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Influences of N, P, K, Ca, and Mg fertilization on soil characteristics and nutrient uptake of ratoon pineapple (*Ananas comosus* L.) in acid sulfate soil

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Abstract: Ratoon pineapple is a type of pineapple that grows from the existing sucker of a former plant. In this way, the production cost can be decreased while the yield can be increased. Therefore, the study aimed to determine the effects of applying N, P, K, Ca, and Mg nutrients on soil features, nutrient uptake of ratoon pineapple, and its growth and yield. An omission plot trial was conducted on pineapple in acid sulfate soil following a completely randomized block design with 8 treatments and 4 replications each. The treatments included (i) NF: no fertilizer, (ii) NPKCaMg: N, P, K, Ca, and Mg fertilization, (iii) PKCaMg: no N fertilization, (iv) NKCaMg: no P fertilization, (v) NPCaMg: no K fertilization, (vi) NPKMg: no Ca fertilization, (vii) NPKCa: no Mg fertilization, (viii) LFF: local farmer fertilization. The result revealed that the PKCaMg treatment reduced N availability (NH_4^+) and the NKCaMg treatment reduced soluble P content in the soil, compared with the fertilized treatments. The NKCaMg treatment also reduced insoluble P compounds such as Al-P and Ca-P. Likewise, the NPKMg and NPKCa treatments decreased Ca^{2+} and Mg^{2+} concentrations in the soil. The treatments without N, P, K, Ca, or Mg reduced crown, pulp, core, peduncle, butt, and leaf biomass. The treatments without N, P, K, Ca, or Mg also decreased the corresponding nutrient uptake of pineapple. Pineapple yield went down by 28.5, 20.9, 20.1, and 20.1% when N, P, Ca, and Mg were omitted, respectively. The N, P, K, Ca, and Mg fertilizer formula was optimized as 462 N, 341 P_2O_5, 510 K_2O, 1207 CaO, and 618 MgO kg ha^{-1}.

Keywords: acid sulfate soil, nutrient omission plot, ratoon pineapple.

Abbreviations: AE_ Agronomic efficiency, Ca_ Calcium, CEC_ Cation exchange capacity, DAP_Diammonium phosphate, EC_ Electrical conductivity, LFF_ Local farmer fertilization, Mg_ Magnesium, N_ Nitrogen, NF_No fertilizers, P_ Phosphorus, K_ Potassium.

Introduction

Pineapple (*Ananas comosus* L.) is a monocotyledon plant of the Bromeliaceae family. It is a popular tropical fruit due to its odor and sweetness. Moreover, pineapple fruits contain many nutritious components that benefit human health and are potent in agriculture and the food industry (d'Eeckenbrugge et al., 2011; Ali et al., 2020). Two cropping types can be considered when growing a pineapple field: ratoon and plant pineapples. The plant pineapple is grown from crowns and suckers on a new field, while the ratoon pineapple is grown from suckers or slips of a form pineapple plant that has been harvested (Bartholomew et al., 2002; Biswas and Nishat, 2019). As can be seen, the ratoon pineapple can generate more profit for farmers after the first cycle (Apeksha, 2020; Matthew et al., 2023), because the old pineapple plants can be reused for up to 3 to 7 years with an increase in the yield after every crop, which can ultimately provide a sustainable income for the farmers. Moreover, the ratoon cropping gains a greater yield than the plant cropping (Borah et al., 2020). Thus, using the suckers from former plants is more common to propagate pineapple than growing a new plant (Matthew et al., 2023). Besides suckers, slips can also be used to grow a ratoon pineapple plant (Paull et al., 2022). Therefore, in Vietnam, the government advises farmers to grow ratoon pineapple after the first season to save production costs and increase productivity and profit.

Nutrients are essential for living creatures including plants which also require nutrients to live and grow (Naz, 2023). Different nutrients have different requiring thresholds, when plants are deficient in one of the nutrients, symptoms or death appear (Saleem et al., 2023). Nitrogen (N) is the component of amino acids, proteins, nucleic acid, pyrimidine, chlorophyll, and enzymes. N is vital for the growth and metabolism of plants (Jose, 2023). However, plants cannot absorb N_2 in the atmosphere, and N is taken and transported in the forms of NH_4^+ and NO_3^-. Phosphorus (P) is also important for nucleic acids (DNA and RNA). P is the main factor in photosynthesis, respiration, and synthesis of nucleic acids and cell membranes (Hawkesford et al., 2023). Lacking available P in the soil can reduce plant nutrient uptake and poor growth (Malhotra et al., 2018). Potassium (K) is important in balancing ions within and without plants. K deficiency can result in changes in photosynthesis and plant growth.

