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Research Article

Influence of Tropical Climate Parameters on Properties of Acid Sulfate Soils for Sustainable Oil Palm Cultivation

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To promote effective oil palm plantation and environmental sustainability, this research assessed influence of climatic parameters on physicochemical properties of Thai acid sulfate soils (ASSs). ASSs under oil palm planting areas (Topsoil: Ap, Subsoil-1: Ap-60 cm, Subsoil-2: 60–100 cm, and Rootzone: sum of the three depth levels) and historical climate data in tropical savanna and tropical monsoon were investigated. Stepwise approach of multiple regression analysis from component defining variable of principal component analysis revealed that, in tropical savanna, daily solar radiation influenced clay content ($p < 0.05$) in Topsoil, cation exchange capacity ($p < 0.05$) in Subsoil-1, soil pH by water ($p < 0.01$) in Subsoil-2, and silt content ($p < 0.001$) in Rootzone. In tropical monsoon, daily solar radiation influenced exchangeable magnesium ($p < 0.01$) in Subsoil-2, and exchangeable sodium ($p < 0.01$) and silt content ($p < 0.01$) in Rootzone. We concluded that daily solar radiation is the most influential climatic parameter on soil properties due to the transport of heat in soils, whereas particle size distribution is mostly influenced by climatic parameters due to their clay and silt fractions. OPP in ASSs under these climates should include management of water usage by using raised beds with irrigation canals, considering the rooting depth and depth of acidic horizon before applying fertilizer or amendment and liming along with integrated organic material management to raise soil pH.

1. Introduction

Oil palm (*Elaeis guineensis Jacq.*) is a native of Central Africa, but it can thrive successfully as a commercial crop in tropical lowland areas [1], and it has been considered as the most efficient oilseed crop in the world [2]. In addition, the global market of biodiesel and aviation biofuel has been increasing continually that creates opportunities in Southeast Asia, including Thailand to be major producers, consumers, and exporters [3]. Unfortunately, a plan in Thailand to extend oil palm planting areas in the Southern and Eastern regions for alternative energy was restricted because most area has already been used under productive agriculture [4]. Regarding this, the Land Development Department of Thailand had proposed the main target planting area which was not under productive agriculture [5].

Acid sulfate soils (ASSs) are mostly formed in coastal plains in the tropics and generally less in the temperate zones [6]. The soils are found in South Asia, Southeast Asia, and East Asia of the Tropics [7] with the larger part in Indonesia, Thailand, and Vietnam [8]. Thai ASSs are widespread in some parts of country, especially in the Central Plain (CP) with other small areas in the Southeast Coast (SC) and peninsular regions [9].

Acid sulfate soils have been posing problems for crop production management because of their severe acidity. These soils affect oil palm yields by depth of acidic horizon where it occurs within 60 centimeters of soil surface [6, 10]. Nevertheless, oil palm is moderately tolerant to soil acidity and can be grown on ASS under proper management practices [11] which consider parameters affecting growth performance [12].

The Department of Alternative Energy Development and Efficiency of Thailand estimated the potential ability of palm oil for biodiesel production at 14 million liters per day in 2036 [13]. The planting areas have been expanding into the northern and northeastern regions [14] even though these regions were never planted in the past due to their low climate suitability that requires an intensive treatment and irrigation supply [15]. These lead to high greenhouse gas emissions and water scarcity footprint per ton of fresh fruit bunch (FFB) products [15]. Oil palm plantation areas are somewhat limited by climatic conditions [15, 16], especially oil palm in ASS can be affected by droughts in an El Nino year. The yields are reduced due to severe acidity from low water level [17]. Therefore, improving oil palm productivity should take into consideration the control and management of climatic parameters [18]. However, it is difficult to determine climatic limitations in different regions or countries by comparing the FFB yields because many other parameters may influence this comparison [17]. The main climatic elements affecting growth and yield of oil palms are temperature, solar radiation intensity and duration, rainfall, atmospheric vapor pressure deficit, evaporation rate, and wind speed [19, 20].

The suitability of soil and climate combinations for oil palm development can be calculated by using Surre [21] method [22] which has been continuously used in oil palm industry to calculate water deficit [23–25]. Seasonal water deficit is considered as the most important climatic parameter affecting oil palm yields [17]. The yields will be lost about 10% for every 100 mm increase in water deficit [26] and 20% if it exists for 3 years continually [27]. The FFB yield will be reduced between 10% and 20% by water deficit depending on each soil's quality [23, 28]. Therefore, the promotion for expanding oil palm planting areas must consider environmental sustainability based on suitability of land and climate along with good practices for productivity improvement [15]. In addition, the rooting depth should be at least 100 cm as it is important for nutrition, water uptake, and anchoring in the ground [17]. To support the increasing demand and consider environmental sustainability, there is a need to analyze the suitability of climate and ASS and their influence in CP and SC so as to devise an efficient plan for sustainable oil palm cultivation in tropical setting including Thailand.

2. Materials and Methods

2.1. Soil Sampling. Twenty study sites of ASS under oil palm planting areas in CP (10 sites) and SC (10 sites) of Thailand were examined (Table 1 and Figure 1). These soils have developed under tropical savanna and tropical monsoon climates, respectively. The soils in CP were classified by soil taxonomy [29] as Typic Sulfaquepts and Sulfic Endoaquepts, whereas the soils in SC were classified as Typic Sulfaquepts. These soils in both CP and SC were classified by World Reference Base [30] as Thionic Gleysols. The soils were collected during September and October in 2013 by hand auger to a maximum depth of 100 cm consisting of Topsoil (Ap), Subsoil-1 (Ap–60 cm), and Subsoil-2 (60–100 cm), whereas Rootzone (0–100 cm) was the sum of the three depth levels. The Topsoil depth varies in the range of 18–30 cm in CP and 14–26 cm in SC. In order to minimize oxidation of sulfidic materials, soil samples were kept in sealed plastic bags and cooled to 4°C in an ice container during transportation from field to laboratory.

2.2. Climatic Data. Historical climate data downloaded from the "WorldClim version 2" database (http://www.worldclim.org/version2) [31] for the period 1970–2000 consist of monthly minimum temperature, maximum temperature, mean temperature, precipitation, solar radiation, wind speed, and water vapor pressure. The spatial resolutions with 30 seconds (~1 km^2) containing 12 GeoTiff files, one for each month of the year, were used in this study.

2.3. Soil Analysis. Physicochemical properties of soil samples were determined for field-moist conditions but are reported on an oven-dried (105°C) basis. The methods of physicochemical analysis are summarized in Table 2.

