, Polyhalite was applied and finally covered the whole seedlings with soil until soil surface. The surrounding soil of the seedlings was well compacted. To align with the estate practice, all immature palm trees were mulched with one whorl of empty fruit bunches. The mulching was conducted at the same time using the same rate across all treatments to minimise potential confounding effects.

The control treatment is the conventional practice in the oil palm industry, whereby 0.5 kg of RP is incorporated into the planting hole together with the CRF, aiming to reduce fertiliser application rounds during the first year of planting, leading to savings in the manuring cost. As both RP and Polyhalite share the function of improving root growth, the reduced dosage for T2 was added to determine the optimum dosage when applying RP and Polyhalite together. The treatment is determined based on the conventional practice as baseline, addition of Polyhalite at the same dosage is included as T3, while a reduced dosage by half for all types of fertiliser is treated as T2. The vegetative parameters include palm height and girth diameter, which were measured on a quarterly basis. Other vegetative parameters, such as the number of green fronds and leaf area, were excluded from this study due to severe beetle attack at the trial plot, which affected the results. Leaf samples of frond #9 were taken twice throughout the trial, at the beginning and at the end of the trial, to compare the leaf nutrient level between the treatments. A study was conducted on testing nutrient prediction on oil palm using spectroscopy, which found that the calibration performance for frond #9, as indicated by R^2 is good for all three nutrients (N, P, K), respectively, with a relatively low root mean square error of calibration (Jayaselan, et al., 2017). In occasional practices, frond #9 is used for routine leaf sampling for oil palm trees of 3 years and below (Fairhurst et al., 2004).

All vegetative growth data collected were analysed using IBM SPSS Statistics 30.0.0.0. The vegetative parameters were further analysed using repeated-measures ANOVA to test if there were any significant differences among different fertiliser treatments at $\alpha = 0.05$ across the trial period.

Table 1
Description on the treatments in this study

No.	Treatment Number	Type of Fertilisers
1	T1 (control)	0.5kg ERP + 0.5kg AgCOTE 18/6/8/2+ME (AgCOTE)
2	T2	0.3kg ERP + 0.3kg AgCOTE 18/6/8/2+ME + 0.3kg Polyhalite (PS)
3	T3	0.5kg ERP + 0.5kg AgCOTE 18/6/8/2+ME+ 0.5kg Polyhalite (PS)

Table 2
Monthly rainfall at the trial plot throughout the trial period

Year	2022		2023	
	mm	Day	mm	Day
January	505	5	300	17
February	242	17	308	13
March	139	30	511	12
April	383	18	236	20
May	134	8	57	4
June	102	6	200	11
July	54	5	193	9
August	124	8	174	9
September	112	8	216	9
October	319	18	141	13
November	298	18	190	13
December	216	19	254	16
Total	2,628	160	2,780	146

The ideal principle of a CRF should have maximum control of the release so that the nutrients are supplied at a rate similar to the plant growth. Therefore, the estate's practice using AgCOTE was maintained as a control treatment in this study. This fertiliser coated with the special resin is an epoch-making well controlled releasing high analysis compound coated fertiliser based on nitrate. The release of nutrients from AgCOTE is controlled by the amount of a special chemical release agent in the resin coating. Only the amount of this special release agent varies according to the required period of release, i.e. 360 days. When AgCOTE is placed in the soil, the granules begin to absorb moisture through the coating membrane. This moisture then dissolves the nutrients inside the capsule, which in turn builds up an osmotic pressure. The nutrients can then diffuse through the coating. The amount of release agent contained in the coating will determine how porous the coating is, which determines exactly how fast the nutrients will diffuse.