Moreover, K can modify physiological and biochemical processes (Praveen and Singh, 2023). Calcium (Ca) is important in plant cell development (Kumari et al., 2022). Furthermore, Ca can improve responses to stresses by adjusting plant physiology. Ca is also crucial in nutrient uptake, phytohormones and enzyme regulation, and cell membrane stabilization to reduce stresses from non-biotic factors. By activating enzymes, balancing salt and water in plant cells, and activating K during stomata opening and closure, Ca shows its importance in the growth and development of plants (Monib et al., 2023). Magnesium (Mg) has some functions in plants. Some physiological and biochemical processes are affected by Mg deficiency leading to reduced growth and yield of plants (Cakmak and Yazici, 2010). Unlike other cations, Mg is extremely mobile in the soil, thus it rarely binds with soil electrical charge. This results in a large amount of Mg in soil solution and a greater leaching possibility of Mg (Senbayram et al., 2015). This study was proposed to evaluate the changes in soil characteristics, nutrient uptake of pineapple and pineapple growth, yield, and fruit quality influenced by N, P, K, Ca, and Mg fertilization.

Results

Effects of N, P, K, Ca, and Mg fertilization on acid sulfate soils in ratoon pineapple fields

The parameters of pH_{H2O}, organic matter, CEC, pH_{KCl}, $acidity_{total}$, Al^{3+}, Mn^{2+}, total N, and total were not significantly different between treatments and ranged from 3.16 – 3.33, 2.45 – 2.92 %C, 14.1 – 15.4 meq 100 g^{-1}, 2.67 – 2.78, 19.6 – 21.2 meq 100 g^{-1}, 2.16 – 2.85 meq 100 g^{-1}, 0.443 – 0.603%, 0.260 – 0.283%, and 0.264 – 0.278%, respectively. The EC in the fully fertilized treatment was equivalent to the other treatments, with 0.370 – 0.593 mS cm^{-1}. The concentrations of K^+, Ca^{2+}, and Mg^{2+} in the treatments correspondingly omitted with K, Ca, and Mg were lower than the NPKCaMg treatment, with 0.382, 0.713, and 0.383 meq 100 g^{-1} compared with 0.473, 1.58, 0.531 meq 100 g^{-1}. The dissolved Fe and Fe_2O_3 contents in the treatment omitted with Ca (137.3 mg kg^{-1} and 1.97%, respectively) were greater than the NPKCaMg treatment (97.5 mg kg^{-1} and 1.46 %). However, the NPKMg treatment resulted in insignificantly different Fe^{2+} content compared to the NPKCaMg treatment (34.4 – 37.5 mg kg^{-1}). The concentrations of NH_4^+ and NO_3^- in the treatment omitted with N were lower than the NPKCaMg treatment, with 14.9 and 33.7 mg kg^{-1} compared with 23.7 and 42.8 mg kg^{-1}. The soluble P, Al-P, and Ca-P contents in the treatment omitted with P were lower than the NPKCaMg treatment, with 25.8, 23.7, and 18.7 mg kg^{-1} compared with 67.3, 63.7, and 39.7 mg kg^{-1}. The Fe-P content was equivalent between the NPKCaMg treatment and the treatment omitted with P and fluctuated from 228.1 to 246.4 mg kg^{-1} (Table 1).

Effects of N, P, K, Ca, and Mg fertilization on total nutrient uptakes by ratoon pineapple plants

Dry biomass

The dry biomass in crown, pulp, core, peduncle, butt, and leaf in the NPKCaMg treatment was greater than those in the treatments omitted with each of N, P, K, Ca, or Mg. In particular, the crown dry biomass in the NPKCaMg treatment (450.6 kg ha^{-1}) was greater than the treatments omitted with N, P, K, Ca, and Mg (315.7 – 388.0 kg ha^{-1}). Likewise, the same happened in dry biomass in pulp (1886.1 kg ha^{-1} compared with 740.6 – 1668.5 kg ha^{-1}), core (364.2 kg ha^{-1} compared with 225.4 – 309.5 kg ha^{-1}), peduncle (346.7 kg ha^{-1} compared with 177.4 – 313.7 kg ha^{-1}), butt (2629.8 kg ha^{-1} compared with 1256.8 – 2323.5 kg ha^{-1}) and leaf (6995.9 kg ha^{-1} compared with 4332.9 – 6577.8 kg ha^{-1}), respectively. For shell and peduncle, the treatment omitted with K and the NPKCaMg treatment had equivalent dry biomass which was greater than those in the treatments omitted with N, P, Ca, and Mg, with 1265.2 – 1347.1 kg ha^{-1} and 788.4 – 752.3 kg ha^{-1} compared with 441.4 – 1092.5 kg ha^{-1} (Table 2).