2.4. Data Analysis. Monthly potential evapotranspiration (ETP) was calculated based on Hargreaves and Semani [43] equation following Läderach et al. [44]:

$$\mathrm{ETP} = 0.0023 \times R_a \times (T - t)^{0.5} \times (t_m + 17.8), \tag{1}$$

where ETP = evapotranspiration (mm·day^{-1}), R_a = extraterrestrial solar radiation expressed in water equivalent (mm·day^{-1}), $T - t$ = different between monthly maximum and minimum mean temperature (°C), and t_m = mean air temperature (°C). R_a was converted into water equivalent (mm·day^{-1}) with 1 mm·day^{-1} = 2.45 MJ·m^{-2}·day^{-1} [45].

ETP was converted to monthly water balance (B) based on the Surre (1968) equation by following Rhebergen et al. [25]:

$$B = S_{\mathrm{res}} + \mathrm{PPT_m} - \mathrm{ETP}, \tag{2}$$

where B = monthly water balance (mm), S_{res} = residual soil water from previous month (mm), $\mathrm{PPT_m}$ = monthly precipitation (mm), and ETP = monthly potential evapotranspiration (mm).

Available water capacity (AWC) for each soil texture class (Topsoil, Subsoil-1, and Subsoil-2) was calculated based on the Epebinu and Nwadialo equation [33]:

$$\mathrm{AWC} = 0.93 + 0.54S + 0.13C, \tag{3}$$

where S = silt (%) and C = clay (%). The sum of AWC was the maximum amount of available soil water in the top 100 cm. The excess of water was assumed to be lost as drainage or runoff; water deficit was indicated by the negative values of B' S_{res} of the following month was set to zero; S_{res} was set to the maximum (total possible AWC) if it was greater than the sum of AWC, the sum of all negative monthly water balances was annual water deficit [25].

Table 1: Site descriptions of acid sulfate soils under oil palm planting areas in Central Plain and Southeast Coast.

ID	Region[a]	Province	Elevation (m) MSL[b]	Soil series[c]	Latitude, longitude
1	CP	Pathum Thani	4	Ok	14.16516, 100.78867
2	CP	Saraburi	5	Rs	14.25838, 100.85240
3	CP	Nakhon Nayok	5	Rs-a	14.25973, 100.96311
4	CP	Nakhon Nayok	3	Rs-a	14.25081, 100.96831
5	CP	Nakhon Nayok	3	Rs-a	14.24884, 100.96704
6	CP	Saraburi	4	Rs-a	14.26024, 100.90631
7	CP	Saraburi	5	Rs-a	14.26008, 100.91031
8	CP	Nakhon Nayok	7	Rs-a	14.27255, 100.96386
9	CP	Nakhon Nayok	6	Rs-a	14.28120, 100.97413
10	CP	Nakhon Nayok	4	Rs-a	14.28188, 100.96186
11	SC	Chanthaburi	11	Ca	12.75267, 101.86470
12	SC	Chanthaburi	4	Ca	12.61623, 101.93433
13	SC	Chanthaburi	4	Ca	12.61759, 101.93652
14	SC	Chanthaburi	2	Ca	12.63581, 101.94968
15	SC	Chanthaburi	3	Ca	12.62373, 101.96834
16	SC	Chanthaburi	2	Ca	12.45328, 102.21149
17	SC	Chanthaburi	1	Ca	12.42625, 102.27559
18	SC	Chanthaburi	2	Ca	12.42857, 102.27592
19	SC	Chanthaburi	4	Ca	12.39205, 102.35682
20	SC	Chanthaburi	3	Ca	12.39916, 102.29920

[a]CP = Central Plain; SC = Southeast Coast. [b]MSL = mean sea level. [c]Ok = Ongkharak series, Rs = Rangsit series, Rs-a = Rangsit series-very acid phase, and Ca = Cha-am series.

2.5. Climate and Soil Suitability Evaluation for Oil Palm. We used climatic suitability classification of Goh [19], water deficit suitability classification of Rhebergen et al. [25], and ideal climate requirement of Hartley [46] to evaluate climatic suitability (Table 3). Also, we used soil limitation of Shamshuddin et al. [47] and soil nutrient status of Goh [48] to evaluate soil suitability (Table 4).

2.6. Statistical Analysis. The climate and ASS data were analyzed by using principal components analysis (PCA) and multiple regression analysis (MRA) from SPSS (version 24) for Windows. The PCA was performed to reduce the set of climate and soil variables; component defining variable (CDV) selected the variables with the highest principal component loading from the rotated principal components, and stepwise approach of MRA determined the relative effects of climatic parameters on physicochemical properties of ASSs.

3. Results

3.1. Climatic Parameters. The climatic parameters of CP and SC are shown in Table 5. Climate suitability for sustainable oil palm was considered by climatic suitability classification of Goh [19]. Figure 2 shows the climatic conditions of CP and SC classified as currently unsuitable and suitable annual precipitations, highly suitable annual mean temperatures, suitable daily solar radiations, and highly suitable annual wind speeds, respectively. Also, by water deficit suitability classification of Rhebergen et al. [25], Figure 3(a) shows CP is favorable, while SC is optimal. In addition, Figure 3(b) shows CP and SC are in the ranges of ideal climate requirement of Hartley [46] with their annual maxima temperatures and minima temperatures, respectively.

3.2. Physicochemical Properties of ASS. Physicochemical properties of ASS under oil palm planting areas in CP and SC are shown in Tables 6 and 7. The median $pH_{1:1}$-H_2O (soil pH by water) of CP are low at all depth levels, whereas the median $pH_{1:1}$-H_2O of SC are low but slightly increased with depth from Topsoil to Subsoil-2 (Table 7). The median TN (total nitrogen) of CP are high but slightly decreased with depth from Topsoil to Subsoil2, whereas the median TN of SC are high and slightly increased with depth from Topsoil to Subsoil2 (Table 7). The median Avail-P (available phosphorus) of CP are high in Topsoil but low in Subsoil1 and Subsoil2, whereas the median Avail-P of SC are low at all depth levels (Table 7). The median Exch-K (exchangeable potassium) of CP are high at all depth levels, whereas the median Exch-K of SC are low but slightly increased with depth from Topsoil to Subsoil2 (Table 7). The median Exch-Mg (exchangeable magnesium) of CP are high at all depth levels, whereas the median Exch-Mg of SC are high and slightly increased with depth from Topsoil to Subsoil2 (Table 7).

