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Research article

Yield gap reduction of pineapple (*Ananas comosus* L.) by site-specific nutrient management

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A B S T R A C T

Acid-sulfate soils and overuse of chemical fertilizers have been obstacles to sustainable agriculture. The variation of fertilization due to poor soil fertility has remarkably affected the yield gap and the quality of the environment, so an optimal fertilizing rate should be formulated. Therefore, this study aimed at (i) detecting obstacles in soil characteristics reducing pineapple yield between farms and (ii) assessing the effects of NPKCaMg fertilizers on soil fertility, uptakes, and pineapple yield. The on-farm experiment was carried out according to site-specific nutrient management (SSNM) arranging in acid-sulfate soil for pineapple, including (i) no fertilizers used; (ii) NPKCaMg: fully fertilizing with nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg); (ii) PKCaMg: fertilizing without N; (iii) NKCaMg: fertilizing without P; (iv) NPCaMg: fertilizing without K; (v) NPKMg: fertilizing without Ca; (vi) NPKCa: fertilizing without Mg; and (vii) FFP: farmers' fertilizing practice. The result of the principal component analysis revealed that the soil had low availability of N, P, and K nutrients. Available P concentration was negatively correlated with concentrations of Al^{3+}, Fe^{2+}, and total Mn, whose correlation coefficients were −0.34 to −0.59, −0.52 to −0.74, and −0.63 to −0.70, respectively. Fertilizing NPKCaMg obtained the highest result in the uptakes of N, P, K, Ca, and Mg, which were 289.1–327.4, 25.4–29.3, 137.4–166.0, 41.9–48.9, and 39.8–43.1 kg ha^{-1}, respectively. Fertilizing by SSNM has increased pineapple yield by 22.9 %–44.9 % compared to the FFP. This fertilizer formula should be transferred to the local farmers in order not only to enhance productivity, but also to limit the damage of chemical fertilizers on the environment. Moreover, this formula should be tested globally in other places that share similar soil characteristics.

1. Introduction

Pineapple fruit is rich in minerals such as calcium (Ca), phosphorous (P), iron (Fe), copper (Cu), and potassium (K) and many essential vitamins such as A, B1, B2, and C [1]. In its juice, there is bromelain which can hydrolyze protein, stimulating good digestion in the intestine [2]. Areas of pineapple cultivation in Asia up to 2020 have been 437,571 ha, while those in Vietnam reached 38,554 ha [3] and mainly located in the Mekong Delta, e.g., Hau Giang [4]. On the other hand, pineapple farmers have encountered risks due to low soil fertility and high concentrations of Al^{3+} and Fe^{2+} toxicities in acid-sulfate soil (ASS), inhibiting plant growth [5]. Low soil nutrients and high toxins such as Al^{3+} and Fe^{2+} are common issues in acid-sulfate soil in Vietnam [6]. This type of soil is usually found in coastal wetlands and agricultural land and contains large amounts of organic matter which can emit greenhouse gases [7]. Acid-sulfate soil can be seen globally, especially in low-lying areas [7], which are similar to the geographical characteristics of the Mekong Delta, in Vietnam. Therefore, the majority of the area here is ASS [8]. Meanwhile, pineapple is one of the most popular crops that are grown in ASS in Vietnam [9], because of its fairly adaptability to the conditions of ASS [8]. However, ASS can cause damage to

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agriculture when oxidized [10]. The oxidation of ASS can decrease soil pH below 4.0 [11], which is undesirable for the growth of crops. In the other word, low pH decreases the nutrient availability [12]. Some other approaches have been made to fix this, such as using biocompost and biochar [13], adjusting plant density [14,15], using organic fertilizer [16], and using plant growth substances [15]. However, the common point of these studies is that the role of chemical fertilizers is still undeniable, i.e., chemical fertilizers were still used to maintain the yield of pineapple, while these approaches can be considered as amendments. In the meantime, the use of sewage sludge and wastewater to replace chemical fertilizer on pineapple may contain contaminants and some biological risks [17]. In addition, Mahmud et al. [18] claimed that the use of both vermicompost (an organic fertilizer) and the chemical fertilizer should be together for the maximum pineapple performance. Moreover, using chemical fertilizers is a well-known approach to provide nutrients for the pineapple to reach its high yield [19], but plant demands cannot be met by fertilizers since they can leak or run off [20]. However, fertilization over the recommended dose leads to nutrition imbalance, negatively affecting the environment and exhausting greenhouse gases [19]. Furthermore, the cultivation and fertilization techniques of farmers are mainly based on their own experience, which is one of the causes of the high yield gap between farms. Therefore, site-specific nutrient management (SSNM) has been known as a solution for this issue. Hence, applying SSNM boosts the efficiencies of fertilizers, cuts down environmental pollution, enlarges profits, and lessens yield gaps between farms in the same region [21]. The SSNM approach has been widely used in several types of fruits, like mandarin, and has been applied in divergent countries worldwide [22]. The SSNM has also been applied to rice, maize, and cassava production systems [23]. In ASS, recently, the SSNM has been only applied to rice [24], it has not been utilized to reduce yield gaps between pineapple farms in ASS until now. Furthermore, the factors underlying the yield differences have not been identified neither [25]. Moreover, because the cost of fertilizers is relatively high in Vietnam, a minimum use of chemical fertilizers for the maximum yield of pineapples is required. Therefore, this study was carried out in order to (i) find out soil characteristics restricting pineapple yield between pineapple farms and (ii) evaluate the influences of chemical fertilization on soil properties, nutrient uptakes, and pineapple yield.

2. Materials and methods

2.1. Materials

Place and time: The experiment was arranged in Tan Tien commune, Vi Thanh city, and Vinh Vien commune, Long My district, Hau Giang province, Vietnam, from November 2020 to June 2022. The climatic conditions in the field were recorded as mean temperature (34 °C), moisture (54 %), and rainfall (1800 mm/year).

Pineapple cultivar: The Queen cultivar (*Ananas comosus* [Linn.] Merr.) was propagated from the lateral shoots.

Fertilizers: They comprised urea, which had 46 % nitrogen; superphosphate, which encompassed 16 % P_2O_5 and 20 % CaO; potassium chloride, which harbored 60 % K2O; and lime powder, which embodied 50 % CaO; and MgO fertilizer, which encompassed 90

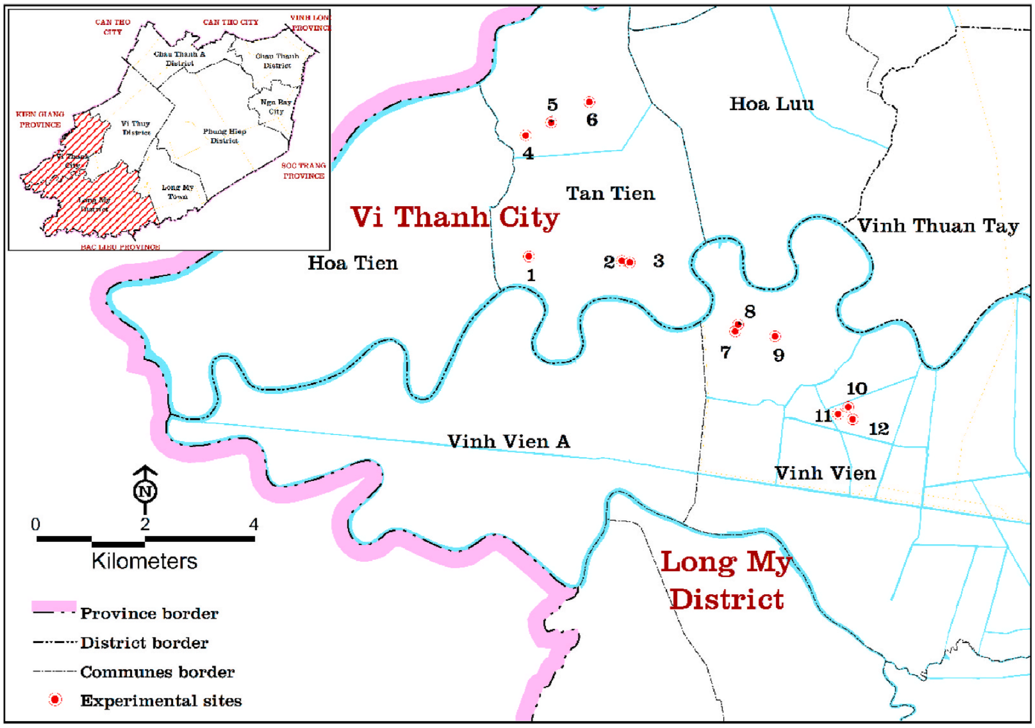

Fig. 1. Locations of the 12 experimental farms in Vi Thanh city and Long My district.

% MgO. However, the diammonium phosphate (DAP) fertilizer, with 18 % N and 46 % P_2O_5, was exclusively employed in the treatment lacking the Ca nutrient but required the P nutrient.

2.2. Methods

Experimental design: The experiment was conducted following a completely randomized block design on 12 farms (Fig. 1). The treatments in each farm were as follows: (i) no fertilizer; (ii) NPKCaMg: fully fertilizing with nitrogen (N), P, K, Ca, and magnesium (Mg) fertilizers; (ii) PKCaMg: fertilizing without N fertilizer; (iii) NKCaMg: fertilizing without P fertilizer; (iv) NPCaMg: fertilizing without K fertilizer; (v) NPKMg: fertilizing without Ca fertilizer; (vi) NPKCa: fertilizing without Mg fertilizer; and (vii) farmer's fertilization practice FFP. Four replications were applied to each treatment. Each experimental plot was 25 m^2 (5 × 5 m) area. The pineapple cultivation was performed according to the study by Be and Hoa [26] in 6 months. The Mekong Delta has a 6:4 bed-to-ditch ratio for pineapple growing. When being a seedling, the plant should be irrigated 2–3 times a week. Once the plant has developed, the irrigation should be once a week.

Pineapple fertilizer formula: The formula following SSNM was 290 N-261 P_2O_5-232 K_2O-1160 CaO-580 MgO kg ha^{-1} (our preliminary work), and the one following FFP was 834 N–474 P_2O_5 – 105 K_2O kg ha^{-1}. The fertilization followed the study by Be and Hoa [26] with modifications. It was divided into 5 times of fertilization separating each month. In the first time, 12.3 %N, 29.2 % P, 12.3 % K, 50 % Ca, and 50 % Mg were applied. In the second time, 17.7 % N, 17.7 % P, 17.7 % K, 50 % Ca, and 50 % Mg were managed. In the third time, 30 % N, 17.7 % P, and 20 % K were handled. In the fourth time, the application rate was 20 % N, 17.7 % P, and 20 % K. Finally, the final fertilization was 20 % N, 17.7 % P, and 30 % K. This regime was executed in every fertilizer formula.

Soil chemical characteristics at the beginning and the end of the crop: Soil samples were collected at a depth of 0–20 cm both before planting and after harvesting. The soil was left to dry naturally before being milled via a 0.5 and 2.0 mm sieve. All the properties were analyzed according to the method of Sparks et al. [27]. The soils pH_{H2O} and EC were measured at a soil-to-distilled water ratio (1: 2.5) by a pH meter. The soil pH_{KCl} was estimated at a soil-to-1.0 M KCl ratio (1: 2.5) by a pH meter. The total N content was measured by the Kjeldahl digestion method. The soil NH_4^+ concentration was extracted by 2.0 M KCl, indicated in color by a mixture of sodium nitroprusside, sodium salicylate, sodium citrate, sodium tartrate, sodium hydroxide, and sodium hypochlorite and detected at 650 nm in wavelength. The NO_3^- concentration was obtained by 2.0 M KCl, shown by a mixture of 0.5 M HCl, vanadium (III) chloride, sulfanilamide, and N-(1-naphthyl) ethylenediamine dihydrochloride and detected at the 540 nm in wavelength. The total P content was derived from the perchloric acid and nitric acid mixture and calculated by the ascorbic acid method in a spectrophotometer at a wavelength of 880 nm. The Bray II method was adopted to determine the available P. Fractions of inorganic P were extricated by 0.5 M NH_4F, 0.1 M NaOH, and 0.25 M H_2SO_4 for Al–P, Fe–P, and Ca–P compounds at 880 nm in wavelength. Total acidity was obtained with 1.0 M KCl and titrated with 0.01 N NaOH. To determine the exchangeable Al^{3+}, the soil was derived from 1.0 M KCl and measured by a spectrometer at 395 nm in wavelength. Fe^{2+} was extricated with H_4EDTA and $Na_2S_2O_4$ and estimated by a spectrometer at 248.3 nm in wavelength. Organic matter was determined by the method of Walkley-Black, where the soil was oxidized by saturated H_2SO_4–$K_2Cr_2O_7$ before being titrated with 0.5 N $FeSO_4$. Cation exchange capacity (CEC) was elicited with 0.025 M $BaCl_2$ and 0.02 M $MgSO_4$ and titrated with 0.01 M EDTA. K^+, Na^+, Ca^{2+}, and Mg^{2+} concentrations in the CEC extract were measured by an atomic absorption spectrometer at 766, 589, 422.7, and 285.2 nm in wavelengths, respectively.