At the 9th month of the trial period, one round of Royal Terra 15/15/15/2 at 1.50 kg/palm was applied on all treatments due to high temperatures in the tropical region, which shortened the release period of the CRF from 12 months to 9 months. The nutrient release of AgCOTE is moderately affected by temperature. As temperatures warm in the spring and cool in the fall, the release of nutrients will increase or decrease (Figure 2). This keeps the rate of release in tune with the rate of plant growth. Next, the nutrient release of AgCOTE is not significantly affected by soil moisture levels. This release is also unaffected by soil type or soil pH and AgCOTE does not depend upon microbiological decomposition for its action. As the polymer coating is photodegradable, over time, the coating on AgCOTE will be degraded without leaving residues in the soil.

Figure 1. Trial site in Keratong, Pahang, Malaysia

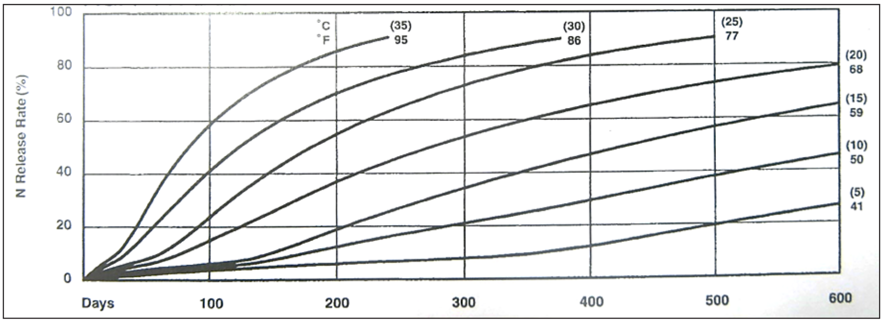

Figure 2. N release rate of AgCOTE at 25 °C, 30°C and 35 °C

Table 3

Soil chemical properties at the trial site

No.	Sampling Depth (m)	Treatment	pH Value	CEC	Organic Carbon	Total N	Phosphorous		Exchangeable Potassium (K)	Exchangeable Magnesium (Mg)	Exchangeable Calcium (Ca)
							Total P	Available P			
				m.e %	%	%	mg/kg	mg/kg	m.e %	m.e %	m.e %
1	0.15	T1	4.48	5.50	0.82	0.17	88	8	0.19	0.21	0.35
		T2	4.87	5.10	1.21	0.22	88	5	0.36	0.24	0.50
		T3	4.66	4.80	0.69	0.11	46	4	0.14	0.15	0.37
2	0.3	T1	4.49	5.00	0.79	0.15	70	6	0.30	0.17	0.27
		T2	4.57	5.40	0.67	0.12	58	4	0.24	0.12	0.32
		T3	4.33	4.70	0.66	0.13	40	3	0.11	0.10	0.31

RESULTS AND DISCUSSION

Normality Test

Normality test results show that the dataset is normally distributed, as the p-value is more than 0.05 based on the Shapiro-Wilk (Table 4). Despite the p-value of 0.041 for the palm height collected for T1 at the 9th Month, the data is still treated as normally distributed due to its minor deviation.

Table 4
Tests of normality using the Shapiro-Wilk

Treatment		Kolmogorov-Smirnov[a]			Shapiro-Wilk		
		Statistic	**df**	**Sig.**	**Statistic**	**df**	**Sig.**
M0 - Palm Height (cm)	T1	0.210	12	0.151	0.917	12	0.261
	T2	0.244	9	0.130	0.923	9	0.416
	T3	0.180	15	.200*	0.957	15	0.638
M0 - Girth Diameter (mm)	T1	0.202	12	0.192	0.899	12	0.153
	T2	0.169	9	.200*	0.946	9	0.643
	T3	0.138	15	.200*	0.929	15	0.261
M3 - Palm Height (cm)	T1	0.156	12	.200*	0.949	12	0.620
	T2	0.172	9	.200*	0.941	9	0.591
	T3	0.184	15	0.181	0.938	15	0.359
M6 - Palm Height (cm)	T1	0.167	12	.200*	0.923	12	0.315
	T2	0.184	9	.200*	0.906	9	0.287
	T3	0.141	15	.200*	0.955	15	0.605
M6 - Girth Diameter (mm)	T1	0.235	12	0.066	0.894	12	0.134
	T2	0.212	9	.200*	0.927	9	0.449
	T3	0.110	15	.200*	0.961	15	0.718
M9 - Palm Height (cm)	T1	0.201	12	0.196	0.854	12	0.041
	T2	0.236	9	0.159	0.859	9	0.094
	T3	0.167	15	.200*	0.962	15	0.730
M9 - Girth Diameter (mm)	T1	0.203	12	0.186	0.890	12	0.119
	T2	0.167	9	.200*	0.945	9	0.637
	T3	0.130	15	.200*	0.980	15	0.968
M12 - Palm Height (cm)	T1	0.166	12	.200*	0.952	12	0.663
	T2	0.187	9	.200*	0.903	9	0.270
	T3	0.168	15	.200*	0.956	15	0.626