Contents of N, P, K, Ca, and Mg nutrients

Nitrogen: In the treatment omitted with N, crown, pulp, core, shell, sucker, peduncle, and butt had lower N content than the NPKCaMg treatment, with 0.071 – 2.17% compared with 1.07 – 2.69%. On the other hand, the N content in the leaf was not significantly different between the treatment omitted with N and the NPKCaMg treatment, with 1.58 and 1.73%, respectively (Table S1).

Phosphorus: The P contents in the core and peduncle in the treatment omitted with P were insignificantly different from the NPKCaMg treatment, with 0.075 and 0.070% compared to 0.072 and 0.076%, respectively. The other plant parts in the treatment omitted with P all had lower P content than the NPKCaMg treatment, with 0.178% compared with 0.220% (Table S2).

Potassium: In plant parts, including crown, pulp, peduncle, butt, and leaf, the treatments fertilized with K had greater K content than the treatment omitted with K, with 0.292 – 3.21% compared with 0.159 – 0.360%, respectively. Simultaneously, the treatment omitted with K had lower K content than the NPKCaMg treatment in shell and sucker, with K contents of 0.286 and 0.360% compared with 0.551 and 0.515%. Furthermore, the K content in the NPKCaMg treatment (0.282%) and the one omitted with K (0.288%) was insignificantly different (Table S3).

Calcium: Likewise, the treatment omitted with Ca had lower Ca content than the treatments fertilized with Ca in the crown, core, shell, and butt, with 0.027 – 0.032% compared with 0.036 – 0.300%. In other plant parts, the treatment omitted with Ca had lower Ca content than the NPKCaMg treatment, with 0.104 – 0.229% compared with 0.047–0.314% (Table S4).

Magnesium: In core and shell, Mg content between treatments varied insignificantly between treatments and fluctuated from 0.031 to 0.045%. The treatment omitted with Mg had lower Mg content in pulp, butt, and leaf than the treatments fertilized with Mg, with 0.047 – 0.057% compared with 0.058 – 0.419%, respectively. Moreover, the Mg content in the other plant parts in the treatment omitted with Mg was lower than the NPKCaMg treatment, with 0.032 – 0.895% compared with 0.035 – 1.16% (Table S5).

The total uptake of N, P, K, Ca, and Mg

The total uptake of N, P, K, Ca, and Mg in the corresponding omission plots was lower than the

Table 1. Effects of site-specific nutrient management on acid sulfate soil in ratoon pineapple fields.

Treatment	pH_{H2O}	EC	Organic matter	CEC	Na^{+}	K^{+}	Ca^{2+}	Mg^{2+}	pH_{KCl}	Total acid	Al^{3+}
		mS cm^{-1}	%C	meq 100 g^{-1}						meq 100 g^{-1}	
NF	3.24	0.370^{c}	2.45	14.1	0.471^{d}	0.283^{f}	0.447^{f}	0.207^{f}	2.72	21.1	2.21
NPKCaMg	3.27	0.457^{abc}	2.71	14.1	0.543^{cd}	0.474^{abc}	1.58^{b}	0.531^{bc}	2.78	19.8	2.41
PKCaMg	3.33	0.368^{c}	2.78	14.5	0.467^{d}	0.449^{bcd}	1.25^{c}	0.527^{bc}	2.78	20.2	2.38
NKCaMg	3.26	0.568^{a}	2.92	15.4	0.567^{c}	0.516^{ab}	1.12^{d}	0.536^{b}	2.74	21.2	2.22
NPCaMg	3.25	0.513^{abc}	2.45	14.4	0.603^{c}	0.382^{de}	1.75^{a}	0.671^{a}	2.77	20.0	2.16
NPKMg	3.17	0.553^{ab}	2.82	14.3	0.888^{a}	0.409^{cd}	0.713^{e}	0.445^{cd}	2.67	20.5	2.27
NPKCa	3.27	0.593^{a}	2.45	14.8	0.749^{b}	0.526^{a}	1.73^{a}	0.383^{d}	2.76	19.6	2.30
LFF	3.16	0.395^{bc}	2.73	14.4	0.548^{cd}	0.331^{ef}	0.559^{f}	0.293^{e}	2.67	20.8	2.85
Significance level	ns	*	ns	ns	*	*	*	*	ns	ns	ns
CV (%)	3.06	21.7	16.2	6.46	9.31	11.1	7.18	12.6	2.76	4.85	19.9