3.3. Result of PCA on Climatic Parameters. The result of PCA based on the correlation matrix analysis with Varimax rotation indicated 2 principal components (PCs) with the extraction of eigenvalues greater than 1 of CP and SC (Table S1). The extracted components had overall cumulative variances about 88.3% and 90.1%, respectively, based on the significant variables which factor loading ≥0.7 and the concept of CDV which selected the highest component loading of each principal component. The result indicated the main climate parameters that influence the physicochemical properties of ASSs (Table S1). The main climatic parameters of CP were daily solar radiation and annual water deficit, while those for SC were annual water vapor

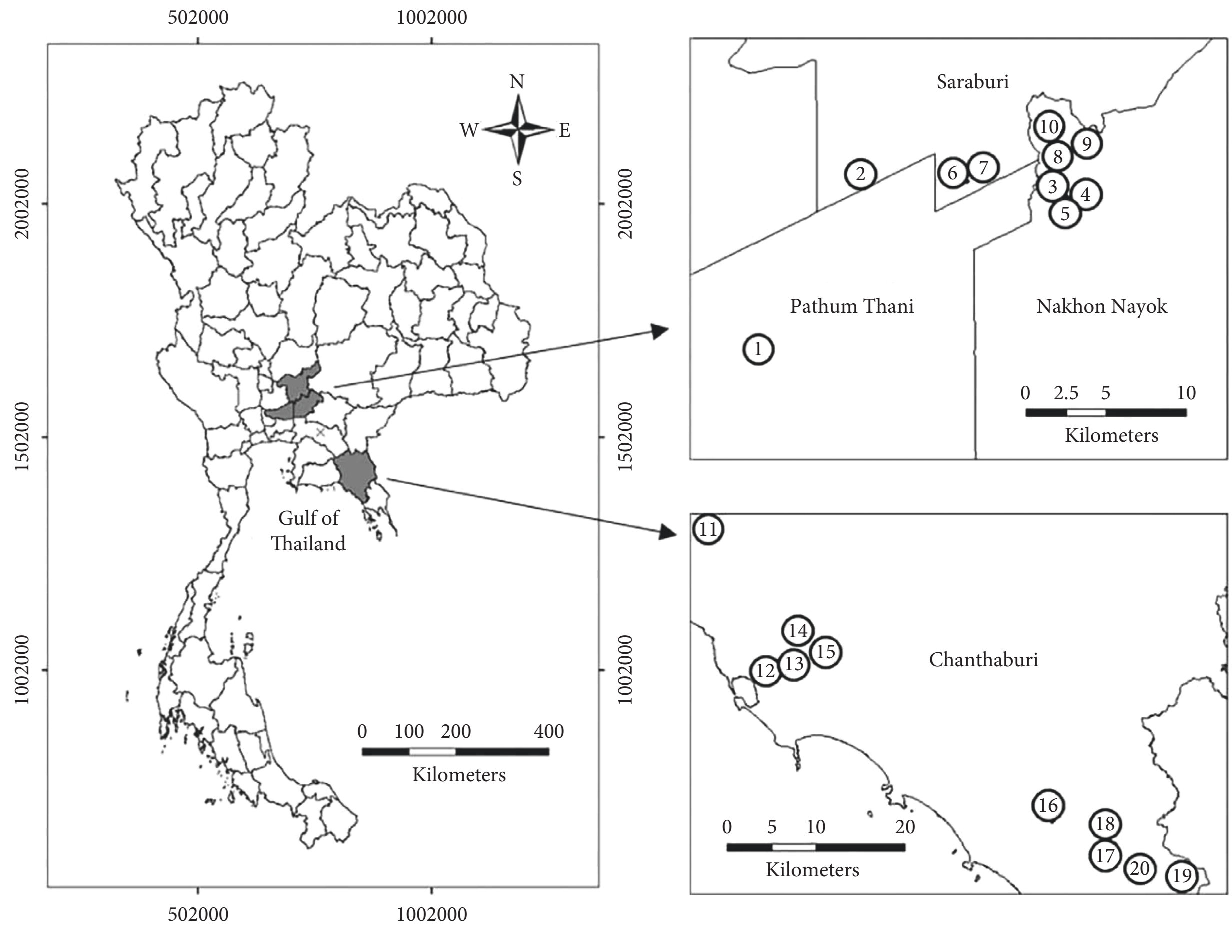

Figure 1: Sampling locations of acid sulfate soils under oil palm planting areas in Central Plain (ID 1–10) and Southeast Coast (ID 11–20) regions, Thailand.

pressure, annual minimum temperature, and daily solar radiation (the values of annual water vapor pressure and annual minimum temperature were equal).

3.4. Results of PCA on Physicochemical Properties of ASSs. Likewise, the PCA results of CP and SC had overall cumulative variances of the extracted components of Topsoil about 90.4% and 95.4%, Subsoil-1 about 93.0% and 95.6%, Subsoil-2 about 91.3% and 92.6%, and Rootzone about 90.7% and 90.4%, respectively. The CDV results indicated the main soil properties of each area. The Topsoil of CP were Exch-Ca (exchangeable calcium), clay content, CEC, and Acid-BC (acid buffering capacity), while the Topsoil of SC were Extr-SO_4^{2-} (extractable sulfate), Exch-K, silt content, clay content, and Exch-Ca (Table S2). The Subsoil-1 of CP were Exch-Ca, CEC, Exch-Na (exchangeable sodium), $pH_{1:1}$-H_2O_2 (soil pH by hydrogen peroxide), and EC, while the Subsoil-1 of SC were Acid-BC, Exch-Na, Avail-P, silt content, and clay content (Table S3). The Subsoil-2 of CP were $pH_{1:1}$-H_2O, TN, Exch-Mg, Extr-SO_4^{2-}, and sand content, while the Subsoil-2 of SC were Exch-Mg, AWC, Acid-BC, Avail-P, and EA (Table S4). The Rootzone of CP were Exch-Ca, TN, silt content, EC, sand content, and Acid-BC, while the Rootzone of SC were Acid-BC, Exch-Na, silt content, clay content, Avail-P, and TN (Table S5).

3.5. Influence of Climate on Physicochemical Properties of ASSs. Stepwise MRA was used to select variables of climatic parameters and physicochemical properties from CDV results in order to determine the effects of climatic parameters on physicochemical properties of ASS under oil palm planting areas in CP and SC (Table 8).

In CP, the results showed (i) clay content ($F = 5.46$, $p < 0.05$) in Topsoil, CEC ($F = 9.58$, $p < 0.05$) in Subsoil-1, $pH_{1:1}$-H_2O ($F = 12.79$, $p < 0.01$) in Subsoil-2, and silt content ($F = 31.59$, $p < 0.001$) in Rootzone, were significantly influenced by daily solar radiation; (ii) Acid-BC in Rootzone was significantly influenced by annual water deficit. In other words, (i) daily solar radiation accounted for 33% of clay content in Topsoil, 49% of CEC in Subsoil-1, 57% of $pH_{1:1}$-H_2O in Subsoil-2, and 51% of silt content in Rootzone; (ii) annual water deficit accounted for 11% of Acid-BC in Rootzone.

