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Agronomic Characteristics of Maize Grown in Paddy Soil, Along with Root Zone Soil Chemical Properties and Soil Bacterial Numbers

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Abstract

Maize is being considered as an alternative crop for off-season rice production in Thailand due to increasing water scarcity. The objective of this study was to evaluate the agronomic characteristics and root-zone soil properties of 4 hybrid maize varieties grown in paddy soil during off-season rice cultivation, in order to assess their growth and development after the flooded-rice harvest and the associated soil microorganisms. The randomized complete block design with 4 treatments and 4 replications was used. The 4 treatments were 2 new maize varieties (Suwan 5731 and Suwan 5819), 1 check variety (Suwan 4452), and 1 local use variety (PAC 789). Suwan 5819 showed significantly higher plant height than Suwan 4452, Suwan 5731 and PAC 789, with the highest plant height recorded for Suwan 5819 (221 cm). Similarly, Suwan 5819 exhibited significantly higher estimated leaf area index than Suwan 4452, Suwan 5731 and PAC 789, with differences of 32.67, 42.57 and 29.29 % at VT, respectively. These superior performances of Suwan 5819 could be attributed in part to increased dry matter and nutrient accumulation at the VT stage. The grain yield for PAC 789 was 13.71 t ha^{-1}, Suwan 4452 was 13.23 t ha^{-1}, Suwan 5731 was 12.83 t ha^{-1}, and Suwan 5819 was 12.25 t ha^{-1}. However, there was no significant difference in the grain yields among the 4 varieties. The soil in the root zone of Suwan 5819 at VT was significantly less acidic (pH 5.08) than Suwan 4452 (pH 4.58), PAC 789 (pH 4.61) and Suwan 5731 (pH 4.75). The nitrogen-fixing bacteria were most abundant in PAC 789 (84 %), phosphate-solubilizing bacteria in Suwan 4452 (15 %), and potassium-solubilizing bacteria in Suwan 5819 (16 %). Overall, the study suggests that Suwan 5819 is a promising maize variety for agronomic performance in the tested region.

Keywords: Rice-maize cropping system, Paddy soil, Maize, Dry matter, Plant nutrients, Grain yield, Soil bacteria

Introduction

Drought has devastating impacts on agricultural production, often with global consequences [1]. A recent study using a probabilistic modeling framework to estimate the risk of yield loss in maize (*Zea mays* L.) found that India has the highest risk of drought-related maize yield reduction, while Thailand and Vietnam face the highest risk of drought-induced rice yield reduction [1]. These risks are increasingly pressing, as evidenced by the unstable off-season rice yields in Thailand due to increasing water scarcity since 2011 [2]. In an effort to sustainably intensify cereal crop production, switching from dry-season rice to other upland crops that require less water is becoming more common in South and Southeast Asia [3]. The rice-maize crop rotation system has already been adopted in parts of South Asia, including southern and northeastern India and Bangladesh [4]. In comparison to paddy cropping with a rice-rice sequence, a rice-maize sequence has been shown to save 388 L m^{-2} of percolation water losses and reduce total nitrogen (N) and dissolved organic carbon leaching losses by an average of 0.6 and 1.6 g m^{-2}, respectively [5]. This not only conserves water resources but also helps to improve soil health and reduce environmental degradation.

Maize is a highly demanded crop in Thailand, with increasing demand for its use as feed, food and fuel both domestically and globally. However, domestic production is unable to meet the country's consumption demand [6]. Currently, maize is mainly planted during the early rainy season (72 %), late rainy season (23 %) and dry season (5 %) in Thailand. To address water scarcity and meet the growing demand for maize from the livestock industry, the Thai government has proposed an ambitious plan to increase the maize planting area during the dry season from 5 to 50 %. This would involve converting paddy fields from a rice-rice cropping sequence to a rice-maize cropping system during the wet-dry seasons. Growing maize in paddy fields has been reported to improve the production of domestic concentrated feed and is considered a labor-saving crop due to its lower cultivation requirements compared to rice and soybeans [7]. With its potential benefits, the shift to a rice-maize cropping system can help increase maize production, meet the growing demand and contribute to the country's food security.

In Thailand, maize is typically grown in rain-fed field soil. Most hybrid maize varieties have been developed with the assumption that they will be grown in field soil, which has different soil properties than paddy soil. This can pose a challenge when shifting to a rice-maize cropping system, as crops grown in paddy soil after flooded-rice harvest often have poor germination and crop establishment [8]. Selecting suitable maize varieties will overcome the challenge and support the rice-maize cropping system.