Treatment	$Fe_{dissolved}$ mg kg^{-1}	Fe_2O_3 %	Fe^{2+} mg kg^{-1}	Mn^{2+} %	N_{total} %N	NH_4^{+} mg kg^{-1}	NO_3^{-}	P_{total} %P	$P_{soluble}$ mg kg^{-1}	Al-P	Fe-P	Ca-P
NF	116.0^{bc}	1.56^{bc}	19.7^{c}	0.542	0.260	18.5^{cd}	37.3^{bc}	0.066	31.9^{c}	17.0^{d}	188.0^{c}	18.2^{d}
NPKCaMg	97.5^{de}	1.46^{c}	34.4^{b}	0.540	0.278	23.7^{ab}	42.8^{a}	0.070	67.3^{ab}	63.7^{a}	246.4^{bc}	39.7^{a}
PKCaMg	80.1^{f}	1.69^{abc}	23.9^{c}	0.566	0.274	14.9^{d}	37.7^{bc}	0.078	74.8^{a}	62.5^{ab}	392.8^{a}	29.5^{b}
NKCaMg	126.9^{ab}	1.71^{abc}	58.1^{a}	0.462	0.276	27.1^{a}	32.3^{d}	0.069	25.8^{c}	23.7^{d}	228.1^{bc}	18.7^{d}
NPCaMg	106.9^{cd}	1.90^{ab}	35.1^{b}	0.493	0.283	22.6^{abc}	39.1^{abc}	0.073	61.0^{b}	43.8^{c}	292.1^{b}	23.9^{c}
NPKMg	137.3^{a}	1.97^{a}	37.5^{b}	0.517	0.276	26.2^{a}	40.9^{ab}	0.078	68.6^{ab}	44.3^{c}	384.6^{a}	39.7^{a}
NPKCa	90.2^{ef}	1.51^{bc}	27.4^{bc}	0.603	0.264	26.0^{a}	37.1^{bc}	0.077	78.1^{a}	55.0^{b}	406.8^{a}	39.0^{a}
LFF	102.2^{d}	1.54^{bc}	36.8^{b}	0.443	0.277	20.2^{bc}	36.1^{cd}	0.064	59.9^{b}	9.08^{e}	183.6^{c}	22.2^{cd}
Significance level	*	*	*	ns	ns	*	*	ns	*	*	*	*
CV (%)	7.19	15.0	18.3	25.0	ns	*	*	ns	*	*	*	*

*Note: In the same column, numbers with the same superscripted letters are insignificantly different according to Duncan test. *: different at significance level of 5% (p<0.05). NF: no fertilizer; NPKCaMg: fully-fertilized; PKCaMg: N-omitted; NKCaMg: P-omitted; NPCaMg: K-omitted; NPKMg: Ca-omitted; NPKCa: Mg-omitted; LFF: local farmers' fertilization.*

Table 2. Effects of N, P, K, Ca, and Mg according to the site-specific nutrient management on dry biomass in ratoon pineapple plants.

Treatment	Dry biomass (kg ha^{-1})							
	Crown	Pulp	Core	Shell	Sucker	Peduncle	Butt	Leaf
NF	218.1^{d}	611.5^{g}	211.5^{c}	601.2^{e}	387.6^{f}	123.6^{f}	700.9^{f}	3620.5^{e}
NPKCaMg	450.6^{a}	1886.1^{a}	364.2^{a}	1347.1^{a}	788.4^{a}	346.7^{a}	2629.8^{a}	6995.9^{a}
PKCaMg	315.7^{c}	740.6^{f}	225.4^{c}	825.2^{d}	441.4^{e}	177.4^{e}	1256.8^{e}	4332.9^{d}
NKCaMg	341.2^{c}	1386.4^{cd}	320.8^{b}	1080.5^{b}	552.7^{c}	303.3^{bc}	1907.8^{c}	6577.8^{b}
NPCaMg	349.8^{bc}	1668.5^{b}	292.5^{b}	1265.2^{a}	752.3^{a}	313.7^{b}	1534.1^{d}	6456.4^{b}
NPKMg	388.0^{b}	1322.4^{d}	309.5^{b}	1092.5^{b}	518.3^{cd}	260.1^{d}	2238.9^{b}	6480.7^{b}
NPKCa	334.8^{c}	1130.3^{e}	304.1^{b}	963.7^{c}	638.2^{b}	273.0^{d}	2323.5^{b}	5511.8^{c}
LFF	327.2^{c}	1467.3^{c}	301.3^{b}	1024.5^{bc}	499.6^{d}	283.0^{cd}	2590.5^{a}	6525.0^{b}
Significance level	*	*	*	*	*	*	*	*
CV (%)	2.52	5.32	7.93	5.84	4.40	6.14	3.70	2.41

*Note: In the same column, numbers with the same superscripted letters are insignificantly different according to Duncan test. *: different at significance level of 5% ($p<0.05$). NF: no fertilizer; NPKCaMg: fully-fertilized; PKCaMg: N-omitted; NKCaMg: P-omitted; NPCaMg: K-omitted; NPKMg: Ca-omitted; NPKCa: Mg-omitted; LFF: local farmers' fertilization.*

Table 3. Effects of N, P, K, Ca, and Mg according to the site-specific nutrient management on total nutrient uptake in ratoon pineapple plants.