In SC, the results showed (i) clay content ($F = 8.55$, $p < 0.05$) in Topsoil, AWC ($F = 7.75$, $p < 0.05$) in Subsoil-2 and clay content ($F = 28.23$, $p < 0.001$) in Rootzone were

Table 2: Method of soil analyses.

No.	Analysis	Method	Reference
Physical analysis			
1	Particle size analysis (sand, silt, and clay)	Pipette method	Kilmer and Alexander [32]
2	Available water capacity (AWC)	0.93 + 0.54 silt + 0.13 clay	Epebinu and Nwadialo [33]
Chemical analysis			
3	Soil pH ($pH_{1:1}$-H_2O and $pH_{1:1}$-H_2O_2)	1 : 1 soil to solution in H_2O and 6% H_2O_2	National Soil Survey Center [34]
4	Electrical conductivity (EC)	Extract of saturated soil to water	National Soil Survey Center [34]
5	Organic carbon (OC)	Walkley and Black method	Nelson and Sommers [35]
6	Total nitrogen (TN)	Kjeldahl method	Bremner [36]
7	pH buffering capacity (Acid-BC and Base-BC)	Acid-base titration	Natscher and Schwertmann [37]
8	Cation exchange capacity (CEC)	Saturating the exchange site and displacing by 1 M NH_4OAc	Chapman [38]
9	Exchangeable bases (Exch-Ca, Exch-Mg, Exch-K, and Exch-Na)	1 M NH_4OAc at pH 7 extraction	Thomas [39]
10	Extractable acidity (EA)	Barium chloride-triethanolamine at pH 8.2 extraction	Peech [40]
11	Available phosphorus (Avail-P)	Bray II method	Bray and Kurtz [41]
12	Available potassium (Avail-K)	1 M NH_4OAc at pH 7.0 extraction	National Soil Survey Center [34]
13	Extractable aluminum (Extr-Al)	1 M KCl extraction	National Soil Survey Center [34]
14	Base saturation percentage (BSP)	The sum of bases extracted by NH_4OAc at pH 7.0, divided by CEC, and multiplied by 100	National Soil Survey Center [34]
15	Extractable sulfate (Extr-SO_4^{2-})	0.008 M $Ca(H_2PO4)_2 \bullet H_2O$ extraction	Combs et al. [42]

Table 3: Climatic suitability evaluation for oil palm.

Climatic suitability classification[a] (Goh [19])<	Highly suitable	Suitable	Moderately suitable	Currently unsuitable	Permanently unsuitable
PPT (mm $year^{-1}$)	2000–2500	1700–2000, 2500–3000	1400–1700, 3000–4000	1100–1400, 4000–5000	>5000
MeanT (°C)	26–29	23–26, 29–32	20–23, 32–34	17–20, 34–36	<20, >30
SR ($MJ \cdot m^{-2}$)	16–17	14–16, 17–19	11–14, 19–21	8–11, 21–23	<8
WS ($m \cdot s^{-1}$)	<10	10–15, 14–16	11–14, 15–25	8–11, 25–40	>40
Water deficit suitability classification[b] (Rhebergen et al. [25])	Optimal	Favorable	Suitable	Unsuitable	
WD (mm)	<150	<250	<400	>400	
Ideal climate requirement[c] (Hartley [46])	Range				
MaxT (°C)	29–33				
MinT (°C)	22–24				

[a]PPT = annual precipitation; MeanT = annual mean temperature; SR = daily solar radiation; WS = annual wind speed. [b]WD = annual water deficit. [c]MaxT = annual maximum temperature; MinT = annual minimum temperature.

Table 4: Soil suitability evaluation for oil palm.

Soil limitation (Shamshuddin et al. [47])	Desirable range	Minor limitation	Serious limitation	Very serious	
Soil pH	>4.0	3.5–4.0	3.0–3.5	<3.0	
Soil nutrient status[a] (Goh [48])	Very low	Low	Moderate	High	Very high
TN ($g \cdot kg^{-1}$)	<0.8	0.8–1.2	1.2–1.5	1.5–2.5	>2.5
Avail-P ($mg \cdot kg^{-1}$)	<10	10–25	25–40	40–60	>60
Exch-K ($cmol_c \cdot kg^{-1}$)	<0.08	0.08–0.20	0.20–0.25	0.25–0.30	>0.30
Exch-Mg ($cmol_c \cdot kg^{-1}$)	<0.08	0.08–0.20	0.20–0.25	0.25–0.30	>0.30

[a]TN = total nitrogen; Avail = available; Exch = exchangeable.

significantly influenced by annual minimum temperature; (ii) clay content ($F = 7.29$, $p < 0.01$) in Subsoil-1 and Acid-BC ($F = 6.53$, $p < 0.05$) in Rootzone were significantly influenced by annual water vapor pressure; (iii) Exch-Mg ($F = 20.30$, $p < 0.01$) in Subsoil-2 and Exch-Na ($F = 10.05$, $p < 0.01$) and silt content ($F = 7.85$, $p < 0.01$) in Rootzone

Table 5: Climate parameters of Central Plain and Southeast Coast.

Climate parameter[a] (Unit)	Central Plain Median (range)	Southeast Coast Median (range)
PPT (mm·year^{-1})	1255.50 (1171–1265)	2823.50 (2167–3245)
SR (MJ·m^{-2})	18.61 (16.73–21.48)	18.45 (15.86–21.55)
MeanT (°C)	27.70 (24.90–29.90)	27.44 (25.70–29.00)
MaxT (°C)	32.30 (29.60–34.20)	30.88 (28.80–32.50)
MinT (°C)	23.06 (19.90–25.60)	24.00 (21.50–26.10)
WVP (kPa)	2.69 (2.05–2.99)	2.86 (2.25–3.15)
WS (m·s^{-1})	1.04 (0.7–1.4)	2.23 (1.5–2.8)
ETP (mm·day^{-1})	2.41 (2.19–2.84)	2.04 (1.77–2.50)
WD (mm)	211.21 (195.10–222.51)	51.22 (9.82–89.73)

[a]PPT = annual precipitation; SR = daily solar radiation; MeanT = annual mean temperature; MaxT = annual maximum temperature; MinT = annual minimum temperature; WVP = annual water vapor pressure; WS = annual wind speed; ETP = evapotranspiration; WD = annual water deficit.