Principal component analysis (PCA): Because the soil had too many influencing components, PCA was adopted to cut down the number of dependent variables into a smaller group of basic ones based on a correlation model, entailing the first principal component (PC1) and the second component (PC2) [28]. Thereby, the importance of each influencing soil component and its relationships with others would be revealed. The PCA was calculated by the XLSTAT software.

Pineapple growth: In total, 20 pineapple plants in a test plot were randomly selected to estimate growth parameters at harvest [29]. Plant height (cm) was measured vertically from the growth to the peak of the highest leaf. The number of leaves per plant was derived from total counting from the highest A-leaf. The D-leaf length (cm) was measured between both ends of a D-leaf, and the D-leaf width (cm) was measured at the position with the widest diameter. The stem length (cm) was measured between both ends of a pineapple, and the stem diameter (cm) was the mean derived from the diameter at the top, the middle, and the bottom of a stem. The peduncle length (cm) was measured between both ends of a peduncle, and the peduncle diameter (cm) was the mean calculated from the diameter at the top, the middle, and the bottom of a peduncle. The crown length (cm) was measured from the top of the peduncle to the peak of the crown, and the crown diameter (cm) was measured as the width of a crown.

Yield components and yield of pineapple: The yield components were determined randomly on 20 pineapple fruits in a test plot at harvest [30]. Fruit length (cm) was assessed from the head to the bottom of each fruit, fruit diameter (cm) was the average value calculated from three positions (top, middle, and bottom), and fruit weight (kg) was weighed for each fruit. Pineapple yield (t ha^{-1}) was derived from the total weight of fruits in 5 m^2 in each treatment and then converted into t ha^{-1}.

Pineapple fruit quality: The fruit quality of pineapple fruit was analyzed on 20 random fruits in a test plot at the end of the crop. For the water content (mL), the fruits were peeled and squeezed for water to be quantified. Brix (%) and pH were determined in pineapple juice using a refractometer and a pH meter, respectively. Total acidity content was elicited from samples with water at a 1: 25 ratio and titrated with NaOH (0.01 N) [31]. Vitamin C content was adjusted using the method of the Association of Official Analytical Chemists (AOAC): samples were extorted with HCl and 1 % oxalic acid and titrated with 0.001 N 2,6 dichlorophenol indophenol (DIP) [32]. Colors (L*, a*, and b*) were marked using a color reader CR-20 at three positions on a fruit (top, middle, and bottom).

Nutrient concentrations in parts of pineapple: From each treatment, five plants were randomly collected and dried at 70 °C for 72 h and then analyzed for concentrations of N, P, K, Ca, and Mg in the crown, core, shell, slip, peduncle, stem, and leaves according to the method of Houba et al. [33].

Table 1

Influences of specific-site nutrient management on chemical characteristics of acid sulfate soil for pineapple in Vi Thanh city and Long My district.

Location	Treatment	pH_{H2O}	pH_{KCl}	N_{total}	NH_4^+	NO_3^-	P_{total}	$P_{available}$	Al–P	Ca–P	Fe–P	EC
				%N	mg kg^{-1}	%P_2O_5	mg kg^{-1}					mS cm^{-1}
VT	No fertilizer	2.72	2.66	0.236	19.9^{b}	13.4^{b}	0.164	15.8^{b}	42.5^{b}	20.6^{c}	71.43^{b}	2.51
	NPKCaMg	3.00	2.81	0.288	31.7^{a}	23.5^{a}	0.184	48.9^{a}	105.3^{a}	67.7^{a}	195.5^{a}	2.96
	PKCaMg	2.78	2.72	0.238	22.6^{b}	13.5^{b}	0.189	45.7^{a}	99.0^{a}	66.4^{a}	190.9^{a}	2.80
	NKCaMg	2.75	2.67	0.271	31.1^{a}	19.2^{a}	0.165	20.8^{b}	71.8^{b}	33.3^{c}	73.02^{b}	2.76
	NPCaMg	2.87	2.70	0.285	32.6^{a}	19.0^{a}	0.187	49.4^{a}	88.9^{ab}	61.0^{ab}	177.0^{a}	2.91
	NPKMg	2.77	2.67	0.291	30.1^{a}	19.1^{a}	0.165	53.8^{a}	98.1^{a}	30.6^{c}	168.1^{a}	2.85
	NPKCa	2.91	2.77	0.280	28.9^{a}	22.1^{a}	0.180	50.7^{a}	97.0^{a}	56.5^{ab}	179.3^{a}	2.90
	FFP	2.89	2.68	0.246	30.1^{a}	20.7^{a}	0.174	49.4^{a}	98.3^{a}	51.9^{b}	167.5^{a}	2.86
LM	No fertilizer	2.95	2.86	0.254	26.9^{b}	14.3^{c}	0.159	21.9^{b}	32.8^{c}	12.2^{e}	59.3^{c}	2.30
	NPKCaMg	3.15	3.05	0.272	41.0^{a}	25.1^{a}	0.180	52.5^{a}	56.8^{a}	48.8^{a}	100.8^{b}	2.57
	PKCaMg	3.22	3.08	0.246	29.1^{b}	14.5^{c}	0.183	45.2^{a}	44.1^{b}	45.9^{ab}	115.9^{ab}	2.46
	NKCaMg	2.97	2.88	0.272	35.7^{a}	16.1^{bc}	0.169	28.4^{b}	34.2^{c}	16.7^{e}	62.4^{c}	2.39
	NPCaMg	3.02	2.90	0.284	36.2^{a}	16.5^{bc}	0.170	41.9^{a}	45.7^{b}	39.3^{b}	110.5^{b}	2.40
	NPKMg	2.89	2.84	0.250	37.0^{a}	18.8^{b}	0.177	51.8^{a}	51.1^{ab}	24.1^{d}	130.4^{a}	2.56
	NPKCa	3.04	2.97	0.267	38.5^{a}	16.0^{bc}	0.180	41.7^{a}	47.5^{ab}	44.2^{ab}	106.1^{b}	2.57
	FFP	3.16	3.01	0.249	37.0^{a}	16.1^{bc}	0.182	45.0^{a}	46.5^{ab}	31.1^{c}	103.2^{b}	2.41
VT	F	ns	ns	ns	*	*	ns	*	*	*	*	ns
	CV (%)	6.38	3.24	14.6	18.1	7.20	23.6	18.2	19.7	23.8	23.5	18.4
LM	F	ns	ns	ns	*	*	ns	*	*	*	*	ns
	CV (%)	8.25	5.16	9.85	11.7	14.8	8.15	24.7	18.8	13.7	13.9	22.3

Location	Treatment	OM	CEC	Na^+	K^+	Ca^{2+}	Mg^{2+}	$Acidity_{total}$	Al^{3+}	Fe_{total}	$Fe_{dissolved}$	Fe_2O_3	Fe^{2+}	Mn_{total}
		%C	meq 100 g^{-1}					meq 100 g^{-1}		g kg^{-1}	mg kg^{-1}	%	mg kg^{-1}	%
VT	No fertilizer	2.24	15.1	0.236	0.120^{b}	0.79^{b}	0.96^{c}	22.4	11.6^{a}	2.67	169.9^{a}	2.45	127.5^{a}	4.27^{a}
	NPKCaMg	2.51	16.0	0.237	0.220^{a}	2.12^{a}	2.21^{a}	19.5	7.91^{c}	2.78	113.5^{bc}	2.32	83.0^{b}	2.96^{b}
	PKCaMg	2.33	15.9	0.222	0.209^{a}	2.10^{a}	2.01^{a}	19.1	8.50^{bc}	2.66	117.1^{bc}	2.25	94.9^{b}	3.09^{b}
	NKCaMg	2.42	15.7	0.241	0.218^{a}	2.40^{a}	1.95^{a}	21.4	11.8^{a}	2.78	155.5^{ab}	2.20	126.3^{a}	4.31^{a}
	NPCaMg	2.26	16.2	0.229	0.128^{b}	2.18^{a}	2.05^{a}	19.9	9.87^{b}	2.43	138.7^{abc}	2.28	86.2^{b}	2.90^{b}
	NPKMg	2.31	15.5	0.257	0.211^{a}	1.04^{b}	2.07^{a}	20.9	8.85^{bc}	2.58	135.0^{abc}	2.37	88.6^{b}	3.08^{b}
	NPKCa	2.53	16.2	0.232	0.221^{a}	2.27^{a}	1.28^{bc}	19.6	8.75^{bc}	2.62	110.1^{c}	2.32	89.8^{b}	2.98^{b}
	FFP	2.37	15.7	0.217	0.201^{a}	2.16^{a}	1.60^{ab}	18.0	9.44^{bc}	2.73	130.5^{abc}	2.51	101.2^{b}	3.02^{b}
LM	No fertilizer	5.37	15.5	0.231	0.131^{b}	0.82^{d}	0.82^{c}	18.4	11.4^{a}	2.08	158.5^{a}	2.10	120.8^{a}	3.78^{a}
	NPKCaMg	5.73	16.7	0.209	0.229^{a}	1.44^{abc}	2.06^{a}	17.1	9.12^{b}	2.37	92.3^{c}	2.20	64.6^{c}	2.90^{b}
	PKCaMg	5.47	15.7	0.220	0.224^{a}	1.49^{ab}	1.93^{a}	17.6	8.65^{b}	2.32	97.4^{c}	2.24	67.2^{c}	2.88^{b}
	NKCaMg	5.63	16.1	0.197	0.240^{a}	1.64^{a}	1.99^{a}	18.3	11.6^{a}	2.53	148.7^{ab}	2.09	113.6^{a}	3.80^{a}
	NPCaMg	5.47	16.0	0.162	0.138^{b}	1.43^{abc}	2.00^{a}	17.9	8.52^{b}	2.79	93.8^{c}	2.17	75.9^{b}	2.95^{b}
	NPKMg	5.54	15.6	0.229	0.205^{a}	0.88^{d}	1.93^{a}	18.6	9.11^{b}	2.24	105.7^{c}	2.07	80.5^{b}	2.85^{b}
	NPKCa	5.32	16.2	0.200	0.228^{a}	1.27^{bc}	1.32^{b}	17.8	9.09^{b}	2.40	100.3^{c}	2.43	76.0^{b}	2.94^{b}
	FFP	5.24	16.3	0.215	0.216^{a}	1.24^{c}	1.64^{ab}	17.6	9.90^{ab}	2.11	118.3^{bc}	2.04	90.4^{b}	2.93^{b}
VT	F	ns	ns	ns	*	*	*	ns	*	ns	*	ns	*	*
	CV (%)	8.07	6.49	14.2	8.12	23.2	27.9	11.4	13.0	9.46	24.4	10.4	13.9	14.7
LM	F	ns	ns	ns	*	*	*	ns	*	ns	*	ns	*	*
	CV (%)	6.53	8.10	18.1	13.8	13.4	19.5	6.00	16.7	16.9	27.4	9.46	23.8	10.4

Note: VT: Vi Thanh city. LM: Long My district. In the same column, numbers followed by the same letters were different insignificantly from each other via Duncan post-hoc test.*: different at 5 % significance. Ns: not significant. NPKCaMg: full fertilization; PKCaMg: fertilization without nitrogen; NKCaMg: fertilization without phosphorous; NPCaMg: fertilization without potassium; NPKMg: fertilization without calcium; NPKCa: fertilization without magnesium; FFP: farmers' fertilizing practice. CEC, EC, and OM stand for Cation Exchange Capacity, Electrical conductivity, and Organic Matter.