Treatment	Total uptake (kg/ha)				
	N	P	K	Ca	Mg
NF	83.2^{e}	10.2^{f}	56.8^{f}	6.27^{f}	7.18^{e}
NPKCaMg	244.5^{a}	32.8^{a}	306.5^{a}	23.7^{a}	25.9^{a}
PKCaMg	114.3^{d}	17.5^{e}	165.5^{d}	12.2^{e}	12.9^{d}
NKCaMg	191.8^{b}	21.1^{d}	178.6^{cd}	14.0^{d}	17.7^{c}
NPCaMg	199.5^{b}	27.4^{b}	106.9^{e}	19.1^{b}	19.5^{b}
NPKMg	197.4^{b}	27.4^{b}	241.3^{b}	12.1^{e}	20.8^{b}
NPKCa	169.4^{c}	23.6^{c}	231.5^{b}	18.3^{b}	13.5^{d}
LFF	202.8^{c}	23.3^{c}	202.1^{c}	16.6^{c}	16.4^{c}
Significance level	*	*	*	*	*
CV (%)	4.50	5.83	10.2	5.60	7.09

*Note: In the same column, numbers with the same superscripted letters are insignificantly different according to Duncan test. *: different at significance level of 5% ($p<0.05$). NF: no fertilizer; NPKCaMg: fully-fertilized; PKCaMg: N-omitted; NKCaMg: P-omitted; NPCaMg: K-omitted; NPKMg: Ca-omitted; NPKCa: Mg-omitted; LFF: local farmers' fertilization.*

NPKCaMg treatment, with 114.3 compared with 244.5 kg N ha^{-1}, 21.2 compared with 32.8 kg P ha^{-1}, 106.9 compared with 306.5 kg K ha^{-1}, 12.1 compared with 23.7 kg Ca ha^{-1}, and 13.5 compared with 25.9 kg Mg ha^{-1} (Table 3).

Effects of N, P, K, Ca, and Mg fertilization on the yield of ratoon pineapple

All the treatments omitted with N, P, Ca, and Mg resulted in reduced yield compared with the NPKCaMg treatment. However, the treatment omitted with K (37.9 t ha^{-1}) had equivalent yield to the NPKCaMg treatment (39.7 t ha^{-1}). The yield of the other treatments omitted with P, Ca, and Mg was equivalent to the LFF. Furthermore, the treatment omitted with N had a lower yield than the LFF treatment with 28.4 t ha^{-1} compared with 31.5 t ha^{-1} (Table 4).

Calibration of N, P, K, Ca, and Mg fertilizer formula for ratoon pineapple

The AEs of N, P, K, Ca, and Mg fertilizers were 26.1, 26.5, 4.90, 7.36, and 14.5 $kg_{pineapple}$ $kg_{fertilizer}^{-1}$. The calibrated fertilizer formula was 462 N, 341 P_2O_5, 510 K_2O, 1207 CaO, and 618 MgO kg ha^{-1} (Table 5).

Discussion

Soil characteristics

Soil pH among treatments varied from 3.16 to 3.33 (Table 1). Soil acidity is one of the most important chemical characteristics because it involves nutrient availability. All pineapple varieties can live under pH from 4.5 to 5.5 and adjusting pH to an appropriate value is necessary to ensure optimum nutrient supply for plants (Vásquez-Jiménez & Bartholomew, 2018). EC among the treatments ranged from 0.369 – 0.593 mS cm^{-1}. According to Horneck et al. (2011), EC below 1 mS cm^{-1} does not affect plants and is suitable for farming. However, the organic matter was 2.45 – 2.92% C (Metson, 1961) and CEC is low (14.1 – 15.4 meq 100 g^{-1}) (Landon, 2014) (Table 1).
The total N content in the soil of 0.2 – 0.5% is considered moderate according to Metson (1961). The treatments had a total N content of 0.260 – 0.283%. Thus, the N nutrient in the soil used in the current experiment was considered moderate. NH_4^+ and NO_3^- concentrations in the treatment omitted with N were lower than the NPKCaMg treatment, with 14.9 and 37.7 mg kg^{-1} compared with 23.7 and 42.8 mg kg^{-1}. According to Dayo-Olagbende et al. (2019), N fertilizers promote soil characteristics such as N content, organic matter,

Table 4. Effects of N, P, K, Ca, and Mg according to the site-specific nutrient management on yield of ratoon pineapple plants.