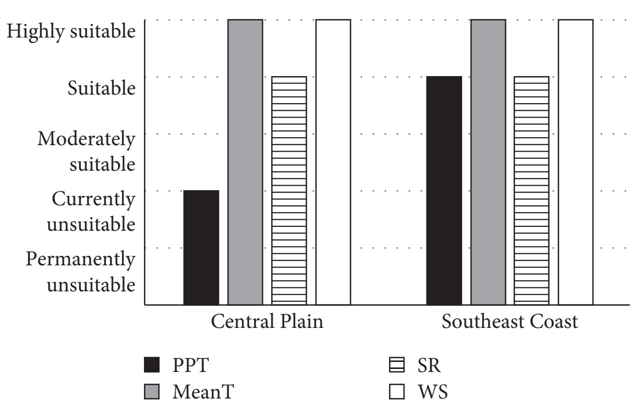

Figure 2: Climatic suitability classification (PPT = annual precipitation; MeanT = annual mean temperature; SR = daily solar radiation; WS = annual wind speed) for oil palm of acid sulfate soils under oil palm planting areas in Central Plain and Southeast Coast, Thailand.

were significantly influenced by daily solar radiation. These indicated that (i) annual minimum temperature accounted for 46% of clay content in Topsoil, 43% of AWC in Subsoil-2, and 48% of clay content in Rootzone; (ii) annual water vapor pressure accounted for 41% of clay content in Subsoil-1 and 16% of Acid-BC in Rootzone; (iii) daily solar radiation accounted for 68% of Exch-Mg in Subsoil-2, and 24% of Exch-Na and 19% of silt content in Rootzone.

4. Discussion

4.1. Suitability of Climate for Oil Palm. Due to the climatic suitability classification [19], oil palm yields in SC may decrease because the median annual precipitation (Table 5) is greater than 2,500 mm (Table 3). Too high continuous rains reduce the population of pollinating weevils and subsequently decrease the yields of oil palm because of more precipitation and associated cloudy conditions affecting less radiation can reach the surface [49]. Due to the climatic suitability classification [19] and water deficit suitability classification [25], oil palm plantation in CP should have to compensate precipitation rate and decrease water deficit because the median annual precipitation (Table 5) is lower than 2,000 mm (Table 3) and the median annual water deficit (Table 5) is greater than 150 mm (Table 3). In Ghana, a previous study by Rhebergen et al. [25] demonstrates that optimal areas (Table 3) for oil palm are in the south of the Western Region and a smaller area west of Koforidua in the Eastern Region which estimated at 580,000 ha or 2% of the total land areas.

It would be better for the oil palm growers in CP and SC to manage water by using raised beds with irrigation canals to compensate unsuitable precipitation and decrease water deficit in CP. This also include draining water excess before flooding, and controlling water table level carefully to prevent aluminum toxicity [12].

4.2. Suitability of ASSs for Oil Palm. In both CP and SC, their $pH_{1:1}$-H_2O_2 of Topsoil, Subsoil-1, and Subsoil-2 (Table 7) are extremely lower than their $pH_{1:1}$-H_2O because the lower $pH_{1:1}$-H_2O_2 values are caused by oxidation of iron sulfides [29, 50] and soil organic matter [51]. Hydrogen peroxide causes not only the oxidation of OM but also the degradation of clay minerals, especially 2 : 1 clay minerals [51]. Therefore, both ASS areas require soil pH adjustment so as to reduce aluminum toxicity affecting oil palm roots. In addition, considering the median of $pH_{1:1}$-H_2O in each depth level of CP and SC (Table 7) by soil limitation [48], their soil pH is not in the desirable range except Subsoil-2 and Rootzone of SC (Figure 4). As a result, the pH level should be increased to at least pH 4.3 [52] and not to exceed about pH 6.0, with optimal in the range of pH 5.0–5.5 [53] by liming at an appropriate rate and applying organic materials, especially green manure [54]. Liming improve soil conditions and increase oil palm yields in ASS [12], whereas pH neutralization is faster by sulfate reducing bacteria when adding high-organic carbon in anoxic condition [55, 56]. Besides, high acid buffering capacity (Acid-BC) of both areas (Table 7) was good to maintain their soil pH when the pH was raised to the desired level.

The very high Extr-Al (extractable aluminum) contents of both CP and SC are due to their very low soil pH levels (Table 7). At the low pH, toxic aluminum species can form that inhibit the growth of plant roots and subsequently limit ecosystem productivity [57]. Aluminum toxicity is the most important limiting factor for growing plant in ASS [58] and has different effects on the length of primary roots of oil palm in different varieties [59]. Therefore, before applying fertilizer or amendment in ASSs, it is essential to consider (i) the rooting depth of oil palm which can be impeded by dense layers of lateritic or other gravel, solid rock, or unfavorable chemical conditions [17], and (ii) the depth of acidic horizon which oil palm can grow without acidity limitation when the presence of acidic layers occur below 100 cm from soil surface [60, 61]. Considering the rooting depth covering the