Table 4 (*continued*)

Treatment		Kolmogorov-Smirnov[a]			Shapiro-Wilk		
		Statistic	df	Sig.	Statistic	df	Sig.
M12 - Girth Diameter (mm)	T1	0.247	12	0.042	0.886	12	0.105
	T2	0.255	9	0.094	0.898	9	0.243
	T3	0.141	15	.200*	0.954	15	0.582

*. This is a lower bound of the true significance.
a. Lilliefors Significance Correction

Vegetative Growth

Mauchly's test indicated that the assumption of sphericity had been violated for both palm height, at χ^2 (2) = 54.787, $p < 0.001$ (Table 5), and girth diameter, at χ^2 (2) = 11.279, $p = 0.046$ (Table 6). Therefore, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = 0.515$ for palm height and $\varepsilon = 0.807$ for girth diameter).

Table 5
Mauchly's test of sphericity for palm height

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[b]		
					Greenhouse-Geisser	Huynh-Feldt	Lower-bound
Time	0.175	54.787	9	0.000	0.515	0.583	0.250

Tests the null hypothesis that the error covariance matrix of the orthonormalised transformed dependent variables is proportional to an identity matrix.
a. Design: Intercept + Treatment
Within Subjects Design: Time
b. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

Table 6
Mauchly's test of sphericity for girth diameter

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[b]		
					Greenhouse-Geisser	Huynh-Feldt	Lower-bound
Time	0.701	11.279	5	0.046	0.807	0.929	0.333

Tests the null hypothesis that the error covariance matrix of the orthonormalised transformed dependent variables is proportional to an identity matrix.
a. Design: Intercept + Treatment
Within Subjects Design: Time
b. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

Results from Table 7 and Table 8 indicate that the palm height and girth diameter grow significantly across the nine-month period at $p < 0.001$, but different fertilisers did not significantly produce different average palm height and girth diameter at $p = 0.503$ and $p = 0.685$, respectively. The results suggest that the addition of Polyhalite into a conventional manuring program is comparably effective even at reduced dosage.

Table 7
Tests of within-subjects effects for palm height

	Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Time	Sphericity Assumed	164897.305	4	41224.326	113.775	0.000
	Greenhouse-Geisser	164897.305	2.060	80046.424	113.775	0.000
	Huynh-Feldt	164897.305	2.332	70702.135	113.775	0.000
	Lower-bound	164897.305	1.000	164897.305	113.775	0.000
Time * Treatment	Sphericity Assumed	2454.743	8	306.843	0.847	0.563
	Greenhouse-Geisser	2454.743	4.120	595.805	0.847	0.503
	Huynh-Feldt	2454.743	4.665	526.254	0.847	0.514
	Lower-bound	2454.743	2.000	1227.372	0.847	0.438
Error (Time)	Sphericity Assumed	47827.690	132	362.331		
	Greenhouse-Geisser	47827.690	67.981	703.548		
	Huynh-Feldt	47827.690	76.965	621.419		
	Lower-bound	47827.690	33.000	1449.324		