Soil-supplying abilities of N, P, K, Ca, and Mg: These were determined based on nutrient uptakes in corresponding omission treatments [34]. In detail, N uptake was calculated by multiplying the biomass values in each part by the N concentrations in that part. Total N uptake was the sum of N uptakes in the crown, core, shell, slip, peduncle, stem, and leaves. Uptakes of P, K, Ca, and Mg followed similar calculations.

Yield responses of plants to N, P, K, Ca, and Mg fertilizers: They were determined as differences in yield between the fully fertilized plot with NPKCaMg fertilizers and the corresponding omission plot [35].

Agronomic efficiencies: They were calculated using yield responses divided by fertilizer amounts of corresponding fertilizers [36].

Fertilizer formula calibration: Regarding the SSNM method described by Pasuquin et al. [37], the fertilizer formula was adjusted as follows: FX (kg ha^{-1}) = ($FY-FY_{0X}$)/AE_X, where X was N, P, K, Ca, and Mg nutrients, FX was nutrient demands to reach the target (38.6 t ha^{-1}), FY was the target yield, FY_{0X} was the yields obtained in corresponding nutrient omission plot (t ha^{-1}), and AE_X was the agronomic efficiencies ($kg_{pineapple}$ $kg^{-1}_{fertilizer}$).

Multivariate linear regression analysis: The regression model was used to evaluate the influences of soil nutrients on pineapple fruit yield via determining coefficients r^2: $FY = a_0 + a_1X_1 + a_2X_2 + \ldots + a_{13}X_{13}$. FY is the dependent variable (yield: t ha^{-1}); X_1, X_2, X_3, X_4, X_5, X_6, X_7, X_8, X_9, X_{10}, X_{11}, X_{12}, and X_{13} are the independent variables (NH_4^+: mg kg^{-1}, NO_3^-: mg kg^{-1}, $P_{available}$: mg kg^{-1}, Al–P: mg kg^{-1}, Fe–P: mg kg^{-1}, Ca–P: mg kg^{-1}, K^+: meq 100 g^{-1}, Ca^{2+}: meq 100 g^{-1}, Mg^{2+}: meq 100 g^{-1}, Al^{3+}: meq 100 g^{-1}, Fe^{2+}: mg kg^{-1}, and Mn_{total}: %, respectively). A_0 is the blocking coefficient. A_1, a_2, a_3, a_4, a_5, a_6, a_7, a_8, a_9, a_{10}, a_{11}, a_{12}, and a_{13} are the regression coefficients. The "a" values were calculated according to the change in the yield depending on the shift of a certain soil-independent variable. From this, we shall know how soil variables affect the yield. If a regression coefficient was positive, its soil component supported the productivity of pineapple, and vice versa. If the number was zero, the component did not cause changes in the pineapple yield. Moreover, the greater the absolute value of "a" was, the greater influence its component had.

Statistical analysis: Microsoft Excel 2017 software was employed to determine Pearson's correlation coefficients between yield and soil properties. The SPSS software, version 13.0, was run to conduct regression analysis and variances and compare differences between means in treatments by the Duncan post-hoc test.

3. Results

3.1. Determination of obstacles of acid sulfate soil characteristics in pineapple cultivation

Twelve farms in Vi Thanh city and Long My district shared some similar soil characteristics, which are common in acid-sulfate soil (Table 1, Supplementary Data). First of all, both pH values were quite low and were roughly 2.62–3.39 for pH_{H2O} and 2.26–2.55 for pH_{KCl}. This was caused by a great presence of ASS; additionally, the total acidity was 22.6–24.4 mS/cm. Low available nutrient concentrations could also be found at both sites. In particular, the N availability was roughly 37.8–46.1 mg/kg for NH_4^+ and 16.0–16.9 mg/kg for NO_3^-. The soluble P concentration was 43.7–56.3 mg/kg, while the contents of insoluble P compounds were much greater (Table 1, Supplementary Data). ASS was also associated with high levels of Al^{3+} and Fe^{2+} toxicity, which were 9.4–12.0 mg/kg and 210.8–222.0 mg/kg at both locations, respectively. However, there are some distinct characteristics between Vi Than city and Long My district. For example, the soil in Vi Thanh city was more saline and contained a greater amount of insoluble P (Al–P, Ca–P, and Fe–P) than that in Long My district. Results of PCA displayed the influences of soil components on the others. In particular, low pH and high concentrations of Al^{3+}, Fe^{2+}, and total acidity in soil for pineapple led to reductions in the available nutrient contents in soil, which

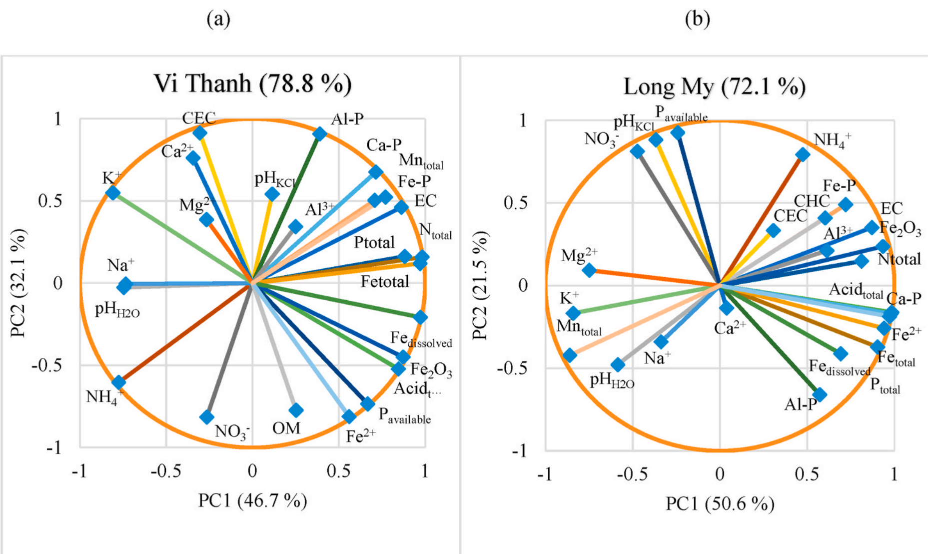

Fig. 2. Principal component analysis of acid sulfate soil for pineapple in (a) Vi Thanh city and (b) Long My district.

was a factor affecting pineapple yield, accounting for 78.8 % and 72.1 % in Vi Thanh city (Fig. 2a) and Long My district (Fig. 2b), respectively.

CEC, EC, and OM stand for Cation Exchange Capacity, Electrical conductivity, and Organic Matter.

3.2. Influences of site-specific nutrient management on properties of acid sulfate soil for pineapple at harvest

Concentrations of NH_4^+, $P_{available}$, K^+, Ca^{2+}, and Mg^{2+} went down in the treatments fertilized without corresponding nutrients of N, P, K, Ca, and Mg. In addition, amounts of Al^{3+}, Fe^{2+}, and Mn_{total} toxicities went up in the treatment fertilized without P in both sites (Table 1). Therefore, pineapple yield was positively correlated to concentrations of NH_4^+, NO_3^-, $P_{available}$, K^+, Ca^{2+}, and Mg^{2+} (r = 0.32–0.61 in Vi Thanh and r = 0.32–0.63 in Long My district) and negatively correlated to contents of Al^{3+}, Fe^{2+}, and Mn_{total} toxicities in both sites, except for Al^{3+} concentration in Long My district. Furthermore, available P content was correlated positively to Al–P, Fe–P, and Ca–P concentrations (r = 0.56–0.64 in Vi Thanh and r = 0.49–0.61 in Long My) but negatively to Al^{3+}, Fe^{2+}, and Mn_{total} concentrations, with correlation coefficients from −0.74 to −0.59 in Vi Thanh (Fig. 3) and from −0.63 to −0.34 in Long My district (Fig. 4).

3.3. Influences of site-specific nutrient management on nitrogen, phosphorous, potassium, calcium, and magnesium uptakes in a pineapple in acid sulfate soil

3.3.1. Dry biomass in parts of pineapple

Omitting any of the essential nutrients, such as N, P, K, Ca, or Mg, during the fertilization treatments led to decreased biomass in various plant parts, involving the flesh, core, slip, peduncle, stem, and leaves, within Long My district. Biomass values in the crown and shell in the treatment fertilized without N were lower than those in the treatments fully fertilized with NPKCaMg or in the ones fertilized without P, K, Ca, or Mg. Similarly, the dry biomass of the flesh, core, shell, stem, and leaves reached its maximum in the treatment that received full fertilization with NPKCaMg. Following that, the treatments without N, P, K, Ca, or Mg fertilizers, as well as the treatment following FFP, exhibited the second-highest biomass. Finally, in the treatment without any fertilizers, the biomass was at

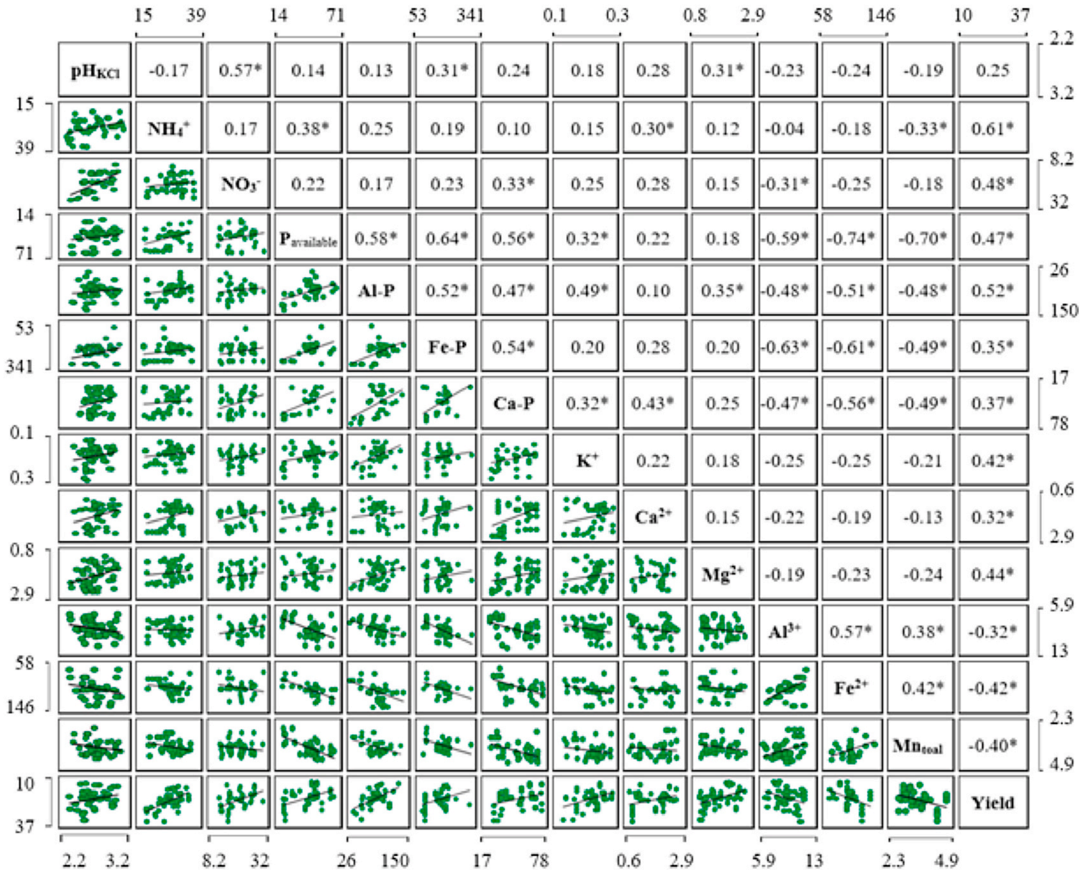

Fig. 3. Pearson correlation coefficient (r, n = 48) between soil characteristics and pineapple yield in Vi Thanh
Note: (*) correlated at 5 % significance. Units of NH_4^+: mg kg^{-1}; NO_3^-: mg kg^{-1}; $P_{available}$: mg kg^{-1}; Al–P: mg kg^{-1}; Fe–P: mg kg^{-1}; Ca–P: mg kg^{-1}; K^+: meq 100 g^{-1}; Ca^{2+}: meq 100 g^{-1}; Mg^{2+}: meq 100 g^{-1}; Al^{3+}: meq 100 g^{-1}; Fe^{2+}: mg kg^{-1}; Mn_{total}: %.