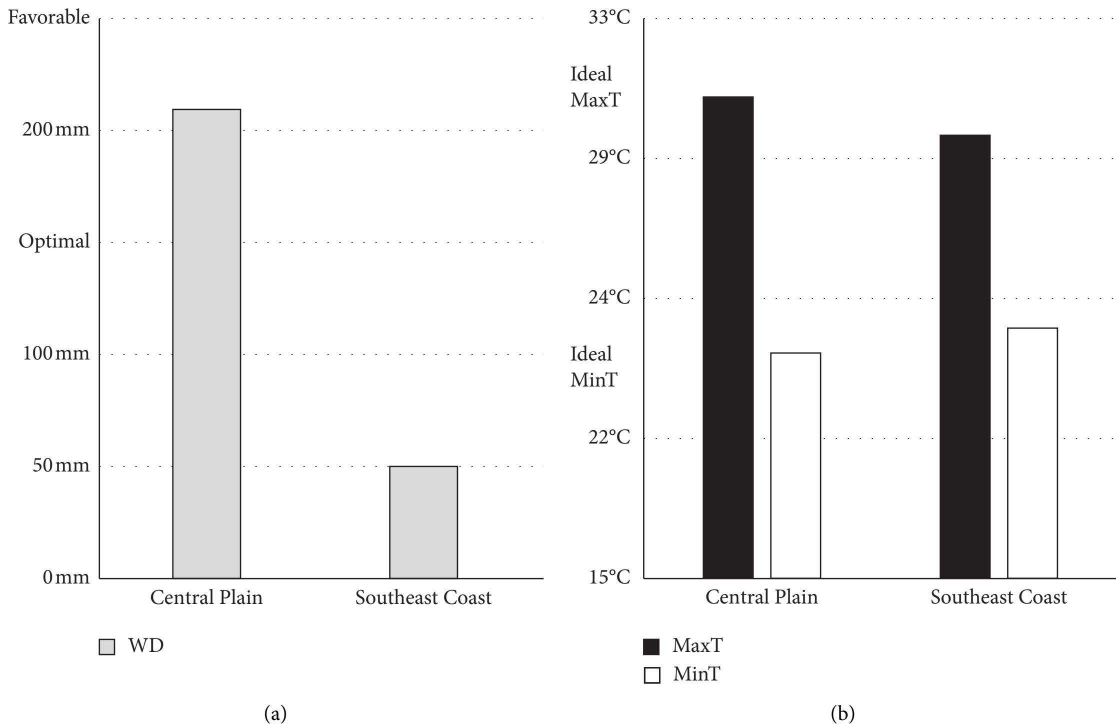

Figure 3: Water deficit suitability classification (WD = annual water deficit) and ideal climate requirement (MaxT = annual maximum temperature; MinT = annual minimum temperature) for oil palm of acid sulfate soils under oil palm planting areas in Central Plain and Southeast Coast, Thailand.

Table 6: Physical properties of acid sulfate soils under oil palm planting areas in Central Plain and Southeast Coast.

	Central Plain				Southeast Coast			
Physical property[a] (Unit)	Topsoil[b] Median (range) $n = 10$	Subsoil-1[c] Median (range) $n = 10$	Subsoil-2[d] Median (range) $n = 10$	Rootzone Median (range) $n = 30$	Topsoil[b] Median (range) $n = 10$	Subsoil-1[c] Median (range) $n = 10$	Subsoil-2[d] Median (range) $n = 10$	Rootzone Median (range) $n = 30$
Sand ($g{\cdot}kg^{-1}$)	35.50 (15–70)	25.00 (9–125)	36.00 (11–112)	33.00 (9–125)	346.00 (81–524)	223.50 (80–564)	262.00 (66–576)	292.00 (66–576)
Silt ($g{\cdot}kg^{-1}$)	304.50 (269–404)	292.50 (265–423)	282.50 (253–482)	296.00 (253–482)	385.00 (254–464)	377.50 (251–554)	387.00 (297–472)	387.00 (251–554)
Clay ($g{\cdot}kg^{-1}$)	666.00 (526–704)	681.00 (553–712)	666.50 (489–708)	674.50 (489–712)	292.50 (76–531)	288.50 (74–574)	3560 (79–493)	313.50 (74–574)
AWC (mm)	26.06 (24.32–29.58)	25.38 (24.12–30.96)	25.26 (23.05–33.32)	25.54 (23.05–33.32)	25.36 (18.20–31.90)	27.33 (17.08–35.34)	27.23 (20.23–31.15)	26.51 (17.08–35.34)

[a]AWC = available water capacity. [b,c,d]Topsoil = Ap; Subsoil-1 = Ap–60 cm; Subsoil-2 = 60–100 cm; Rootzone = top 100 cm.

total 100 cm from soil surface with the interpretation of soil nutrient status for fertilizer recommendations [48] (Figure 5). The growers in CP should maintain N and P fertilizer rate, and not input K and Mg fertilizer except to correct nutrient imbalance because the Rootzone had moderate TN, low Avail-P, and very high Exch-K and Exch-Mg. The input K fertilizer rate is different from the recent study by Palykaew et al. [62] that the rate should be sufficient due to the low to very high of Avail-K (available potassium) which tends to increase with depth levels, whereas the growers in SC should decrease N and K fertilizer rates, maintain P fertilizer rate, and not input Mg fertilizer except to correct nutrient imbalance because the Rootzone had high TN and Exch-K, very low Avail-P, and very high Exch-Mg. The P fertilizer rate of both ASSs areas should not be increased because the reactions that fix P in relatively unavailable forms are related to soil pH [63].

4.3. Influence of Climate on Physicochemical Properties of ASSs. Physical properties of soils are grossly static in their response to change in climatic conditions, whereas chemical properties are more dynamic to changes in climatic conditions [64, 65]. The findings of this study indicated that (Table 8) (i) in CP, daily solar radiation was the most significant climate parameter that influenced ASS properties in all depth levels; it influenced clay content in topsoil, CEC in the range of topsoil-60 cm, soil pH by water in the range of

Table 7: Chemical properties of acid sulfate soils under oil palm planting areas in Central Plain and Southeast Coast.