Table 8
Tests of within-subjects effects for girth diameter

	Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Time	Sphericity Assumed	298236.231	3	99412.077	275.623	0.000
	Greenhouse-Geisser	298236.231	2.422	123146.724	275.623	0.000
	Huynh-Feldt	298236.231	2.786	107056.002	275.623	0.000
	Lower-bound	298236.231	1.000	298236.231	275.623	0.000
Time * Treatment	Sphericity Assumed	1325.482	6	220.914	0.612	0.720
	Greenhouse-Geisser	1325.482	4.844	273.657	0.612	0.685
	Huynh-Feldt	1325.482	5.572	237.900	0.612	0.708
	Lower-bound	1325.482	2.000	662.741	0.612	0.548
Error (Time)	Sphericity Assumed	35707.519	99	360.682		
	Greenhouse-Geisser	35707.519	79.919	446.795		
	Huynh-Feldt	35707.519	91.931	388.415		
	Lower-bound	35707.519	33.000	1082.046		

There was no significant difference in palm growth with the addition of Polyhalite, as shown in Figure 3, Figure 4, and Figure 5. However, palm growth performed slightly better with the addition of 0.3 kg Polyhalite compared to the palm tree without Polyhalite and the palm tree with 0.5 kg Polyhalite. Too high rate of Polyhalite may suppress palm growth because excessive cations supplied are not balanced with the nitrogen and phosphorus. Furthermore, the absence of an immediate morphological response despite improved leaf nutrient concentrations suggests a phase of internal nutrient accumulation. During the first year of planting, immature oil palms prioritise establishing a robust physiological foundation. Increased internal nutrient levels, particularly K and Mg, which may be diverted toward metabolic sink strength and root architecture development rather than immediate above-ground biomass expansion (Mohidin et al., 2019).

Nutrient release rate of Polyhalite demonstrated a prolonged releasing pattern reaching 50 days and constantly delivered nutrients to the tree despite heavy rain following application (Massawe, 2010). According to Huang (2020), Polyhalite's slow-dissolving nature minimises leaching losses during heavy rain by retaining nutrients within the root zone longer than conventional fertilisers. Such a mechanism is particularly suited for

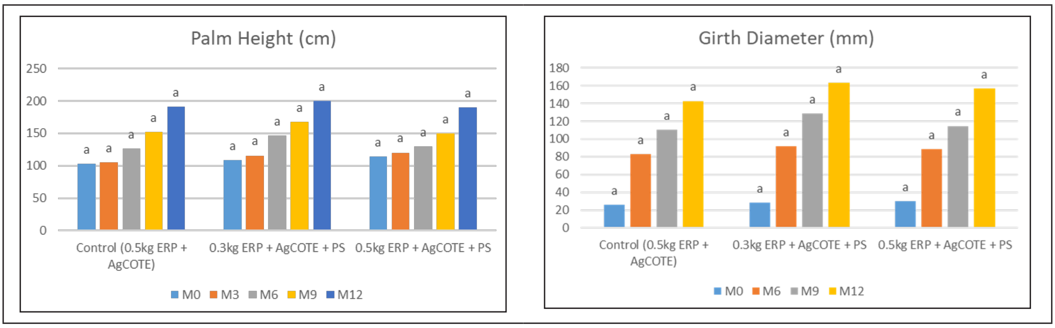

Figure 3. Change in the palm height and girth diameter across different treatments

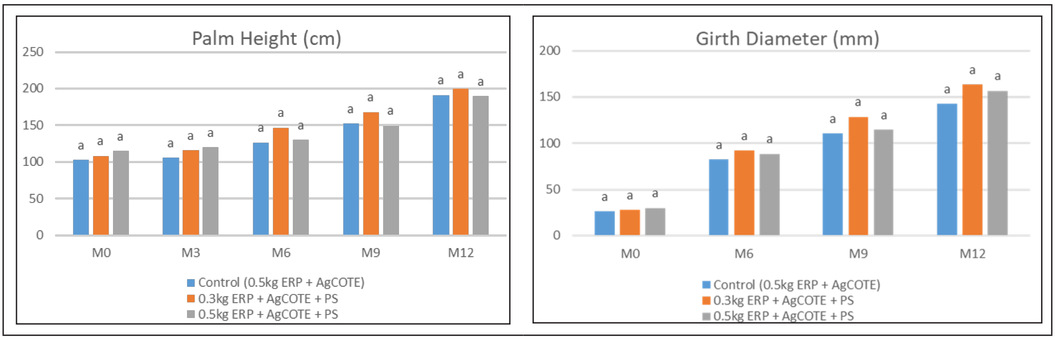

Figure 4. Change in the palm height and girth diameter across the one-year trial period