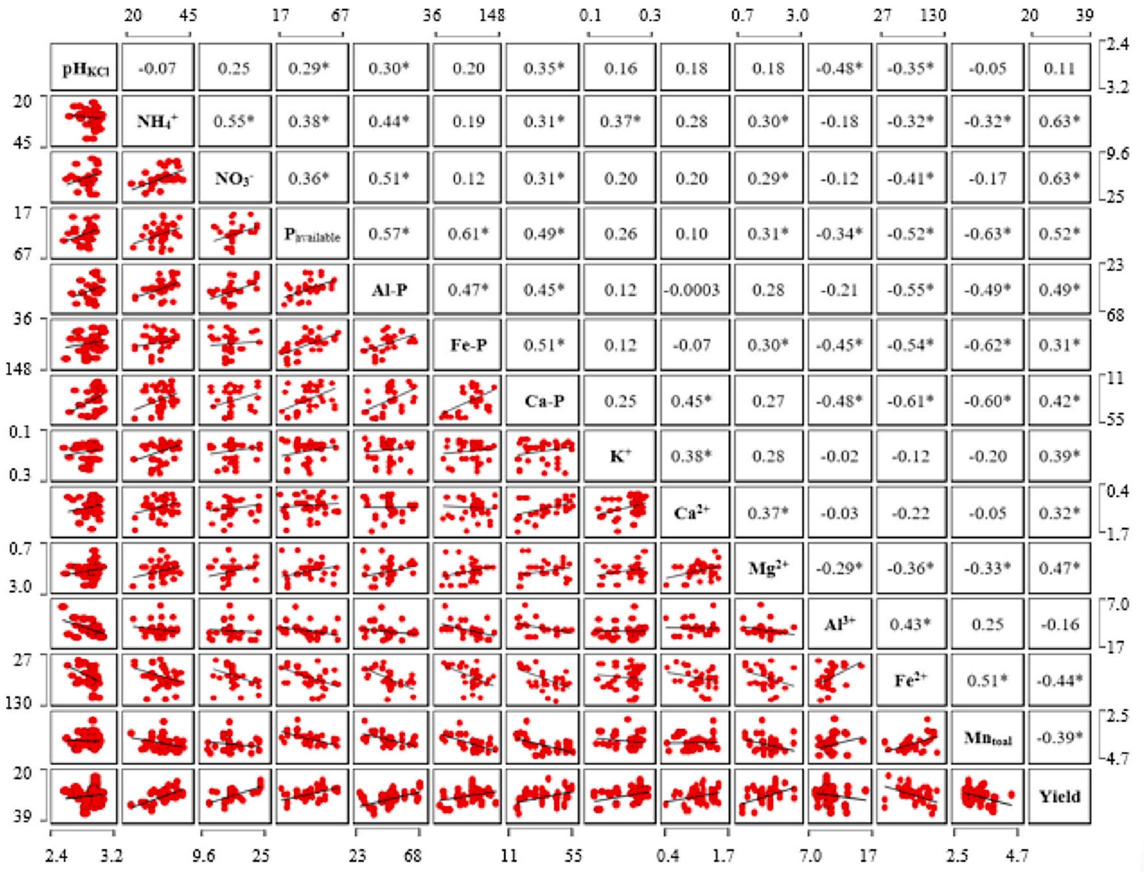

Fig. 4. Pearson correlation coefficient (r, n = 48) between soil characteristics and pineapple yield in Long My
Note: (*) correlated at 5 % significance. Units of NH_4^+: mg kg^{-1}; NO_3^-: mg kg^{-1}; $P_{available}$: mg kg^{-1}; Al–P: mg kg^{-1}; Fe–P: mg kg^{-1}; Ca–P: mg kg^{-1}; K^+: meq 100 g^{-1}; Ca^{2+}: meq 100 g^{-1}; Mg^{2+}: meq 100 g^{-1}; Al^{3+}: meq 100 g^{-1}; Fe^{2+}: mg kg^{-1}; Mn_{total}: %.

its lowest point (Table 2).

3.3.2. Uptakes of nitrogen, phosphorous, potassium, calcium, and magnesium in pineapple

Concentrations of N, P, K, Ca, and Mg are shown in Tables 2–6 in the Supplementary Data. Moreover, the treatment fertilized without N had lower N uptakes in crown, flesh, shell, core, slip, peduncle, stem, and leaves than the treatment fertilized with N in both sites (Table 7, Supplementary Data). Similarly, P, K, Ca, and Mg uptakes in the crown, flesh, shell, core, slip, peduncle, stem, and leaves were lower in the corresponding nutrient omission treatments than in the treatments fertilized with that corresponding nutrient at both sites (Tables 8–11, Supplementary Data). Thereby, in Vi Thanh and Long My district, N uptake in the treatment fully fertilized with NPKCaMg amounted to the highest point at 289.1 and 327.4 kg ha^{-1}; however, treatments fertilized with P, K, Ca, or Mg and the one following FFP came second at 190.6–201.8 and 242.4–254.6 kg ha^{-1}, respectively, which were lower than those in the treatment fertilized without N. The lowest result was in the treatment without fertilizers. Likewise, total uptakes of P, K, Ca, and Mg in the pineapples in the treatment fully fertilized with NPKCaMg were the highest in both sites. In the treatment without fertilizers, they were lowest. In the treatments fertilized without N or P, total N uptakes were lower than those in the treatments fertilized without K, Ca, or Mg and the one following FFP (Table 3).

3.4. Influences of site-specific nutrient management on the growth of pineapple in acid sulfate soil

In Table 4, the measurements for plant height, number of leaves per plant, D-leaf width, and stem length in the treatment fully fertilized with NPKCaMg were recorded as follows: In Vi Thanh, the plant height was 85.5 cm, the number of leaves per plant was 56.9, the D-leaf width was 6.87 cm, and the stem length measured 23.4 cm. In Long My district, the corresponding measurements were noticed as 85.5 cm for plant height, 67.7 for the number of leaves per plant, 7.31 cm for D-leaf width, and 18.1 cm for stem length. These values were higher than those in the treatments fertilized without N, P, K, Ca, or Mg in both sites. In addition, peduncle diameter, crown length, and crown diameter in the treatment fertilized without N were outweighed by those in the treatment fully fertilized with NPKCaMg at both locations.

Table 2
Influences of specific-site nutrient management on biomass of pineapple in acid sulfate soil in Vi Thanh city and Long My district.

Location	Treatment	Dry biomass (kg ha^{-1})							
		Crown	Flesh	Core	Shell	Slip	Peduncle	Stem	Leaves
VT	No fertilizer	366.7^{b}	718.63^{d}	238.7^{f}	1080.0^{d}	185.4^{d}	292.2^{c}	803.66^{c}	3878.7^{c}
	NPKCaMg	633.4^{a}	2359.9^{a}	650.7^{a}	2154.5^{a}	677.7^{a}	679.7^{a}	1394.9^{a}	8024.3^{a}
	PKCaMg	414.2^{b}	1034.0^{c}	328.6^{e}	1365.7^{c}	384.6^{c}	397.1^{bc}	1050.9^{b}	5256.9^{b}
	NKCaMg	526.9^{a}	2105.9^{b}	500.2^{c}	1950.4^{ab}	406.0^{c}	395.7^{bc}	1158.1^{b}	5642.5^{b}
	NPCaMg	573.8^{a}	2138.2^{b}	556.5^{bc}	1989.2^{ab}	527.9^{b}	412.0^{bc}	1061.1^{b}	4908.7^{b}
	NPKMg	581.5^{a}	2016.8^{b}	541.1^{bc}	1905.6^{ab}	581.0^{b}	437.0^{ab}	1085.8^{b}	5317.7^{b}
	NPKCa	542.2^{a}	2056.7^{b}	575.7^{b}	1824.6^{b}	575.2^{b}	424.4^{ab}	1102.9^{b}	5772.9^{b}
	FFP	626.8^{a}	1975.1^{b}	408.9^{d}	1894.3^{ab}	541.3^{b}	455.6^{ab}	1072.6^{b}	5940.0^{b}
LM	No fertilizer	568.2^{c}	1084.4^{d}	294.5^{d}	1384.3^{f}	352.9^{c}	398.9^{c}	816.78^{c}	5457.0^{c}
	NPKCaMg	783.3^{a}	2718.1^{a}	653.1^{a}	2390.7^{a}	811.7^{a}	663.1^{a}	1443.3^{a}	8235.0^{a}
	PKCaMg	638.3^{bc}	1473.6^{c}	330.3^{cd}	1558.5^{e}	403.4^{c}	459.7^{bc}	1070.9^{b}	6767.3^{b}
	NKCaMg	709.2^{ab}	2383.3^{b}	473.7^{b}	1865.5^{bc}	603.3^{b}	495.1^{bc}	1144.7^{b}	6784.7^{b}
	NPCaMg	715.0^{ab}	2376.4^{b}	409.9^{bc}	1734.8^{cd}	614.6^{b}	556.5^{ab}	1157.7^{b}	6840.7^{b}
	NPKMg	628.6^{bc}	2335.7^{b}	423.1^{bc}	1707.1^{d}	710.7^{ab}	555.7^{ab}	1161.9^{b}	6960.4^{b}
	NPKCa	693.9^{ab}	2395.3^{b}	473.1^{b}	1906.5^{b}	688.0^{ab}	578.3^{ab}	1146.8^{b}	6736.1^{b}
	FFP	761.6^{a}	2328.2^{b}	375.8^{cd}	1867.1^{bc}	766.5^{ab}	579.2^{ab}	1142.3^{b}	6363.7^{bc}
VT	F	*	*	*	*	*	*	*	*
	CV (%)	16.3	9.65	11.4	12.7	1.05	23.2	10.3	15.0
LM	F	*	*	*	*	*	*	*	*
	CV (%)	3.48	12.5	17.2	6.70	20.8	18.3	7.37	14.1

Note: VT: Vi Thanh city. LM: Long My district. In the same column, numbers followed by the same letters were different insignificantly from each other via Duncan post-hoc test.*: different at 5 % significance. ns: not significant. NPKCaMg: full fertilization; PKCaMg: fertilization without nitrogen; NKCaMg: fertilization without phosphorous; NPCaMg: fertilization without potassium; NPKMg: fertilization without calcium; NPKCa: fertilization without magnesium; FFP: farmers' fertilizing practice.

Table 3
Influences of specific-site nutrient management on total nitrogen, phosphorous, potassium, calcium and magnesium uptakes in pineapple in acid sulfate soil in Vi Thanh city and Long My district.