Chemical property[a] (unit)	Central Plain				Southeast Coast			
	Topsoil[b] Median (range) $n = 10$	Subsoil-1[c] Median (range) $n = 10$	Subsoil-2[d] Median (range) $n = 10$	Rootzone Median (range) $n = 30$	Topsoil[b] Median (range) $n = 10$	Subsoil-1[c] Median (range) $n = 10$	Subsoil-2[d] Median (range) $n = 10$	Rootzone Median (range) $n = 30$
$pH_{1:1}$-H_2O	3.65 (3.3–6.9)	3.45 (3.3–5.5)	3.50 (3.3–5)	3.50 (3.3–6.9)	3.80 (2.8–4.9)	3.90 (2.8–5)	4.80 (3.3–6.6)	4.15 (2.8–6.6)
$pH_{1:1}$-H_2O_2	2.35 (1.8–5.8)	2.30 (1.9–3)	2.30 (1.9–2.6)	2.30 (1.8–5.8)	2.60 (2.2–3.2)	2.55 (2.2–3.7)	2.45 (2.1–5.7)	2.50 (2.1–5.7)
OC ($g{\cdot}kg^{-1}$)	19.10 (11.4–51.7)	16.75 (8.9–22.7)	9.20 (5.6–23.2)	16.75 (5.6–51.7)	32.90 (5.3–102)	18.95 (2.9–140)	25.45 (1.9–112)	25.45 (1.9–140)
TN ($g{\cdot}kg^{-1}$)	1.68 (0.84–3.22)	1.44 (0.7–2.87)	0.81 (0.42–1.89)	1.40 (0.42–3.22)	1.925 (1.33–4.54)	1.955 (1.05–3.22)	2.06 (1.19–2.79)	1.99 (1.05–4.54)
Avail-P ($mg{\cdot}kg^{-1}$)	46.50 (6–1045)	10.00 (0.9–203)	11.30 (0.4–19)	13.00 (0.4–1045)	6.10 (1.1–42.2)	4.40 (0.9–127)	14.75 (2.3–126)	6.20 (0.9–127)
Avail-K ($mg{\cdot}kg^{-1}$)	128.00 (64–907)	99.00 (55–269)	96.50 (69–173)	115.00 (55–907)	54.50 (8–168)	53.00 (3–313)	181.50 (4–338)	74.00 (3–338)
Extr-SO_4^{2-} ($mg{\cdot}kg^{-1}$)	258.50 (32–441)	385.00 (199–933)	484.00 (313–1042)	380.50 (32–1042)	349.00 (33–5890)	574.00 (12–6583)	525.00 (3–4290)	525.00 (3–6583)
EA ($cmol_c{\cdot}kg^{-1}$)	35.00 (6–58)	40.50 (23–56)	36.50 (23–51)	37.00 (6–58)	28.50 (8–58)	17.00 (4–109)	33.50 (7–45)	28.50 (4–109)
EC ($dS{\cdot}m^{-1}$)	0.14 (0.07–0.24)	0.20 (0.13–0.81)	0.32 (0.19–0.8)	0.22 (0.07–0.81)	0.59 (0.04–5.27)	0.62 (0.03–3.63)	1.26 (0.13–5.25)	0.76 (0.03–5.27)
Exch-K ($cmol_c{\cdot}kg^{-1}$)	0.50 (0.17–2.68)	0.29 (0.19–1.78)	0.29 (0.23–0.62)	0.35 (0.17–2.68)	0.19 (0.06–0.67)	0.22 (0.04–1.33)	0.66 (0.05–1.46)	0.28 (0.04–1.46)
Exch-Ca ($cmol_c{\cdot}kg^{-1}$)	5.21 (0.4–25.5)	2.57 (0.97–13.2)	2.28 (0.78–6.87)	2.85 (0.4–25.5)	1.71 (0.59–15.6)	2.43 (0.68–4.23)	3.01 (0.81–14.5)	2.40 (0.59–15.6)
Exch-Mg ($cmol_c\ kg^{-1}$)	1.86 (0.2–5.41)	1.35 (0.3–3.03)	1.11 (0.48–5.24)	1.30 (0.2–5.41)	2.36 (0.18–13.1)	3.97 (0.1–10.3)	6.01 (0.22–30.1)	3.90 (0.1–30.1)
Exch-Na ($cmol_c{\cdot}kg^{-1}$)	0.20 (0.05–0.57)	0.34 (0.18–1.24)	0.44 (0.1–1.49)	0.33 (0.05–1.49)	0.34 (0.09–6.09)	0.87 (0.05–7.96)	1.47 (0.13–16.7)	1.00 (0.05–16.7)
CEC ($cmol_c{\cdot}kg^{-1}$)	30.50 (27–39)	29.00 (21–42)	26.50 (18–33)	28.00 (18–42)	18.55 (4.75–31.2)	15.45 (1.5–34.4)	17.30 (1.5–26.6)	16.55 (1.5–34.4)
BSP (%)	16.05 (1.9–85)	11.05 (3.6–32.2)	12.35 (5.6–27.7)	11.60 (1.9–85)	22.40 (3.21–76.9)	28.05 (2.06–78.8)	34.30 (3.71–81.6)	31.65 (2.06–81.6)
Extr-Al ($mg{\cdot}kg^{-1}$)	1037.50 (2–1435)	1161.00 (309–1498)	1316.50 (510–1593)	1133.00 (2–1593)	169.00 (15–2882)	280.00 (0.53–2367)	111.00 (3.8–815)	160.00 (0.53–2882)
Acid-BC (mmol $H^+{\cdot}kg^{-1}$)	82.00 (16–2361)	85.00 (30–2992)	81.50 (53–125)	82.00 (16–2992)	140.50 (57–321)	133.00 (39–332)	129.50 (12–176)	130.50 (12–332)
Base-BC (mmol $OH^-{\cdot}kg^{-1}$)	39.00 (6–86)	23.00 (5–64)	19.00 (6–56)	27.50 (5–86)	58.00 (28–153)	59.50 (13–610)	364.00 (10–878)	80.00 (10–878)

[a]OC = organic carbon; TN = total nitrogen; Avail = available; Extr = extractable; EA = extractable acidity; EC = electrical conductivity; Exch = exchangeable; CEC = cation exchange capacity; BSP = base saturation percentage; BC = buffering capacity. [b,c,d]Topsoil = Ap; Subsoil-1 = Ap–60 cm; Subsoil-2 = 60–100 cm; Rootzone = top 100 cm.

60–100 cm, and silt content covering the overall 100 cm from soil surface; (ii) in SC, annual minimum temperature was one of the most significant climate parameters that influenced ASS properties in almost all of the depth levels. It influenced clay content in topsoil, AWC in the range of 60–100 cm, and clay content covering the overall 100 cm from soil surface, whereas daily solar radiation influenced Exch-Mg in the range of 60–100 cm, Exch-Na and silt content covering the total 100 cm from soil surface. Therefore, it is important to emphasize the daily solar radiation in both areas because it was the major influential one of climatic parameters on soil properties due to the transport of heat in soils which is mostly governed by solar radiation during day time and the soil radiation to atmosphere during night time [66]. In addition, annual minimum temperature was the major influential of climatic parameters on soil properties in SC. These results indicated influence of soil temperature from daily solar radiation and annual minimum temperature on ASS properties due to their effect on the rates of physical, chemical, and biological reactions and process in the soil [67, 68].

On the other hand, particle size distribution was the most significant ASS property in both areas which was influenced by climatic parameters due to their clay and silt fractions (Table 8). Clay fraction is the most active and important fraction of soils because it retains moisture and nutrients, including its minerals that determine the potential fertility of soils via their CEC [69], whereas the silt fraction has not only a larger surface area but also a faster weathering rate and release of soluble nutrients for plant, compared with the sand fraction [70].

Climate can have an important influence on soil properties and their dynamics, especially precipitation and

Table 8: Results of stepwise multiple regression analysis on climate and soil variables.