Treatment	Yield t/ha
NF	26.1^{d}
NPKCaMg	39.7^{a}
PKCaMg	28.4^{c}
NKCaMg	31.4^{b}
NPCaMg	37.9^{a}
NPKMg	31.5^{b}
NPKCa	31.5^{b}
LFF	31.5^{b}
Significance level	*
CV (%)	4.29

*Note: In the same column, numbers with the same superscripted letters are insignificantly different according to Duncan test. *: different at significance level of 5% (p<0.05). NF: no fertilizer; NPKCaMg: fully-fertilized; PKCaMg: N-omitted; NKCaMg: P-omitted; NPCaMg: K-omitted; NPKMg: Ca-omitted; NPKCa: Mg-omitted; LFF: local farmers' fertilization.*

exchangeable cations, and CEC. Soluble P, Al-P, and Ca-P contents in the treatment omitted with P were lower than the fertilized treatments, with 25.8, 23.7, and 18.7 mg kg^{-1} compared with 61.0 – 78.1, 43.8 – 63.7, and 23.9 – 39.7 mg kg^{-1}, respectively (Table 1). The supply of P from soil to plants is limited because Al, Ca, and Fe fix P. Therefore, the P taken by plants is low, roughly 30% (Nierves & Salas, 2015; Gupta et al., 2020).
The Ca and Mg contents in the treatments omitted with Ca and Mg were lower than the NPKCaMg treatment (Table 1). Ca plays a role in neutralizing pH in pineapple fields, though the current pH value was equivalent among treatments. However, a balanced Ca: Mg ratio improves soil characteristics and crop yield (Deru et al., 2023).

Total nutrient uptake

The treatment omitted with N had lower total N uptake than the other treatments fertilized with N, with 114.3 compared with 169.4 – 199.5 kg ha^{-1}, respectively (Table 3). As reported by Omotoso & Akinrinde (2013), pineapple plants fertilized with 200 kg ha^{-1} have increased growth, though fertilizing not over 150 kg ha^{-1} ensures yield and fruit quality.
The treatment omitted with P had lower P uptake (21.1 kg ha^{-1}) than the NPKCaMg treatment (32,8 kg ha^{-1}) (Table 3). In acid sulfate soil, the concentrations of Al and Fe ions are high. This not only damages the pineapple but also immobilizes soil P, leading to an interruption of P supply from the soil and P uptake by the pineapple (Handayani et al., 2022). Besides, pineapple plants only take 40% of P in peat soils. The rest is lost due to leaching. The amount of P uptake is distributed according to the following order: crown > leaf > stem > fruit> peduncle > root (Ahmed et al., 2007).
K uptake in the treatments fertilized with K was greater than the treatment omitted with K, with 165.5 – 306.5 kg ha^{-1} compared with 106.9 kg ha^{-1} (Table 3). The distribution of K in pineapple plants is ranked as follows: fruit > leaf > stem > peduncle > crown > root. The amount of K taken by pineapple plants was 36%, while most of the K loss is caused by leaching (Ahmed et al., 2006).
The Ca and Mg uptake in the NPKCaMg treatment was greater than the corresponding omission treatments, with 23.7 and 25.9 compared with 12.1 and 13.5 kg ha^{-1}, respectively (Table 3). In 100 g of pineapple fruit, there are 13 mg Ca of and 12 – 20 mg of Mg (de Ancos et al., 2017). For Ca, its need is low, with roughly 100 mg Ca kg^{-1} for optimum pineapple growth. Furthermore, a previous study indicates that the Mg and Ca uptake is equivalent among pineapple cultivars via nutrient supply from soils (Maia et al., 2020).