Soil properties are essential for cropping system, particularly to select suitable maize varieties. A 10-year field trial by Chen *et al.* [9], found that a rice-potato rotation with rice straw mulch and a rice-Chinese milk vetch rotation improved paddy soil structure, total nitrogen (N) and soil organic matter (OM). Similarly, Linh *et al.* [10], found that soil organic carbon content and hydrolysable labile carbon at depths of 10 - 20 cm and 20 - 30 cm were enhanced under a rice-maize farming system. Microorganisms play a crucial role in nutrient cycling and plant growth promotion, and the microbial diversity and function can vary depending on the crop rotation and host plant [11,12]. Therefore, analyzing the soil properties and microbial community composition can provide insights into selecting suitable maize varieties for a rice-maize cropping system in paddy soil.

As such, understanding the agronomic characteristics and soil properties may enable the effective use of maize as an alternative crop in rice-dominant regions. However, long-term studies and multi-location experiments are required to confirm and validate the findings. This study aims to evaluate the agronomic characteristics and analyze the root-zone soil chemical properties as well as bacterial community of different hybrid-maize varieties grown in paddy soil after rice harvest during the dry season. The results provide valuable insights and a foundation for further research in this area.

Materials and methods

Site selection

The field experiment was conducted in dry season in Chon Daen District, Phetchabun Province, Thailand (latitude 16.207778, longitude 100.853950) between December 2019 and April 2020. The rice-maize rotation has been practiced in this location for over 5 years. Rice is grown during the rainy seasons and maize is cultivated during the dry seasons.

Composite soil samples were collected from the plot areas at a depth of 0 - 20 cm and analyzed for physical and chemical properties at the Center of Innovative Agriculture, Thailand Institute of Scientific and Technological Research in Pathum Thani, Thailand. The pre-planting soil properties at 0 - 20 cm depth included 44 % clay, 26 % silt, 30 % sand, pH 5.8 (moderately acid), electrical conductivity (EC) 0.1 dS m^{-1}, organic matter (OM) 0.35 %, 1.5 mg kg^{-1} available phosphorus (P) and 27.5 mg kg^{-1} exchangeable potassium (K).

A weather station was installed 3 m away from the experimental field to collect basic agricultural meteorological data from January to March 2020. **Figure 1** shows the temperature and relative humidity data recorded by the real-time weather station. During the dry season (January to March 2020), relative humidity ranged from 56 to 83 %. Daily air temperatures ranged from a minimum of 19 °C to a maximum of 44 °C, with average daily temperatures ranging from 28 to 32 °C.

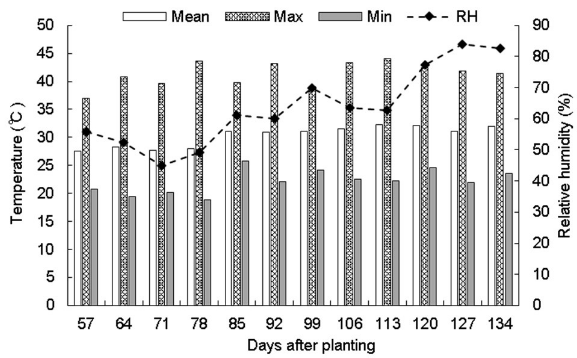

Figure 1 Temperature (°C) and relative humidity (RH, unit in %) during maize cultivating period in the dry season (January 2020 to March 2020) at Chon Daen district, Phetchabun province, Thailand.

Experimental management and design

Before planting the hybrid maize varieties, the designated paddy field was plowed twice using a tractor equipped with a 3-disk plow (Kubota, Japan) to break up the soil. Rice straws were plowed back into the soil. The field was then laid out using a Randomized Complete Block Design with 4 treatments and 4 replications. Four maize varieties were selected: Suwan 4452 (Check variety), Suwan 5819 and Suwan 5731 (2 new hybrid maize varieties recently developed and introduced by the National Corn and Sorghum Research Center, Thailand), and PAC 789 (commercially available hybrid maize variety often used by the farmer in the region). The plots were 5.6 m long and 5 m wide, with a separation of 1 m between plots. Within the plots, the plants were spaced 70 cm apart in rows and 20 cm within the rows. The total harvested area was 7.3 m^2. Fertilizer was applied to all plots according to pre-plant soil test results. The fertilizer included 125 kg N ha^{-1} as urea, 62.5 kg P_2O_5 ha^{-1} and 62.5 kg K_2O ha^{-1}, and was applied 3 times: Basal application at planting day, the 1st topdressing application at 21 days after planting, and the 2nd topdressing application at 45 days after planting. A rain spray irrigation system was used to supply water to the plants as needed. The experimental plots were kept free of weeds and insects using recommended practices.