Location	Treatment	Total uptakes of N, P, K, Ca and Mg in plants (kg ha^{-1})				
		N	P	K	Ca	Mg
VT	No fertilizer	84.04^{d}	7.25^{d}	29.17^{d}	9.53^{e}	9.66^{e}
	NPKCaMg	289.1^{a}	25.4^{a}	137.4^{a}	41.9^{a}	39.8^{a}
	PKCaMg	122.3^{c}	13.2^{c}	73.82^{c}	25.0^{c}	22.9^{c}
	NKCaMg	201.6^{b}	12.1^{c}	92.07^{b}	30.0^{b}	28.2^{b}
	NPCaMg	190.6^{b}	16.9^{b}	62.07^{c}	28.1^{bc}	26.3^{b}
	NPKMg	196.5^{b}	17.4^{b}	100.4^{b}	16.5^{d}	26.9^{b}
	NPKCa	201.8^{b}	17.6^{b}	103.1^{b}	31.5^{b}	18.6^{d}
	FFP	194.6^{b}	17.4^{b}	97.92^{b}	31.1^{b}	27.1^{b}
LM	No fertilizer	139.4^{d}	9.50^{e}	43.91^{e}	13.6^{e}	14.9^{d}
	NPKCaMg	327.4^{a}	29.3^{a}	166.0^{a}	48.9^{a}	43.1^{a}
	PKCaMg	170.6^{c}	16.8^{c}	115.3^{c}	37.2^{bc}	29.7^{b}
	NKCaMg	253.4^{b}	14.3^{d}	135.9^{b}	38.7^{b}	31.3^{b}
	NPCaMg	254.6^{b}	19.2^{bc}	82.68^{d}	39.5^{b}	30.8^{b}
	NPKMg	247.4^{b}	20.0^{b}	127.5^{bc}	22.3^{d}	29.1^{b}
	NPKCa	245.7^{b}	20.1^{b}	132.9^{bc}	38.1^{b}	22.1^{c}
	FFP	242.4^{b}	19.4^{bc}	125.1^{bc}	33.8^{c}	31.3^{b}
VT	F	*	*	*	*	*
	CV (%)	8.91	10.1	13.6	14.3	10.8
LM	F	*	*	*	*	*
	CV (%)	8.39	11.5	12.1	9.05	10.9

Note: VT: Vi Thanh city. LM: Long My district. In the same column, numbers followed by the same letters were different insignificantly from each other via Duncan post-hoc test.*: different at 5 % significance. ns: not significant. NPKCaMg: full fertilization; PKCaMg: fertilization without nitrogen; NKCaMg: fertilization without phosphorous; NPCaMg: fertilization without potassium; NPKMg: fertilization without calcium; NPKCa: fertilization without magnesium; FFP: farmers' fertilizing practice.

3.5. Influences of site-specific nutrient management on yield components and fruit yield of pineapple in acid sulfate soil

Fertilizing without each of N, P, K, Ca, and Mg caused declines in pineapple fruit length, diameter, and weight compared to the fruit with complete NPKCaMg fertilization. Therefore, pineapple yield in the treatment fully fertilized with NPKCaMg was the highest (35.5 t ha^{-1} in Vi Thanh and 35.9 t ha^{-1} in Long My district) and that in the treatment without fertilizers was the lowest one (14.8 t ha^{-1} and 21.6 t ha^{-1}, respectively) (Table 5). Fig. 5 illustrates the differences in pineapple yield between farms in the treatment following FFP,

Table 4
Influences of specific-site nutrient management on growth of pineapple in acid sulfate soil in Vi Thanh city and Long My district.

Location	Treatment	Plant height	Leaves number per plant	D-leaf length	D-leaf width	Stem length	Stem diameter	Peduncle length	Peduncle diameter	Crown length	Crown diameter
		cm	leaves	cm	cm	cm	cm	cm	cm	cm	cm
VT	No fertilizer	68.0^{e}	35.0^{d}	52.0^{e}	4.65^{c}	12.0^{e}	4.16^{c}	23.1	2.47^{b}	10.7^{b}	3.78^{b}
	NPKCaMg	88.3^{a}	56.9^{a}	69.3^{a}	6.87^{a}	23.4^{a}	5.00^{a}	25.2	3.17^{a}	17.0^{a}	4.45^{a}
	PKCaMg	72.8^{d}	41.3^{c}	58.1^{d}	5.00^{c}	13.4^{de}	4.21^{bc}	23.8	2.55^{b}	11.8^{b}	3.79^{b}
	NKCaMg	74.8^{cd}	49.8^{b}	63.7^{c}	5.77^{b}	15.3^{cd}	4.67^{ab}	24.1	2.96^{a}	16.0^{a}	4.30^{ab}
	NPCaMg	76.5^{c}	47.3^{bc}	65.3^{bc}	5.87^{b}	14.9^{cd}	4.81^{a}	24.5	2.82^{ab}	16.3^{a}	4.30^{ab}
	NPKMg	80.6^{b}	48.6^{b}	67.0^{abc}	6.05^{b}	18.1^{b}	4.72^{a}	24.8	3.05^{a}	16.0^{a}	4.38^{a}
	NPKCa	81.3^{b}	49.0^{b}	67.5^{ab}	5.86^{b}	19.1^{b}	4.71^{a}	25.1	3.01^{a}	16.6^{a}	4.37^{a}
	FFP	76.9^{c}	49.3^{b}	64.4^{bc}	5.96^{b}	17.3^{bc}	4.58^{abc}	24.1	2.94^{a}	16.2^{a}	4.25^{ab}
LM	No fertilizer	74.3^{d}	41.5^{d}	55.8^{d}	5.55^{d}	9.60^{d}	4.28	22.8	2.32^{b}	14.1^{c}	4.15^{e}
	NPKCaMg	85.5^{a}	67.7^{a}	73.5^{a}	7.31^{a}	18.1^{a}	4.66	24.6	2.89^{a}	18.2^{a}	5.17^{a}
	PKCaMg	76.7^{c}	49.0^{c}	62.6^{c}	6.07^{c}	11.6^{c}	4.44	23.8	2.35^{b}	14.9^{bc}	4.30^{de}
	NKCaMg	79.3^{b}	58.7^{b}	67.8^{b}	6.51^{b}	14.0^{b}	4.49	24.2	2.54^{ab}	15.1^{bc}	4.59^{bcd}
	NPCaMg	78.0^{bc}	58.3^{b}	67.9^{b}	6.55^{b}	15.1^{b}	4.51	24.5	2.71^{ab}	15.8^{bc}	4.46^{cd}
	NPKMg	78.8^{bc}	56.3^{b}	68.8^{ab}	6.65^{b}	14.2^{b}	4.56	23.6	2.72^{ab}	15.3^{bc}	4.48^{cd}
	NPKCa	79.1^{bc}	58.8^{b}	68.7^{ab}	6.75^{b}	14.6^{b}	4.51	24.2	2.82^{a}	15.0^{bc}	4.65^{bc}
	FFP	77.8^{bc}	55.1^{bc}	67.9^{b}	6.53^{b}	13.2^{bc}	4.50	24.6	2.86^{a}	16.4^{ab}	4.85^{b}
VT	F	*	*	*	*	*	*	ns	*	*	*
	CV (%)	3.06	11.9	4.40	4.16	3.09	8.35	7.26	10.2	8.26	9.62
LM	F	*	*	*	*	*	ns	ns	*	*	*
	CV (%)	2.55	9.33	6.04	3.68	12.0	6.12	5.54	6.86	10.6	1.56

Note: VT: Vi Thanh city. LM: Long My district. In the same column, numbers followed by the same letters were different insignificantly from each other via Duncan post-hoc test.*: different at 5 % significance. ns: not significant. NPKCaMg: full fertilization; PKCaMg: fertilization without nitrogen; NKCaMg: fertilization without phosphorous; NPCaMg: fertilization without potassium; NPKMg: fertilization without calcium; NPKCa: fertilization without magnesium; FFP: farmers' fertilizing practice.

Table 5
Influences of specific-site nutrient management on yield components and fruit yield of pineapple in acid sulfate soil in Vi Thanh city and Long My district.

Location	Treatment	Fruit length	Fruit diameter	Fruit weight	Yield
		cm	cm	kg	(t ha^{-1})
VT	No fertilizer	12.9^{d}	6.50^{d}	0.52^{f}	14.8^{e}
	NPKCaMg	19.4^{a}	9.27^{a}	1.40^{a}	35.5^{a}
	PKCaMg	13.1^{d}	7.33^{c}	0.72^{e}	19.5^{d}
	NKCaMg	15.7^{c}	8.59^{b}	1.03^{cd}	27.4^{bc}
	NPCaMg	16.8^{bc}	8.61^{b}	1.18^{bc}	27.9^{b}
	NPKMg	17.7^{b}	8.63^{b}	1.22^{b}	28.4^{b}
	NPKCa	17.6^{b}	8.66^{b}	1.21^{b}	27.9^{b}
	FFP	15.9^{c}	8.55^{b}	1.00^{d}	24.5^{c}
LM	No fertilizer	14.3^{e}	7.04^{d}	0.90^{e}	21.6^{d}
	NPKCaMg	18.2^{a}	9.30^{a}	1.38^{a}	35.9^{a}
	PKCaMg	15.2^{d}	7.85^{c}	1.03^{d}	24.9^{c}
	NKCaMg	17.2^{bc}	8.65^{b}	1.16^{c}	29.7^{b}
	NPCaMg	17.4^{ab}	8.58^{b}	1.15^{c}	30.1^{b}
	NPKMg	17.1^{bc}	8.61^{b}	1.21^{bc}	30.8^{b}
	NPKCa	17.7^{ab}	8.59^{b}	1.26^{b}	30.8^{b}
	FFP	16.2^{c}	8.57^{b}	1.16^{c}	29.2^{b}
VT	F	*	*	*	*
	CV (%)	8.06	5.25	12.1	10.5
LM	F	*	*	*	*
	CV (%)	4.75	6.21	5.45	5.71

Note: VT: Vi Thanh city. LM: Long My district. In the same column, numbers followed by the same letters were different insignificantly from each other via Duncan post-hoc test.*: different at 5 % significance. ns: not significant. NPKCaMg: full fertilization; PKCaMg: fertilization without nitrogen; NKCaMg: fertilization without phosphorous; NPCaMg: fertilization without potassium; NPKMg: fertilization without calcium; NPKCa: fertilization without magnesium; FFP: farmers' fertilizing practice.

fluctuating from 21.3 to 33.1 t ha^{-1}, while the median was lower than the mean; that is, yield gaps were high between pineapple farms, with 11.8 t ha^{-1}, but SSNM-based fertilization gave out a smaller gap, with 5.40 t ha^{-1}, and formed a more symmetrical boxplot.

Pineapple yield responses to N fertilizer achieved the highest point in Vi Thanh and Long My district, valuing at 16.1 and 11.0 t

Table 6
Regression functions between yield and soil chemical properties in Vi Thanh city and Long My district (n = 48).

Location	Regression function	r^2	p
Vi Thanh	$FY = -0.762 + 1.476X_1 + 0.489X_2 + 0.259X_3 - 0.027X_4 + 0.045X_5 - 0.005X_6 + 0.006X_7 + 15.648X_8 - 0.026X_9 + 2.147X_{10} - 0.151X_{11} - 0.035X_{12} - 0.098X_{13}$	0.705	<0.01
Long My	$FY = 11.928 - 2.706X_1 + 0.172X_2 + 0.345X_3 + 0.065X_4 + 0.014X_5 + 0.005X_6 + 0.038X_7 + 10.095X_8 + 0.243X_9 + 1.692X_{10} + 0.192X_{11} - 0.005X_{12} + 0.477X_{13}$	0.642	<0.01

Note: FY: fruit yield (t ha^{-1}); X1: pHKCl; X2: NH_4^+ (mg kg^{-1}); X3: NO_3^- (mg kg^{-1}); X4: $P_{available}$ (mg kg^{-1}); X5: Al–P (mg kg^{-1}); X6: Fe–P (mg kg^{-1}); X7: Ca–P (mg kg^{-1}); X8: K^+ (meq 100 g^{-1}); X9: Ca^{2+} (meq 100 g^{-1}); X10: Mg^{2+} (meq 100 g^{-1}); X11: Al^{3+} (meq 100 g^{-1}); X12: Fe^{2+} (mg kg^{-1}); X13: Mn_{total} (%).

Table 7
Influences of specific-site nutrient management on fruit quality of pineapple in acid sulfate soil in Vi Thanh city and Long My district.