Pineapple growth and yield

The PKCaMg treatment decreased the yield compared with the fully NPKCaMg fertilization, with 28.4 t ha^{-1} compared with 39.7 t ha^{-1} (Table 4). N is one of the crucial factors deciding the growth and fruit weight and quality of pineapple (Bhugaloo et al., 1988). This is in accordance with the study by Spironello et al. (2004) where fertilizing N increased pineapple yield and fruit size by 3 – 50%. According to Cunha et al. (2021), after 9 months of N deficiency, pineapple had their height, fresh weight, leaf thickness, and peduncle length decreased by 12, 25, 15, and 22%, respectively.
The yield in the treatment omitted with P decreased by 20.9% compared with the NPKCaMg treatment (Table 4). P heavily affects the yield of Jupi pineapple because P deficiency had 26.8% and 33.7% reductions in fruit weight and length (Maia et al., 2022). Lacking P leads to peduncle diameter being reduced by 33%, and leaf thickness, length, and fresh weight being reduced by 33%, 18, and 30%, respectively (Cunha et al., 2021). Huu et al. (2023) noted that yield increased by 12.1% when pineapple takes 42.9% of soil P.
The treatment omitted with K had an equivalent yield to the NPKCaMg treatment, with yields of 37.9 and 39.7 t ha^{-1} (Table 4). Cunha et al. (2021) claimed that K deficiency resulted in reduced leaf length by 12%, leaf thickness by 18%, and peduncle diameter by 13%. On the other hand, Moreover, in the study by Spironello et al. (2004), fertilizing K increased yield and fruit size though its effect is not as significant as the N fertilizer. Thus, the unchanged yield in the treatment omitted with K was reasonable. Moreover, in peat soil, fertilizing K at the rate of 266 – 532 kg ha^{-1} results in superior fruit weight but if this rate is exceeded, the fruit weight, growth, and yield components go down (Razzaque & Hanafi, 2001).
Overall, N, P, and K all affected the growth and yield of pineapple. In the study by Ramos & Pinho (2014), N, P, and K deficiencies reduce fruit weight with or without crown compared with the full fertilization, with 0.532–1.231 kg fruit^{-1} compared with 1.452 – 1.594 kg fruit^{-1}.
Two treatments omitted with Ca and Mg resulted in a yield of 31.7 t ha^{-1} which was 20.1% lower than the NPKCaMg treatment. Ca complexifies with phospholipid phosphate groups so Ca can reduce K content due to nutrient imbalance (Pathak et al., 2020). For pineapple, Ca can aid physiological disorders such as fruit browning (Hearth *et al.*, 2000; Uthairatanakij et al., 2013). According to Razzaque & Hanafi (2000), fruit weight is

Table 5. Adjustment of N, P, K, Ca, and Mg fertilizer formula for ratoon pineapple in acid sulfate soil in Long My District, Hau Giang Province.

Element	GY t/ha	$GY_{(0N,\ 0P,\ 0K,\ 0Ca,\ 0Mg)}$ t/ha	AE kg/ha	F kg/ha
N		28.4	26.1	462
P		31.4	26.5	341
K	40.4	37.9	4.90	510
Ca		31.5	7.36	1207
Mg		31.5	14.5	618

Note: GY: the yield in the NPKCaMg plot; GY_{0N}: the yield in the N omission plot; GY_{0P}: the yield in the P omission plot; GY_{0K}: the yield in the K omission plot; GY_{0Cs}: the yield in the Ca omission plot; GY_{0Mg}: the yield in the Mg omission plot.; F: the amount of fertilizer input; AE; Agronomic efficiency.

proportional to Ca fertilization. However, when it is over 32 kg ha^{-1} CaO, fruit weight decreases. Furthermore, Mg is a component of chlorophyll, so Mg deficiency causes reduced chlorophyll content, leading to lowered photosynthesis and growth. Mg is a mobile element, so the symptoms of deficiency happen in old leaves, especially leaves or plant parts under sunshine (Sanewski et al., 2018). Mg-deficient plants had reduced chlorophyll content and photosynthesis. This phenomenon appears as the presence of old leaves with light yellow margins and dark green young leaves in the upper parts of pineapple plants (Vásquez-Jiménez & Bartholomew, 2018).

Fertilizer rate modification

The NPKCaMg fertilizer formula was modified as 462 N, 341 P_2O_5, 510 K_2O, 1207 CaO, and 618 MgO kg ha^{-1} (Table 5). Moreover, Rios et al. (2018) recommended a fertilizer formula of 285 kg N ha^{-1} and 410.4 kg K_2O ha^{-1} for the development of the Imperial pineapple. According to Djido et al. (2021), fertilizing K_2O: N at the ratio of 1 shows increased pineapple yield from 54.9 – 69.1 to 90.1 t ha^{-1}. This is consistent with the current fertilizer formula with a K_2O: N ratio of 1.1. The NPK fertilizer formula for the “Tainong 11” pineapple is recommended as 317 – 422 kg N, 66 – 92 kg P_2O_5, and 271 – 396 kg K_2O ha^{-1}, with yield from 30 to 50 t ha^{-1} (Zhang et al., 2021). However, a fertilizer formula should be recommended differently according to the regions, irrigation, soils, and climates (Ramos et al., 2020). Thus, the current fertilizer formula, the fertilizer formula calibrated in the current study was suitable for pineapple farming in acid sulfate regions in Hau Giang Province.

Materials and methods

Plant materials

The local Queen pineapple supplied from the local market. The mother plants were grown from suckers in the previous season as the plant pineapple in the study by Khuong et al. (2024), where the pineapples were grown in the nursery house for 3 months before moving to grown in the new field. After the first plant season (18 months), the suckers were kept and grown as the first ratoon season. The first ratoon pineapple was used in this experiment. The ratoon pineapple was grown from May 2021 to February 2022 on acid sulfate soils in pineapple fields, with planting spacing of 0.40 x 0.55 m, in Tan Tien Town, Vi Thanh City, Hau Giang Province, Vietnam.