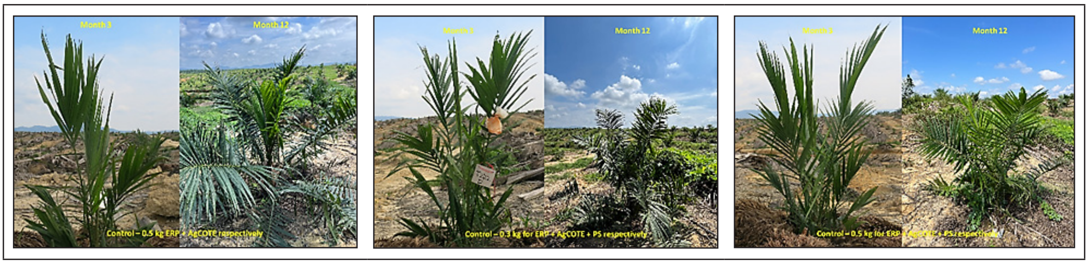

Figure 5. The palm growth progress during month 3 and month 12 after transplanting for (left) control treatment (0.5kg ERP + 0.5kg AgCOTE); (centre) 0.3kg ERP + 0.3kg AgCOTE + 0.3kg PS; (right) 0.5kg ERP + 0.5kg AgCOTE + 0.5kg PS

tropical sites, sustaining vegetative growth by preventing nutrient washout during intense wet periods.

In addition, regular application of calcium minerals on Ultisols and Oxisols maintained soil fertility and improved soil structure. Calcium amendments improved soil aggregation and reduced soil compaction, facilitating better root growth (Shamshuddin et al., 2024). Thus, the addition of 0.3 kg Polyhalite can reduce the dosage of RP and CRF while at the same time achieving a similar growth rate. The application of Polyhalite helps to improve soil structure due to its calcium content, which improves the soil porosity and aggregates soil particles. This helps to reduce erosion, improve water infiltration, and root penetration. In addition, Polyhalite helps to improve soil cation exchange capacity (CEC), which has better nutrient retention and lower nutrient leaching (Huang et al., 2020).

A study found that the partial replacement of potassium chloride (KCl) with Polyhalite improves the soil quality and better growth on peanuts (Tan et al., 2022). Besides, compound fertiliser that contains Polyhalite enhance the yield of winter melon, improves nutrient use efficiency, quality, and reduces environmental pollution (Chen et al., 2022).

A study showed that fertilisers containing Polyhalite increase the content of exchangeable Ca, Mg, and S in the soil. These findings demonstrate the capability of Polyhalite in addressing fertiliser-induced soil acidification, thereby supporting sustainable agricultural practices through enhanced long-term soil health, reduced reliance on chemical amendments, and minimised environmental impacts (Lewis et al., 2019).

Treatment with Polyhalite shows slightly taller palm height, although the difference is not significant, and this could also be due to the contribution of S in Polyhalite. Polyhalite contains 19% of S, the contribution of S helps to enhance leaf area, a higher number of leaves, higher plant height and improve root growth. The enhanced leaf area and plant growth might have supported higher photosynthetic activity, increased N and P uptake, and a higher total dry matter yield, ultimately leading to the higher yields (Li et al., 2025).