Location	Treatment	Water content	Degree Brix	pH	Total acid	Vitamin C	Fruit color		
		mL	%		mg L^{-1}	mg 100 g^{-1}	L*	a*	b*
VT	No fertilizer	180.0^{d}	5.86^{d}	3.52	9.36	20.5^{d}	184.9^{b}	38.8^{b}	99.8
	NPKCaMg	644.8^{a}	7.58^{a}	3.66	10.7	50.2^{a}	213.9^{a}	53.5^{a}	103.0
	PKCaMg	288.2^{c}	7.03^{ab}	3.64	10.2	32.1^{b}	190.3^{b}	46.1^{a}	101.4
	NKCaMg	413.7^{b}	7.10^{ab}	3.65	10.1	34.8^{b}	194.5^{b}	47.1^{a}	101.1
	NPCaMg	425.6^{b}	6.25^{cd}	3.63	9.68	23.2^{cd}	193.4^{b}	47.0^{a}	106.6
	NPKMg	451.6^{b}	7.47^{a}	3.61	10.1	35.5^{b}	195.4^{b}	47.7^{a}	100.2
	NPKCa	404.1^{b}	7.45^{a}	3.58	10.6	31.7^{b}	194.5^{b}	49.5^{a}	99.5
	FFP	347.5^{bc}	6.67^{bc}	3.65	10.1	29.9^{bc}	191.6^{b}	48.7^{a}	100.4
LM	No fertilizer	318.5^{d}	5.63^{c}	3.33	10.6	28.1^{c}	208.9^{b}	47.4^{d}	104.3
	NPKCaMg	614.9^{a}	7.84^{a}	3.39	13.3	53.4^{a}	262.3^{a}	64.0^{a}	110.2
	PKCaMg	406.0^{c}	7.05^{b}	3.38	11.7	48.4^{ab}	215.3^{b}	48.8^{cd}	106.3
	NKCaMg	555.6^{b}	7.19^{ab}	3.34	12.0	46.9^{ab}	225.3^{b}	54.8^{b}	107.7
	NPCaMg	554.3^{b}	6.08^{c}	3.33	11.7	28.9^{c}	210.2^{b}	53.1^{bc}	109.8
	NPKMg	531.7^{b}	7.80^{a}	3.30	11.5	48.8^{ab}	218.8^{b}	53.3^{bc}	107.1
	NPKCa	542.6^{b}	7.12^{b}	3.37	11.8	44.3^{ab}	221.4^{b}	56.3^{b}	105.8
	FFP	495.6^{b}	7.68^{ab}	3.29	11.2	40.5^{b}	237.2^{ab}	54.8^{b}	108.7
VT	F	*	*	ns	ns	*	*	*	ns
	CV (%)	21.4	7.52	2.62	20.8	20.8	6.98	12.8	10.3
LM	F	*	*	ns	ns	*	*	*	ns
	CV (%)	9.70	7.38	7.57	13.6	17.8	12.0	8.16	10.5

Note: VT: Vi Thanh city. LM: Long My district. In the same column, numbers followed by the same letters were different insignificantly from each other via Duncan post-hoc test.*: different at 5 % significance. ns: not significant. NPKCaMg: full fertilization; PKCaMg: fertilization without nitrogen; NKCaMg: fertilization without phosphorous; NPCaMg: fertilization without potassium; NPKMg: fertilization without calcium; NPKCa: fertilization without magnesium; FFP: farmers' fertilizing practice.

ha^{-1}, respectively. For P, K, Ca, and Mg fertilizers, yield responses were 8.13, 7.61, 7.12, and 7.66 t ha^{-1} in Vi Thanh and 6.14, 5.82, 5.11, and 5.05 t ha^{-1} in Long My district, respectively (Fig. 6a). The result also highlighted that 1 kg of N fertilizer led to an increase of 46.7 kg pineapple. Likewise, with P, K, Ca, and Mg fertilizers, the increments were 27.3, 28.9, 5.3, and 11.0 kg of pineapple, respectively. For N fertilizer, boxes had values patterning below the average value. For K fertilizer, the values were concentrated above average, but, for P, Ca, and Mg fertilizers, the values were distributed more symmetrically. As a result, agronomic efficiencies of N and K in each pineapple cultivation were highly cataclysmic (Fig. 6b).

With the target yield at 38.6 t ha^{-1}, conforming to the formula of Pasuqin et al. (2014), amounts of N, P, K, Ca, and Mg fertilizers were calibrated to 354.4 N-375.4 P_2O_5-340.7 K_2O-1740.6 CaO and 849.9 MgO kg ha^{-1} in Vi Thanh and 375.2 N-398.5 P_2O_5-361.0 K_2O-1893.5 CaO and 951.1 MgO kg ha^{-1} in Long My district.

The regression functions were controlled to evaluate the relationships between pineapple fruit yield and soil chemical characteristics, where the correlations between the fruit yield and the regression models were high at $r^2 = 0.705$ and 0.642 in Vi Thanh and Long My district, respectively (Table 6).

3.6. Influences of site-specific nutrient management on fruit quality of pineapple in acid sulfate soil

The treatment fully fertilized with NPKCaMg possessed the highest water content, whereas the one without fertilizers had the lowest results, which were 644.8 and 180.0 mL in Vi Thanh and 614.9 and 318.5 mL in Long My district, respectively. Then, the content of water in the treatments fertilized without P, K, Ca, or Mg was higher than those in the treatment fertilized without N, with a fluctuation of 404.1–451.6 mL compared to 288.2 mL in Vi Thanh and 531.7–555.6 mL compared to 406.0 mL in Long My district. On the other hand, Brix and vitamin C concentrations in the treatment fully fertilized with NPKCaMg and in the treatments fertilized without N, P, Ca, or Mg were higher than those in the treatment fertilized without K and in the one without fertilizers, corresponding to 7.03–7.58 % and 31.7–50.2 mg 100 g^{-1} compared to 5.86–6.25 % and 20.5–23.2 mg 100 g^{-1} in Vi Thanh and 7.05–7.84 % and

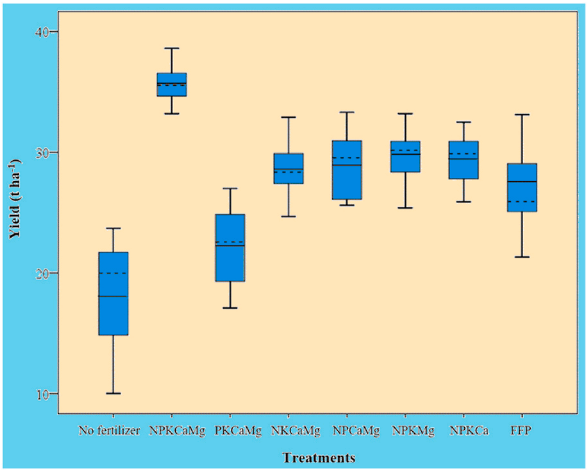

Fig. 5. Influences of specific-site nutrient management on yield gap of pineapple in acid sulfate soil in Vi Thanh city and Long My district. Note: No fertilizer: No application of fertilizers; NPKCaMg: full fertilization; PKCaMg: fertilization without nitrogen; NKCaMg: fertilization without phosphorous; NPCaMg: fertilization without potassium; NPKMg: fertilization without calcium; NPKCa: fertilization without magnesium; FFP: farmers' fertilizing practice. In boxes, the bottom described the first quartile, dashed line described the median, solid line described the mean, the top described the third quartile, the bar described the maximum and minimum values.

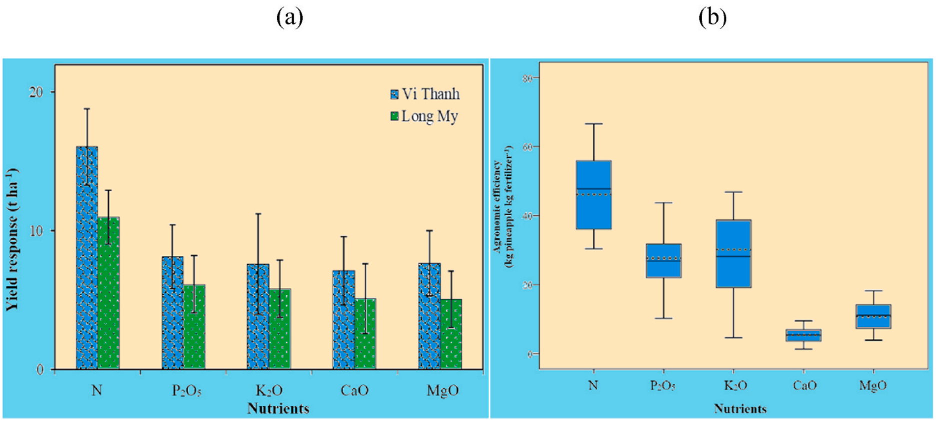

Fig. 6. Influences of specific-site nutrient management on (a) pineapple yield response and (b) agronomic efficiency of NPKCaMg fertilizers in Vi Thanh city and Long My district. Note: In boxes, the bottom described the first quartile, dashed line described the median, solid line described the mean, the top described the third quartile, the bar described the maximum and minimum values.

44.3–53.4 mg 100 g^{-1} compared to 5.63–6.08 % and 28.1–28.9 mg 100 g^{-1} in Long My district. For indexes of L*, a*, and b*, in the treatment fully fertilized with NPKCaMg, the color was brighter than that in the treatments fertilized without N, P, K, Ca, or Mg, with L* values at 213.9 and 262.3 compared to 184.9–195.4 and 208.9–225.3, following the order of the two sites (Table 7).

4. Discussion

Characteristics of soil for pineapple cultivation: The soil for farming pineapple at both sites was definitely acid-sulfate soil, because it featured most of the soil type's characteristics. In particular, the characteristics consisted of low pH, low nutrient availability, and great toxicity of Al^{3+} and Fe^{2+} (Table 1, Supplementary Data). The pineapple soil had a value of pH_{KCl} 2.26 and 2.55 in Vi Thanh and Long My district, which is considered to be highly acidic as mentioned by Horneck et al. [38]. This should be due to the great presence of acids in the soil, which was shown via the total acidity result at both sites. This was the result of the oxidation of acid-sulfate-bearing materials in soil [10,11]. Low soil pH adversely affects plant development, because the condition can not only elevate concentrations of soil toxicities, e.g., Fe^{2+}, Al^{3+}, and Mn^{2+} [39], but also minimize the nutrient availability of P, Mg, and Ca [40], leading to a lack of essential nutrients for plants. This was also expressed via the PCA result (Fig. 2), where the low pH, high concentrations of Al^{3+} and Fe^{2+}, and total acidity were negatively correlated with the N and P availability. Particularly, the P nutrient can become the most available between pH 6 and 7, but when the pH turns lower, the P element is fixed by Al and Fe in the soil [6]. Moreover, reduced ATP production—which is correlated with P concentration—may have a detrimental impact on processes like photosynthesis in plants when P is absent [41]. Moreover, the pH was correlated positively with NO_3^- at 0.57 and 0.25, but negatively with NH_4^+ at −0.17 and −0.07 in Vi Thanh city and Long My district, respectively (Figs. 3 and 4). This is in accordance with the study by Pietri and Brookes [42]. Meanwhile, high concentrations of Al^{3+} and Fe^{2+} toxicities led to remarkably diminished availability of N and P (Fig. 2). As reported by Dibabe et al. [39], P easily bonds to Al^{3+}, Fe^{2+}, or Mn^{2+} to form insoluble P compounds in acid-sulfate soil, reducing toxicity for plants. Therefore, the treatments fertilized with P had contracted concentrations of Al^{3+}, Fe^{2+}, and Mn by roughly 14.7–33.0, 24.9–43.1, and 22.4–32.7 %, compared to those in the treatment without fertilized P (Table 1).