Climate parameter[a]	Soil property[b]	Adjusted R^2	F value	Regression equation[ab]
Topsoil of Central Plain				
SR	Cla	0.332	5.464*	Cla = 1208.807SR – 21836.138
Subsoil-1 of Central Plain				
SR	CEC	0.488	9.584*	CEC = 160.904SR – 2964.165
Subsoil-2 of Central Plain				
SR	$pH_{1:1}$-H_2O	0.567	12.788**	pH-H_2O = -12.160SR + 229.890
Rootzone of Central Plain				
SR	Sil	0.513	31.591***	Sil = -1246.185SR + 23500.175
WD	Acid-BC	0.114	4.719*	Acid-BC = 33.102WD – 6697.325
Topsoil of Southeast Coast				
MinT	Cla	0.456	8.552*	Cla = 653.538MinT – 15356.974
Subsoil-1 of Southeast Coast				
WVP	Cla	0.412	7.294**	Cla = 12485.157WVP – 35328.988
Subsoil-2 of Southeast Coast				
MinT	AWC	0.429	7.752*	AWC = 20.222MinT – 458.125
SR	Exch-Mg	0.682	20.297**	Exch-Mg = -51.119SR + 949.075
Rootzone of Southeast Coast				
MinT	Cla	0.484	28.231***	Cla = 686.109MinT – 16119.176
SR	Exch-Na	0.238	10.045**	Exch-Na = -13.199SR + 245.424
SR	Sil	0.191	7.848**	Sil = -240.493SR + 4811.905
WVP	Acid-BC	0.160	6.525*	Acid-BC = 4053.929WVP – 11432.263

[a]Topsoil = Ap; Subsoil-1 = Ap–60 cm; Subsoil-2 = 60–100 cm; Rootzone = top 100 cm; SR = daily solar radiation; WD = annual water deficit; MinT = annual minimum temperature; WVP = annual water vapor pressure. [b]Acid-BC = acid buffering capacity; Sil = silt content; Cla = clay content; Exch-Na = exchangeable sodium; CEC = cation exchange capacity; $pH_{1:1}$-H_2O = soil pH by water; AWC = available water capacity; Exch-Mg = extractable magnesium. *,**,***Significance at 5%, 1%, and 0.1% alpha levels, respectively.

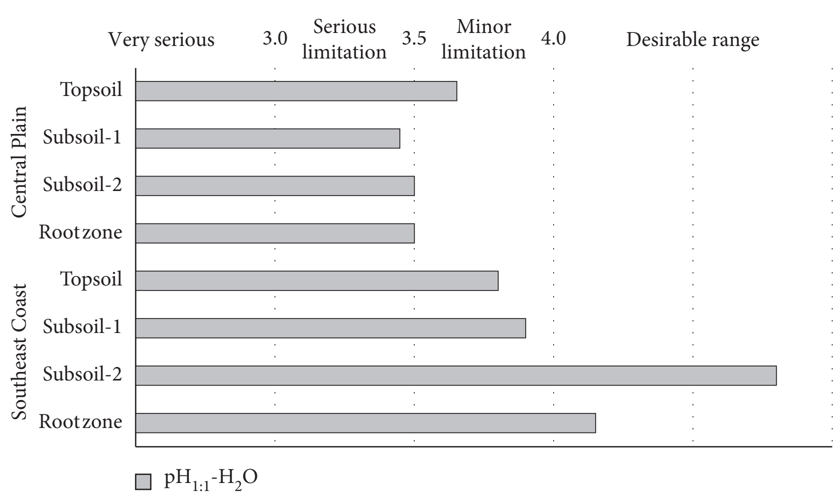

Figure 4: The soil limitation for oil palm of acid sulfate soils under oil palm planting areas in Central Plain and Southeast Coast, Thailand.

temperature [71]. Many significant correlations reported about the increasing precipitation and/or decreasing temperature with increment in soil organic carbon [72–75]. In addition, contents of Mg, Fe, Ca, and Al decreased with increasing precipitation while contents of Na and K increased with increasing temperature [76]. Our study indicated the importance of soil temperature on changing of ASS properties affecting directly or indirectly effective oil palm plantation. For example, magnesium (Table 8), which is influenced by daily solar radiation, is one of the key nutrients affecting oil palm growth and yield [22]. Soil temperature also affects the production of CO_2 in soils which influence the rates of microbial activity [77] and roots respiration [78].

5. Conclusion

The overall results of Thai ASSs under oil palm planting areas in CP and SC indicated that daily solar radiation not only was the most significant climate parameter but it also influenced silt content (mainly quartz) covering the overall 100 cm from soil surface of both ASS areas. Particle size distribution was the most significant ASS property in both areas that was influenced by climatic parameters. These

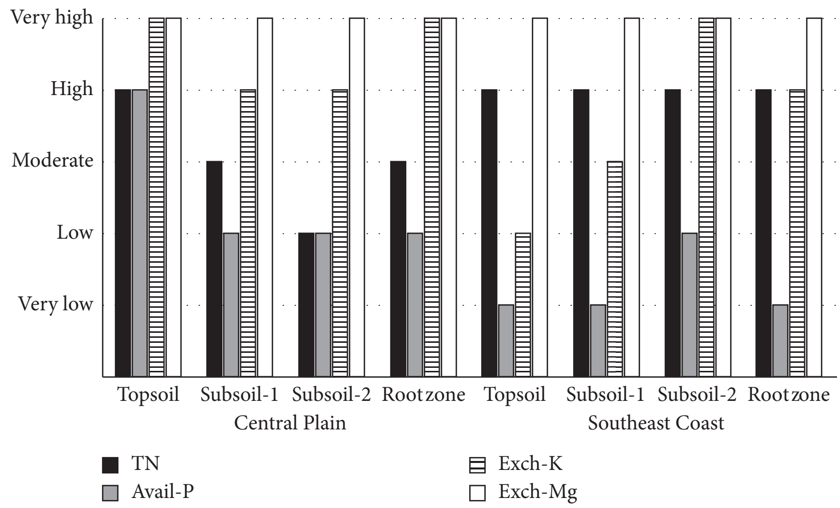

FIGURE 5: The soil nutrient status for fertilizer recommendations (TN = total nitrogen; Avail = available; Exch = exchangeable) of acid sulfate soils under oil palm planting areas in Central Plain and Southeast Coast, Thailand.

results indicated the importance of soil temperature on changing ASS properties affecting directly or indirectly on effective oil palm plantation and suggested that sustainable oil palm plantation in ASS under tropical savanna and tropical monsoon climates should include management of water use by devising raised beds with irrigation canals to compensate precipitation, decrease water deficit, draining water excess before flooding, and controlling water table level carefully to prevent aluminum toxicity. Besides, the rooting depth of oil palm and depth of acidic horizon should be considered before applying fertilizer or amendment. There is a need to improve soil conditions and increase yields by liming along with integrated organic material management to raise the soil pH to at least 4.3 but not exceed 6.

Data Availability

All data generated or analyzed during this study are included within the article as the supplementary information files.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

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Supplementary Materials

Table S1: results of principal component analysis with concept of component defining variable on climate parameters ($n = 10$ and 30). Table S2: results of principal component analysis with concept of component defining variable on soil properties of topsoil ($n = 10$). Table S3: results of principal component analysis with concept of component defining variable on soil properties of subsoil-1 ($n = 10$). Table S4: results of principal component analysis with concept of component defining variable on soil properties of subsoil-2 ($n = 10$). Table S5: results of principal component analysis with concept of component defining variable on soil properties of rootzone ($n = 30$). (*Supplementary Materials*)

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