Sufficient S boosts nutrient uptake, which is essential for root development, acting as a redox regulator and precursor for compounds vital to root growth. Plant starvation with S disrupts N and S metabolism, leading to reduced fine root length, surface area, and biomass, ultimately impairing root activity and nutrient absorption (Zhou et al., 2024). The abundant Ca ions in Polyhalite actively contribute to cell differentiation at the root tip and root elongation by regulating root morphogenesis through phytochrome mediation and stress signalling in the primary root (Zhang et al., 2020).

Leaf Analysis Results

The leaf analysis results from *Figure 6* show that a higher rate of Polyhalite would deliver higher leaf nutrients. In addition, reduced dosage of RP, Polyhalite and CRF from T2 still delivered equivalent leaf P and leaf Ca levels compared to T1 and T3, which are of higher application dosage. The Ca will usually deposit in root tissues rather than staying on the leaf (Khor et al., 2023). Besides delivering nutrients for plant vegetative growth and nutrient use efficiency, the readiness of Ca plays a role in boosting the plant's immune system against diseases through the Ca deposition in the cell wall for membrane firmness (Khor et al., 2023). The addition of Polyhalite also helps to increase nutrient uptake, especially N, Mg and Ca. This enhanced uptake is supported by the fact that the timing of Polyhalite application aligns with the nutrient demand curves of immature oil palms, which require a steady and continuous supply of K, Mg, and Ca for rapid vegetative development. While conventional high-solubility fertilisers often create a 'peak and trough' nutrient profile that leads to temporary surplus and subsequent leaching, Polyhalite’s 50-day release pattern (Massawe, 2010) provides a synchronised nutrient flux. This ensures that nutrient availability matches the palm’s constant physiological requirements during its immature phase, particularly in high-rainfall tropical environments.

The treatment with high input of Polyhalite has the highest leaf calcium level after one year. This could be due to the mode of nutrient release and the natural characteristics of Polyhalite. Polyhalite release nutrient through the dissolution of soil moisture. It supplies the nutrients to the crops at a slow and steady rate over a long period, which reduces the risk of nutrient leaching (Tan, et al., 2022). Besides, the dissolution rate can be higher in acidic soil due to the occurrence of hydrogen ions that promote the breakdown of Polyhalite (Singh et al., 2023).

A balanced supply of readily available S through Polyhalite application significantly enhances N uptake in plants, while also fostering synergistic interactions with other essential nutrients. Sulphur augments N assimilation, it facilitates crucial metabolic processes (NO_2^- and SO_4^- reduction), remains fundamental to the amino acid biosynthesis and is for the efficient nutrient translocation within the plant tissues (Singh et al., 2023).