Plant sampling and growth measurement

The agronomic characteristics observation was carried out at 4 growth stages: Six opened collar leaf (V6), vegetative transition (VT), milky grain stage (R3) and physiologically maturity (PM) using samples from an area of 0.42 m^2 per plot.

At the V6 growth stage, plant height was measured from the base of the plant to the collar of the latest fully developed leaf. At the VT and R3 growth stages, plant height was measured from the base of the plant to the collar of the flag leaf. Ear height was measured from the base of the plant to the base of the ear. Leaf area per plant was estimated by measuring the length and maximum width of the ear leaf, and multiplying these values by 0.75 according to Montgomery [13]. The average leaf area per plant was then estimated by multiplying the calculated leaf area by a factor of 9.39 [14]. Leaf Area Index (LAI) was calculated by dividing the total green leaf area per unit of ground surface area occupied by the crop by 1 side.

A portable SPAD 502 Chlorophyll Meter (Konica Minolta) was used to non-destructively estimate leaf greenness. To measure chlorophyll concentration (Chl *a* and Chl *b*), fully developed leaves were collected from sample plots and extracted using N, N-Dimethylformamide (N, N-DMF). The extraction solution was then analyzed using spectrophotometry at 2 characteristic wavelengths (664 and 647 nm) to determine chlorophyll pigmentation. The concentration of Chl *a*, Chl *b* and total Chl was calculated following the protocols established by [15].

Dry matter accumulation (DMA)

During the V6, VT, R3 and PM growth stages, plants were randomly sampled from an area of 0.42 m^2 per plot. The stems, leaves, tassels and grain of the plants were separated and dried in a hot air oven at 60 °C until reaching a constant weight. The Dry Matter Accumulation (DMA) was expressed in grams per plant.

Yield and yield components

Yield and yield components were determined using maize ears harvested from the 2 center rows of each plot (7.3 m^2) at the PM stage. Five ears were randomly selected and their ear length, ear diameter, number of kernel rows per ear and barren tip length were measured to estimate 100-kernel weight and shelling percentage. The grain yield from the 2 center rows was then calculated (assuming an average moisture content of 11 %) and expressed in tons per hectare.

Plant nutrient analysis

The samples of dried plant parts were sent to the Soil Science Department at Kasetsart University for analysis of their nitrogen (N), phosphorus (P) and potassium (K) content. The accumulation of N, P and K in each plant part was calculated by multiplying the nutrient content (as a percentage) by the DMA (in kilograms per hectare) of each plant part, and then dividing the result by 100. This calculation provided the accumulation of N, P and K in each plant part on a per hectare basis.

Soil chemical analysis

Composite soil samples were collected during the VT and PM stages from 3 separate points on each plot at a depth of 0 - 20 cm. The samples were air-dried at room temperature, sieved to remove crop residue and homogenized, and then sent for analysis at the Center of Innovative Agriculture at the Thailand Institute of Scientific and Technological Research. The soil chemical parameters that were analyzed and the methods used were as follows: Soil OM was measured using the Walkley and Black Titration method [16]; levels of phosphorus (P) were performed using the Bray II and colorimetric methods [17]; exchangeable potassium (K) was extracted using 1 M NH_4OAc (pH 7) and analyzed using a Flame Photometer [18]; electrical conductivity (EC) was determined using a 1:5 (soil:deionized water) suspension [19]; and soil pH was measured using a 1:1 (soil:deionized water) suspension [20].

Quantification of soil microbes by plate counting technique

Composite soil samples were collected during the VT stage from the root zone, at a depth of 20 cm from an area of 0.42 m^2 per plot. The samples were placed in a cool box and then stored at 4 °C in a refrigerator prior to quantification.