Nutrient uptakes in pineapple: Table 2 points out that pineapple responds well to N fertilizer and then to P, K, Ca, and Mg fertilizers, so fertilizing fully with NPKCaMg improves plant growth and development, inducing heightened dry biomass. Each nutrient affects differently pineapple. K is the most important one, due to its effects on pineapple fruit quality; N and P focus on the pineapple yield; and Mg and Ca target pineapple growth, as they contribute to photosynthesis and shoot development [43]. This explained why the treatment fully fertilized with NPKCaMg had the highest total uptakes of N, P, K, Ca, and Mg. In addition, the treatments fertilized without each of N, P, K, Ca, and Mg enticed corresponding reductions in total N, P, K, Ca, and Mg uptakes in pineapple (Table 3). Cunha et al. [29] also had a similar conclusion, which stated that full fertilization multiplied uptake compared to omission fertilization. Uptakes of N, P, K, Ca, and Mg analyzed in leaves in the treatment fully fertilized with NPKCaMg were higher than those in the treatment without fertilizer.

Pineapple growth: Fertilizing without one of the N, P, K, Ca, and Mg nutrients induced reductions in plant height, D-leaf length and width, stem length, and leaves number per plant, compared to fertilizing fully with NPKCaMg (Table 4). This result agreed with that of Tewodros et al. [30], where the treatment fertilized with 281 kg N ha^{-1} and 134 kg P ha^{-1} increased plant height and leaf length by 7.20–14.2 and 5.36–8.98 % compared to those in the treatment without fertilizers. Meanwhile, in the study by Zubir et al. [44], the treatment fertilized fully with NPK escalated plant height, D-leaf length, D-leaf width, stem diameter, and leaves number per plant by 43.8, 35.8, 54.8, 26.8, and 19.2 %, respectively, compared to those in the treatment without fertilizer. Additionally, the treatment fertilized without Ca and Mg caused lower pineapple growth than that in the treatment fully fertilized with NPKCaMg (Table 4).

Yield components and pineapple fruit yield: Fertilizing without each of N, P, K, Ca, or Mg reduced the length, width, and weight of fruits. At the same time, the treatment fertilized without N yielded more significant reductions in fruit length and width, compared to the treatment fully fertilized with NPKCaMg at both sites (Table 5). Plants' response is the highest to N fertilizer, which reflects the role of N in promoting foliage development, strengthening physiological activities in plants, and facilitating the synthesis of assimilating compounds for plant growth, compared to other nutrients, such as P, K, Ca, and Mg [20]. As a result, fruit weight in the treatment fertilized with N tremendously declined, compared to that in the treatment fully fertilized with NPKCaMg by 0.35–0.68 kg, curtailing pineapple yield at both sites (Table 11, Supplementary Data).

The treatment without fertilized N had the lowest yield among treatments with fertilizers, valuing at 19.5 t ha^{-1} in Vi Thanh and 24.9 t ha^{-1} in Long My district (Table 5). The result was consistent with the study of Tewodros et al. [30], where treatment with N fertilizer at 281 kg ha^{-1} raised the yield of Smooth Cayenne by 4.84 t ha^{-1}, compared to the no-applied fertilizer treatment. In the study of Haque et al. [45] on MD2 pineapple, applying N fertilizer expanded yield by 15 % compared to the no-applied fertilizer treatment. According to Cunha et al. [29], the importance of nutrients was in the order of $N > P \sim K > Ca > Mg$, while P is essential in the growth stage of pineapple and K is more vital for fruit formation to obtain high-quality and sweet fruits [20]; that is, full fertilization with NPKCaMg helps plants grow and develop better. Therefore, fertilization following SSNM gained the highest pineapple yield with 35.5 and 35.9 t ha^{-1} in Vi Thanh and Long My district, respectively (Table 5). Yield drop brought about shrunk water content in the following order: fertilizing fully with NPKCaMg > without P ~ K ~ Ca ~ Mg ~ FFP > N > no fertilizer. In the study by Chivenge et al. [23], the SSNM method has a greatly better yield of rice and maize, as compared to both the farmer's practice and the local recommendation. Safflower has been also reported to have the same benefits as SSNM [46]. An intercropping system can be used with SSNM. For instance, the rice-wheat system had its growth, and yield components escalated by the SSNM along with an additional income of 12,953 Indian rupees per ha [47]. The SSNM has been also applied to the maize-sunflower cropping system and was concluded to be an ideal productive cropping system, with lower doses of fertilizers, sustainable yields, and maintenance of soil fertility and health in light of changing climate [48]. However, up to now, this study can be considered as one of the first reports that applied SSNM to formulate a promising fertilizer rate for pineapple grown in ASS.

Correlation between pineapple yield and soil properties: As claimed by Cunha et al. [29] and Chen et al. [49], concentrations of N, P, K, Ca, and Mg nutrients are undeniably crucial for plants to grow and develop. Figs. 3 and 4 demonstrate the correlation between pineapple yield and the concentrations of NH^{4+}, NO^{3-}, available P, K^+, Ca^{2+}, and Mg^{2+}. In Vi Thanh, the correlation coefficients ranged approximately from 0.32 to 0.61, while, in Long My district, they ranged from 0.32 to 0.63. Therefore, nutrient concentrations in the soil enhanced pineapple yield. Besides, pineapple yield rose, whereas concentrations of Al^{3+}, Fe^{2+}, and Mn toxicities dwindled at both sites. In agreement with Liu et al. [50], fertilizing with P immobilizes Al^{3+}, Fe^{2+}, and Ca^{2+} into Al–P, Fe–P, and Ca–P in soil. Figs. 3 and 4 unveil that high available P concentrations raise concentrations of Al–P, Fe–P, and Ca–P due to their positive correlation coefficients and dwindled concentrations of Al^{3+} and Fe^{2+} toxicities.

Pineapple fruit quality: In Table 7, degree Brix and vitamin C concentrations in the treatment without fertilizers and in the one without K were lower than those in the other treatments. The findings from the study conducted by Cunha et al. [51] align with this result, indicating that applying 24 g of potassium per plant provoked a significant increment in both the degree of Brix and vitamin C content, reaching levels of 22.5 and 210.3 % respectively, compared to the control group. Chen et al. [48] studied the influences of N, P, K, Ca, and Mg on the quality of pineapple fruit and proved that increasing concentrations of K boosted concentrations of C in pineapple juice. Therefore, K is an essential element in increasing the degree of Brix and vitamin C content in pineapple juice. On the other hand, pH and total acid content in juice differed insignificantly between treatments at both sites (Table 7). Cunha et al. [29,51] also reported that fertilizing with N, P, K, Ca, and Mg did not affect the pH in pineapple juice compared to the no-fertilizer case. In this study, the average pH was from 3.41 to 3.70, providing evidence that fertilizing with N, P, K, Ca, and Mg had slight impacts on the parameters of the fruit quality of pineapple.

From the above results, it can be seen that SSNM is such a wonderful tool not only to improve crop yield and broaden the income of farmers, but also to be a means of protecting the environment damaged from the overuse of chemical fertilizer. However, the SSNM is considered to be only suitable for a certain location, which is known as a drawback of this approach. Rodriguez [45] argues that the adaptability of the SSNM lies in its ability to account for the interactions between plants and fertilizers, as well as the interactions between fertilizers and the environment. By incorporating these factors into the algorithm used to recommend fertilizer formulas, SSNM can be tailored to different agricultural fields. Hence, the new fertilizer formula made in the current study can be further modified to be suitable for locations around the globe where the environmental condition is similar to that in the Mekong Delta of Vietnam. Moreover, this study should be one of the first studies that apply SSNM to formulate an optimal fertilizer dose for pineapple grown in ASS.

5. Conclusions

Soil with low pH, high concentrations of Al^{3+}, Fe^{2+}, and total acid, and low concentrations of available N, P, and K inhibited pineapple cultivation. Available P concentration negatively correlated to concentrations of Al^{3+}, Fe^{2+}, and total Mn with correlation coefficients at −0.59, −0.74, and −0.70 in Vi Thanh and −0.34, −0.52, and −0.63 in Long My district. Contents of available N and available P, K^+, Ca^{2+}, and Mg^{2+} dropped in the treatments fertilized without N, P, K, Ca, and Mg, respectively. Full fertilization with NPKCaMg obtained the highest total N, P, K, Ca, and Mg uptakes at both sites, with 289.1–327.4, 25.4–29.3, 137.4–166.0, 41.9–48.9, and 39.8–43.1 kg ha^{-1}, respectively. The yield gap between farms scored 11.8 t ha^{-1}, while that fertilized according to SSNM was only 5.40 t ha^{-1} and pineapple yield climbed to 22.9–44.9 %. The new fertilizer formula was suitable for growing pineapple in acid-sulfate soil in Vi Thanh city and Long My district and was promising to be applied in other places sharing similar soil features around the world to expand the pineapple yield and diminish the chemical fertilizer used. Thereby, the environment is conserved, and the profit of farmers is improved. This should contribute to the global sustainable agriculture.

Data availability statement

Data will be made available on request.

CRediT authorship contribution statement

Nguyen Quoc Khuong: Writing – original draft, Methodology, Conceptualization. **Nguyen Minh Phung:** Methodology, Investigation, Formal analysis, Conceptualization. **Le Thanh Quang:** Writing – review & editing, Methodology, Formal analysis, Conceptualization. **Phan Chi Nguyen:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of competing interest

Nguyen Quoc Khuong reports financial support was provided by Hau Giang Department of Science and Technology. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e25541.

References

[1] W. Palachum, W. Choorit, Y. Chisti, Nutritionally enhanced probioticated whole pineapple juice, Fermentation 7 (3) (2021) 178, https://doi.org/10.3390/fermentation7030178.
[2] F.M.C. Gamarra, J.C. Santana, S.A. Llanos, J.A.H. Pérez, F.R. Flausino, A.P. Quispe, E.B. Tambourgi, High retention and purification of bromelain enzyme (*Ananas comosus* L. Merrill) from pineapple juice using plain and hollow polymeric membranes techniques, Polymers 14 (2) (2022) 264, https://doi.org/10.3390/polym14020264.
[3] Food and Agriculture Organization of the United Nations (FAOSTAT). http://www.fao.org/faostat, 2022. (Accessed 10 May 2022).
[4] T.T. Hien, T.B. Long, N. Van Muoi, T.T. Truc, Effect of pretreatment on quality of frozen Cau Duc pineapple (*Ananas comosus*), Mater. Today: Proc. 57 (2022) 447–453, https://doi.org/10.1016/j.matpr.2022.01.070.
[5] H.H. Loc, D. Van Binh, E. Park, S. Shrestha, T.D. Dung, V.H. Son, N.H.T. Truc, N.P. Mai, C. Seijger, Intensifying saline water intrusion and drought in the Mekong Delta: from physical evidence to policy outlooks, Sci. Total Environ. 757 (2021) 143919, https://doi.org/10.1016/j.scitotenv.2020.143919.