The chemical fertilizer consisted of Urea (46% N), DAP (18% N, 46% P_2O_5), potassium chloride (60% K_2O), lime (60% CaO), and magnesium (92% MgO).

Experiment design

The experiment followed a completely randomized block design consisting of 8 treatments and 4 replications each of which was a soil square of 25 m^2. The treatments were (i) NF: no fertilizer, (ii) NPKCaMg: using all N, P, K, Ca, and Mg fertilizers, (iii) PKCaMg: omitting N fertilizer, using P, K, Ca, and Mg fertilizers, (iv) NKCaMg: omitting P fertilizer, using N, K, Ca, and Mg fertilizers, (v) NPCaMg: omitting K fertilizer, using N, P, Ca, and Mg fertilizers, (vi) NPKMg: omitting Ca fertilizer, using N, P, K, and Mg fertilizers, (vii) NPKCa: omitting Mg fertilizer, using N, P, K, and Ca fertilizers, (viii) LFF: local farmer fertilization.

Fertilizer formula

The recommended fertilizer formula by the Site-Specific Nutrient Management (SSNM) method was 434 N - 314 P_2O_5 - 362 K_2O, 1108 CaO, and 568 MgO (kg ha^{-1}) (Khuong et al., 2024). The local farmer fertilizer formula was 720 N - 540 P_2O_5. The fertilizer rates are summarized in the Supplementary Table S6.

Parameter analysis

Soil sample: In each treatment, the soil was collected at 0–20 cm depth. The collected soil was dried and ground via a 2 mm and 0.5 mm sieve to analyze chemical properties. Soil parameters, including pH_{H2O}, electrical conductivity (EC), organic matter, cation exchange capacity (CEC), and cations (K^+, Na^+, Ca^{2+}, Mg^{2+}), soil fertility (N_{total}, NH_4^+, NO_3^-, P_{total}, $P_{soluble}$, Al-P, Fe-P, Ca-P), and soil quality (pH_{KCl}, $acidicty_{total}$, Fe_{total}, $Fe_{dissolved}$, Fe_2O_3, Fe^{2+}, and Mn_{total}) were analyzed according to Sparks et al. (1996)

Plant sampling: Twenty random plants were collected in each plot at harvesting. Then, pineapple plants were dismantled into parts including crown, pulp, shell, sucker, peduncle, butt, and leaf. The contents of N, P, K, Ca, and Mg in pineapple were determined according to Houba et al. (1988). The nutrient uptake by pineapple parts (kg ha^{-1}) was defined as follows: (nutrient content/100) x dry biomass (kg ha^{-1}). The total N, P, K, Ca, and Mg uptake (kg ha^{-1}) by ratoon pineapple was determined as the sum of those by crown, pulp, shell, sucker, peduncle, butt, and leaf.

The fertilizer formula followed by Pasuquin et al. (2014): $FX\ (kg\ ha^{-1}) = (GY - GY_{0X})/AEX$

Where, X is the nutrient such as N, P, K, Ca, and Mg; FX is the amount of nutrient to reach the target yield; GY_{0X} is the yield in an omission plot; GY is the target yield (kg ha-

[1]); AEX is the agronomic efficiency in an omission plot (kg of pineapple per kg of fertilizer).

The AE followed Majumdar et al. (2013):

$AE = (Y - Y_0)/F$

Where, AE is the agronomic efficiency, a rise of yield according to a unit of fertilizer; Y is the yield of the fully fertilized plot; Y_0 is the yield of the omission plot; F is the used amount of fertilizer.

Statistical analysis

The Microsoft Excel 2016 was used to calculate data. The SPSS software 13.0 was used to analyze variance and compare differences between treatments.

Conclusions

The The PKCaMg treatment led to reduced available NH_4^+ and the NKCaMg treatment resulted in reduced soluble P content compared with the fertilized treatments. The insoluble P, such as Al-P and Ca-P, in the treatment omitted with P, was lower than the NPKCaMg treatment. Likewise, the NPKMg and NPKCa treatments caused reductions in Ca^{2+} and Mg^{2+} concentrations in the soil, respectively. Treatments without N, P, K, Ca, or Mg reduced the dry biomass of crown, pulp, core, peduncle, butt, and leaf. Treatments without N, P, K, Ca, or Mg reduced corresponding nutrient uptake in pineapple plants. Pineapple yield was reduced by 28.5, 20.9, 20.1, and 20.1% when N, P, Ca, and Mg nutrients were omitted, respectively. The recommended N, P, K, Ca, and Mg fertilizer formula was calibrated to 462 N, 341 P_2O_5, 510 K_2O, 1207 CaO, and 618 MgO kg ha^{-1}.

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