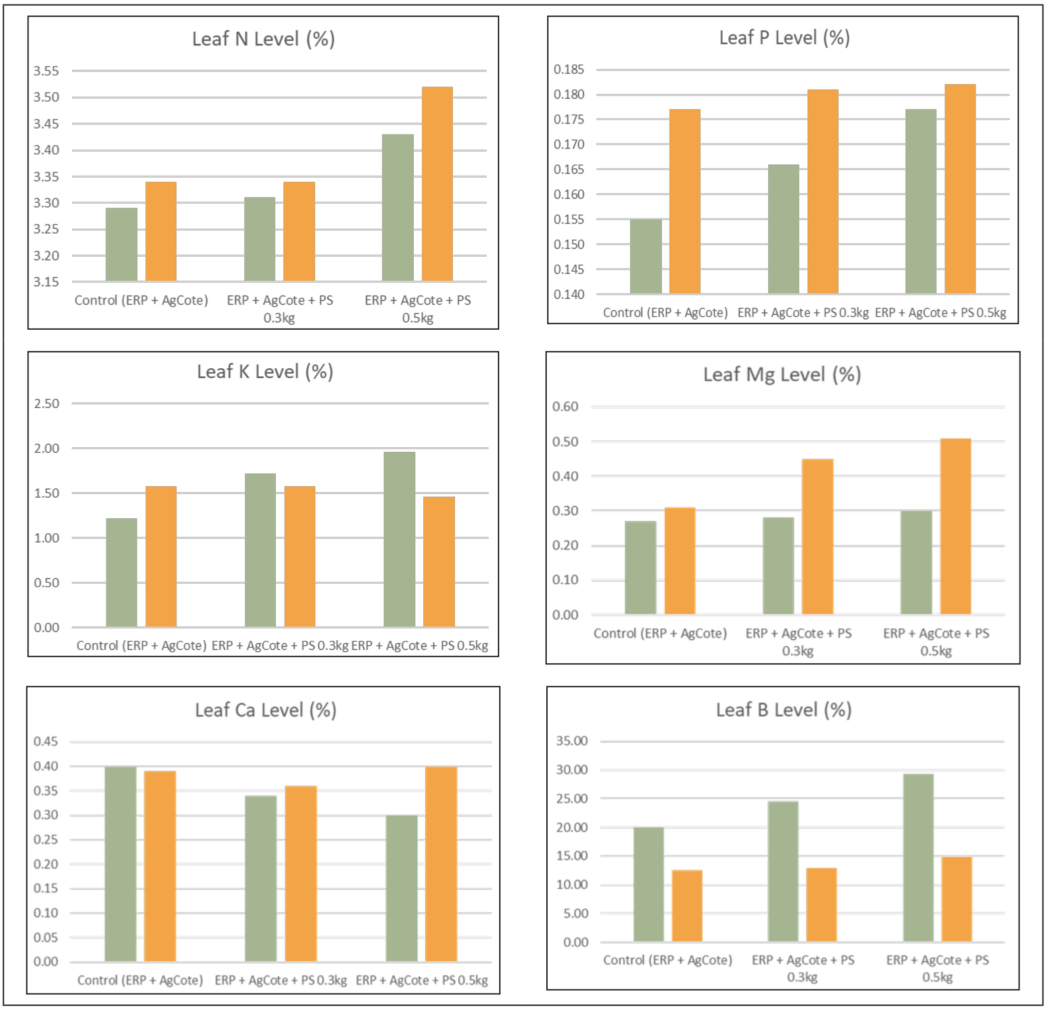

Figure 6. Leaf nutrient level at one year before and after the treatments

Cost Effectiveness

Based on the market price during the trial period, Figure 7 illustrates that the application of 0.3 kg Polyhalite, besides 0.3 kg ERP and 0.3 kg AgCOTE 18/6/8/2+ME, has the lowest fertiliser cost at RM3.05/tree compared to the control treatment (RM4.28/tree) and 0.5 kg treatment (RM5.08/tree). The savings from using 0.3 kg Polyhalite are as high as 40% compared to the control treatment. Each palm can save from RM1.23 by using Polyhalite-combination treatment. Additionally, based on cost sensitivity analysis, every 5% change in the market price of Polyhalite will result in merely 1% change in the total fertiliser cost for the first year of oil palm planting (*Table 9*). The fertiliser price for this study is calculated based on the current market price and varies according to the market.