[6] N.Q. Khuong, D. Kantachote, J. Onthong, A. Sukhoom, The potential of acid-resistant purple nonsulfur bacteria isolated from acid sulfate soils for reducing toxicity of Al^{3+} and Fe^{2+} using biosorption for agricultural application, Biocatal. Agric. Biotechnol. 12 (2017) 329–340, https://doi.org/10.1016/j.bcab.2017.10.022.
[7] C. Xu, Interactions between Coastal Acid Sulfate Soils and Greenhouse Gas Generation Potential (Doctoral Dissertation, Monash University), 2021.
[8] L.W. Morton, N.K. Nguyen, M.S. Demyan, Salinity and acid sulfate soils of the Vietnam Mekong Delta: agricultural management and adaptation, J. Soil Water Conserv. 78 (4) (2023) 85A–92A, https://doi.org/10.2489/jswc.2023.0321A.
[9] V.Q. Minh, P.T. Vu, L.V. Khoa, T.T. Du, L.Q. Tri, T.V. Dung, Major land uses on acid sulfate soils of Hau Giang province, Vietnam, Int. J. Environ. Agric. Biotechnol. 5 (1) (2020) 192–196, https://doi.org/10.22161/ijeab.51.27.
[10] V. Estévez, S. Mattbäck, A. Boman, A. Beucher, K.M. Björk, P. Österholm, Improving prediction accuracy for acid sulfate soil mapping by means of variable selection, Front. Environ. Sci. 11 (2023) 1213069, https://doi.org/10.3389/fenvs.2023.1213069.
[11] C.M. VanZomeren, J.F. Berkowitz, C.D. Piercy, J.K. King, Acid Sulfate Soils in Coastal Environments: a Review of Basic Concepts and Implications for Restoration, Environmental Laboratory (U.S.), 2020, https://doi.org/10.21079/11681/38240.
[12] D. Neina, The role of soil pH in plant nutrition and soil remediation, Appl. Environ. Soil Sci. 2019 (2019) 5794869, https://doi.org/10.1155/2019/5794869.
[13] E. Hanyabui, Effect of Pineapple Waste Biochar and Compost Application on Pineapple Yield and Quality in a Low Nutrient Coastal Savanna Acrisol, Doctoral dissertation, University of Cape Coast), 2020.
[14] J.C. Neri, J.B. Meléndez Mori, N.C. Vilca Valqui, E. Huaman Huaman, R. Collazos Silva, M. Oliva, Effect of planting density on the agronomic performance and fruit quality of three pineapple cultivars (*Ananas comosus* L. Merr.), Int. J. Agron. 2021 (2021) 5559564, https://doi.org/10.1155/2021/5559564.
[15] N.T.N. Hang, Planting density and flowering inducement agents effect on flowering and productivity of MD2 pineapple variety cultivation on acid sulfate soil in Tien Giang province, Vietnam, South Asian, J. Agric. Sci. 3 (1) (2023) 155–158.
[16] W. Annisa, A. Susilawati, A. Jumberi, Response of pineapple on organic fertilizer and potassium on acid sulphate soil, Agroscientiae 20 (1) (2013) 37–40.
[17] V.M. Maia, R.F. Pegoraro, I. Aspiazú, F.S. Oliveira, D.A.C. Nobre, Diagnosis and management of nutrient constraints in pineapple, in: A.K. Srivastava, L. A. Chengxiao Hu (Eds.), Fruit Crops, Elsevier, 2020, pp. 739–760, https://doi.org/10.1016/B978-0-12-818732-6.00050-2.
[18] M. Mahmud, R. Abdullah, J.S. Yaacob, Effect of vermicompost on growth, plant nutrient uptake and bioactivity of ex vitro pineapple (*Ananas comosus* var. MD2), Agronomy 10 (9) (2020) 1333, https://doi.org/10.3390/agronomy10091333.
[19] Z. Liang, X. Jin, P. Zhai, Y. Zhao, J. Cai, S. Li, C. Li, Combination of organic fertilizer and slow-release fertilizer increases pineapple yields, agronomic efficiency and reduces greenhouse gas emissions under reduced fertilization conditions in tropical areas, J. Clean. Prod. 343 (2022) 131054, https://doi.org/10.1016/j.jclepro.2022.131054.
[20] I. Zewide, W. Melash, Review on macronutrient in agronomy crops, Nutr. Food Process. 4 (6) (2021) 62, https://doi.org/10.31579/2637-8914/062.
[21] W. Li, M. Yang, J. Wang, Z. Wang, Z. Fan, F. Kang, Y. Zhang, Agronomic responses of major fruit crops to fertilization in China: a meta-analysis, Agronomy 10 (1) (2020) 15, https://doi.org/10.3390/agronomy10010015.
[22] T.K. Nakade, O.D. Kuchanwar, A.K. Srivastava, M.R. Pandao, U. Thawale, Effect of integrated nutrient management on growth, yield and fertility status of soil after harvest of Nagpur Mandarin, J. Pharmacogn. Phytochem. 10 (1) (2021) 1117–1120.
[23] P. Chivenge, S. Zingore, K.S. Ezui, S. Njoroge, M.A. Bunquin, A. Dobermann, K. Saito, Progress in research on site-specific nutrient management for smallholder farmers in sub-Saharan Africa, Field Crops Res. 281 (2022) 108503, https://doi.org/10.1016/j.fcr.2022.108503.
[24] S. Sukyankij, S. Sukyankij, T. T. Panich-pat, Effect of co-fertilizer application and dolomite amendments on yield and grain quality of rice grown on post-active acid sulfate soil, Agri: J. Agric. Sci. 45 (2) (2023) 311–321, https://doi.org/10.17503/agrivita.v45i2.4079.
[25] K. Khechba, A. Laamrani, D. Dhiba, K. Misbah, A. Chehbouni, Monitoring and analyzing yield gap in Africa through soil attribute best management using remote sensing approaches: a review, Rem. Sens. 13 (22) (2021) 4602, https://doi.org/10.3390/rs13224602.
[26] L.V. Be, L.V. Hoa, Comparing growth and fruit weight of Queen pineapple between sucker material and micropropagation virus-free shoot, Can Tho Univ. J. Sci. 11 (2009) 159–167.
[27] D.L. Sparks, A.L. Page, P.A. Helmke, R.H. Loeppert, P.N. Soltanpour, M.A. Tabatabai, C.T. Johnston, M.E. Sumner (Eds.), Methods of Soil Analysis. Part 3-Chemical Methods. SSSA Book Ser. 5.3., SSSA, ASA, Madison, WI, 1996, https://doi.org/10.2136/sssabookser5.30.
[28] J. Choi, X. Yang, Asymptotic properties of correlation-based principal component analysis, J. Econom. 229 (1) (2022) 1–18, https://doi.org/10.1016/j.jeconom.2021.08.003.
[29] J.M. Cunha, M.S.M. Freitas, L.C.S. Caetano, A.J.C.D. Carvalho, D.A. Peçanha, P.C.D. Santos, Fruit quality of pineapple 'Vitória' under macronutrients and boron deficiency, Rev. Bras. Frutic. 41 (2019) 1–9, https://doi.org/10.1590/0100-29452019080.
[30] M. Tewodros, S. Mesfin, W. Getachew, A. Ashenafi, S. Neim, Effect of inorganic N and P fertilizers on fruit yield and yield components of pineapple (*Annanas comosus* Merr L. Var. Smooth Cayanne) at Jimma, Southwest Ethiopia, Agrotechnology 7 (178) (2018) 2, https://doi.org/10.4172/2168-9881.1000178.
[31] G.O. Guerrant, M.A. Lambert, C.W. Moss, Analysis of short-chain acids from anaerobic bacteria by high-performance liquid chromatography, J. Clin. Microbiol. 16 (2) (1982) 355–360, https://doi.org/10.1128/jcm.16.2.355-360.1982.
[32] AOAC, Official Methods of Analysis of the Association of Official Analytical Chemists, fifteenth ed., Arlington VA, Association of Official Analytical Chemists, 1990, pp. 1058–1059.
[33] V.J.G. Houba, I. Novozamsky, E.J.M. Temminghof, Soil and Plant Analysis, Part 5, Department of Soil Science and Plant Nutrition, Wageningen Agricultural University, The Netherlands, 1997.
[34] A.K. Srivastava, S.N. Das, S.K. Malhotra, K. Majumdar, SSNM-based rationale of fertilizer use in perennial crops: a review, Indian J. Agric. Sci. 84 (1) (2014) 3–17.
[35] D.G.P. Rodriguez, An assessment of the site-specific nutrient management (SSNM) strategy for irrigated rice in Asia, Agriculture 10 (11) (2020) 559, https://doi.org/10.3390/agriculture10110559.
[36] R. Nova, R.S. Loomis, Nitrogen and plant production, Plant Soil 58 (1) (1981) 177–204, https://doi.org/10.1007/BF02180053.
[37] J.M. Pasuquin, M.F. Pampolino, C. Witt, A. Dobermann, T. Oberthür, M.J. Fisher, K. Inubushi, Closing yield gaps in maize production in Southeast Asia through site-specific nutrient management, Field Crops Res. 156 (2014) 219–230, https://doi.org/10.1016/j.fcr.2013.11.016.
[38] D.A. Horneck, D.M. Sullivan, J.S. Owen, J.M. Hart, Soil Test Interpretation Guide, EC 1478, OR, Oregon State University Extension Service, Corvallis, 2011, pp. 1–12.
[39] Y.B. Dibabe, A.M. Taddesse, E. Teju, Y. Bogale, Hydrous Fe-Al-Zr oxide composite filled dialysis membrane tubes for phosphate desorption study from acidic soils, Environ. Nanotechnol. Monit. Manag. 18 (2022) 100723, https://doi.org/10.1016/j.enmm.2022.100723.
[40] K.T. Osman, Acid soils and acid sulfate soils, in: Management of Soil Problems, Springer, Cham, 2018, pp. 299–332, https://doi.org/10.1007/978-3-319-75527-4_11.
[41] N.A. Taliman, Q. Dong, K. Echigo, V. Raboy, H. Saneoka, Effect of phosphorus fertilization on the growth, photosynthesis, nitrogen fixation, mineral accumulation, seed yield, and seed quality of a soybean low-phytate line, Plants 8 (5) (2019) 119.
[42] J.A. Pietri, P.C. Brookes, Nitrogen mineralisation along a pH gradient of a silty loam UK soil. Soil Biol. Biochem. 40 (3) 797-802. https://doi.org/10.1016/j.soilbio.2007.10.014..
[43] L.D.S. Souza, D.H. Reinhardt, Pineapple, L.A. Crisóstomo, A. Naumov, A.E. Johnston (Eds.), Fertilizing for High Yield and Quality Tropical Fruits of Brazil, International Potash Institute, Horgen, 2007, pp. 179–201.
[44] M.N. Zubir, N.S.M. Sam, N.S.A. Ghani, A.A. Ismail, Growth performance of pineapple (*Ananas comosus* var. MD2) with different application of granular fertilizer on tropical peat soil, Inter. J. Agric. For. Plant. 10 (2020) 89–95.
[45] M.A. Haque, S.Z. Sakimin, P. Ding, N.M. Jaafar, M.K. Yusop, B.C. Sarker, Foliar urea with N-(n-butyl) thiophosphoric triamide for sustainable yield and quality of pineapple in a controlled environment, Sustainability 13 (12) (2021) 6880, https://doi.org/10.3390/su13126880.
[46] S.D. Hiwale, A.B. Chorey, M.R. Deshmukh, Balanced crop nutrition to optimized productivity and quality of safflower under rainfed condition, in: Advances in Agricultural and Horticultural Sciences, 2022, p. 125.

[47] U.P. Shahi, V.K. Singh, A. Kumar, P.K. Upadhyay, P.K. Rai, Site-specific nutrient management: impact on productivity, nutrient uptake and economics of rice-wheat system, Indian J. Agric. Sci. 92 (2022) 195–198, https://doi.org/10.56093/ijas.v92i2.122214.
[48] K. Prabhakar, K. Venkataramanamma, B.V.R.P. Reddy, Y.S. Kumar, K. Ramesh, R. Narasimhulu, K.S. Badu, K.A. Kumar, N.C. Venkateswarlu, The effect of site specific nutrient management (SSNM) on sunflower production, Int. J. Plant Soil Sci. 35 (20) (2023) 753–762, https://doi.org/10.9734/ijpss/2023/v35i203862.
[49] J. Chen, H. Zeng, X. Zhang, Integrative transcriptomic and metabolomic analysis of D-leaf of seven pineapple varieties differing in NPK% contents, BMC Plant Biol. 21 (1) (2021) 1–19, https://doi.org/10.1186/s12870-021-03291-0.
[50] H. Liu, Z. Hao, Y. Yuan, C. Li, J. Zhang, Application of mineral phosphorus fertilizer influences rhizosphere chemical and biological characteristics, Arch. Agron Soil Sci. 69 (5) (2022) 771–784, https://doi.org/10.1080/03650340.2022.2034792.
[51] J.M. Cunha, M.S.M. Freitas, A.J.C.D. Carvalho, L.C.S. Caetano, L.P. Pinto, D.A. Peçanha, P.C. dos Santos, Foliar content and visual symptoms of nutritional deficiency in pineapple 'Vitória', J. Plant Nutr. 44 (5) (2021) 660–672, https://doi.org/10.1080/01904167.2020.1849297.