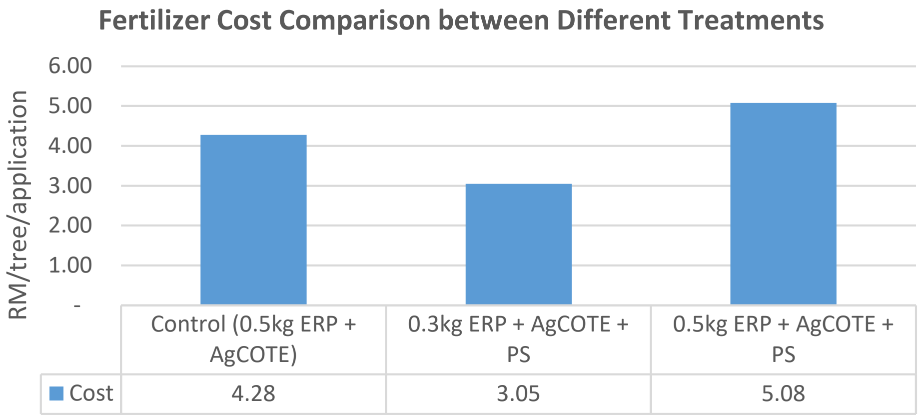

Figure 7. Fertiliser cost comparison between different treatments

Note. ERP -RM550/mt; AgCOTE 18/6/8/2+ME -RM8,000/mt; Polyhalite -RM1,600/mt

Table 9
Cost sensitivity of Polyhalite

No	% Change	Fertiliser Cost (RM/MT)				
		ERP	AgCOTE	Polyhalite	Total Fertiliser Cost	% Increase
1	-10%	550	8,000	1,440	9,990	-2%
2	-5%	550	8,000	1,520	10,070	-1%
3	0%	550	8,000	1,600	10,150	0%
4	5%	550	8,000	1,680	10,230	1%
5	*10%*	550	8,000	1,760	10,310	2%
6	15%	550	8,000	1,840	10,390	2%

The labour savings achieved in this study are distinguished from estate management efficiencies by focusing on the structural design of the manuring program. While the industry's conventional practice (straight fertilisers) requires a high frequency of 4 to 5 rounds (Goh & Härdter, 2003), all treatments in this study utilised CRF technology to consolidate application into fewer rounds. Specifically, T2 achieved additional efficiency by optimising the dosage (0.9 kg/palm) compared to T3 (1.5 kg/palm). This reduces the total weight of material handled and transported by workers, thereby decreasing the man-days required per hectare regardless of the specific labour management protocols of the estate.

Integrated Environmental Assessment

In this study, the integrated use of Polyhalite and polymer-coated CRF represents a dual-strategy for nutrient longevity. However, a comprehensive environmental assessment must account for the different footprints of these technologies. While the polymer-coated component provides precise control over nutrient release, it introduces synthetic coatings into the soil. Although an empirical assessment of microplastic persistence (Li, 2025) was beyond the technical scope of this trial, the inclusion of Polyhalite serves as a vital sustainability bridge.

As a naturally occurring mineral that dissolves completely into K, Ca, Mg, and S, Polyhalite allows for a reduction in the total volume of synthetic-coated material required per hectare (as seen in the optimised T2 dosage) without compromising the prolonged release pattern (Massawe, 2010). Furthermore, the evidence suggests that the palm's growth was governed by nutrient synchronisation rather than osmotic stress. This is supported by the low salt index of Polyhalite at 0.85 (Yermiyahu, 2017), which, when combined with CRF, maintains a stable soil solution conductivity. By integrating mineral-based slow-release sources with coated technologies, estates can achieve the necessary synchronisation with palm demand curves while effectively reducing the cumulative environmental and plastic burden per application.

CONCLUSION

Additional application of 0.3 kg Polyhalite besides 0.3 kg ERP and 0.3 kg AgCOTE 18/6/8/2+ME, is the most cost-effective fertiliser application while at the same time improving vegetative growth and increasing nutrient uptake efficiency for the planting of first-year oil palm. The insignificant differences in terms of palm height and girth diameter suggest the addition of Polyhalite into a conventional manuring program is comparably effective even at reduced dosage. Additionally, the incorporation of Polyhalite into planting holes during transplanting, together with rock phosphate and CRF at 0.3 kg/tree, respectively, can save up to 40% of the fertiliser cost and represents a dual-strategy for nutrient longevity. A primary limitation of this study was the small, localised sample size causing the findings may not be widely generalisable to other demographics. While this study provided preliminary insights, future studies should include a broader, national sample to validate these findings. Besides that, there were no significant growth differences observed in year one, but strong uptake signals are present, indicating that the lag effects are possible and longer-term monitoring of the study is recommended. Further research should focus on optimising application rates and integrating Polyhalite into different soil and cropping systems to maximise its agronomic benefits. The study also focuses on agronomic management for first-year oil palm; the empirical assessment on microplastic risk would require another environmental study. Besides that, future studies can further evaluate the impact of calcium from Polyhalite on the root growth, as well as the nutrient leaching when applying Polyhalite.

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