Soil samples were then suspended in sterile distilled water and subjected to serial dilutions (10^2 - 10^6 CFU g^{-1}). A 0.1 mL aliquot of each dilution was spread onto 3 different agar media: Burk'N-free medium for the analysis of the N-fixing bacteria population, Pikovskaya medium for the analysis of the phosphate-solubilizing bacteria population, and Aleksandrov medium for the analysis of the K-solubilizing bacteria population. The plates were incubated at 28 - 30 °C for 7 days and then the number of colonies was counted on each plate and expressed as colony forming units per g (CFU g^{-1}). The analysis was conducted by the Center of Innovative Agriculture at the Thailand Institute of Scientific and Technological Research.

Statistical analysis

Analysis of variance (ANOVA) of the measured parameters was performed using a Statistical Tool for Agricultural Research (STAR) software, version 2.0.1 (International Rice Research Institute: Los Baños, Philippines). The least significant difference (LSD) test was used to test for significant differences between treatments using 2 significance levels, 0.01 and 0.05.

Results and discussion

Growth and photosynthesis-related characteristics of maize varieties grown in paddy soil

The growth of the maize varieties was monitored by measuring plant height and LAI, while photosynthesis-related characteristics were evaluated by measuring SPAD value and chlorophyll concentration. **Figure 2(A)** shows the plant height of the 4 maize varieties. The highest plant heights for each variety were: Suwan 5819 (221 cm), Suwan 5731 (215 cm), Suwan 4452 (201 cm) and PAC (193 cm). The plant height of all varieties increased rapidly from the V6 to VT stage. No significant differences in plant height were found among the maize varieties at the V6 stage, but significant differences were observed at the VT, R3 and PM stages. Suwan 5819 had significantly greater plant height than the other 3 varieties at the VT, R3 and PM stages. At these later growth stages, Suwan 5819 was higher in plant height than Suwan 4452 (by 15.5 % at VT, 9.6 % at R3 and 10.9 % at PM), Suwan 5731 (by 4.4 % at VT, 2.9 % at R3 and 3.5 % at PM) and PAC 789 (by 17.5 % at VT, 16.5 % at R3 and 15.3 % at PM).

The estimated leaf area index (LAI) of the 4 maize varieties is shown in **Figure 2(B)**. At both the VT and R3 stages, the estimated LAI of Suwan 5819 was significantly higher than that of Suwan 4452, Suwan 5731 and PAC 789, by 32.67, 42.57 and 29.29 % respectively at the VT stage, and by 21.4, 28.0 and 19.12 % at the R3 stage. These results suggest that Suwan 5819 had a larger photosynthetic active area than the other varieties when grown in paddy soil.

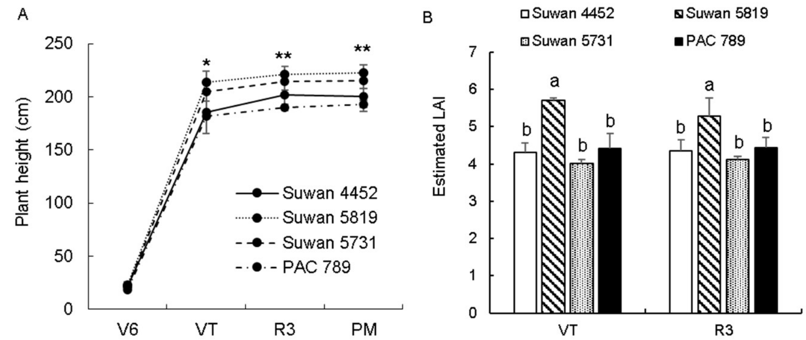

Figure 2 Plant height and leaf area index (LAI) of 4 maize varieties (Suwan 4452, Suwan 5819, Suwan 5731 and PAC 789) at different growth stages. (A) is plant height and (B) is leaf area index (LAI). Data represent the mean ± standard deviation (error bar) of 3 independent biological replicates. Different letters above bar graph indicate differences according to LSD tests at the 0.05 level. *significant at $p < 0.05$, **significant at $p < 0.01$ probability level of significant.

Table 1 shows the SPAD values and chlorophyll (Chl) concentrations (Chl *a*, Chl *b*, total Chl and Chl *a*/*b* ratio) of fully developed leaves from the maize varieties at the V6 and VT stages. The maize varieties showed significant differences in SPAD values at the V6 stage, but not at the VT stage. At the V6 stage, Suwan 5819 had a greater leaf SPAD value than the other varieties. Significant differences in Chl concentrations among the varieties were also observed at both the V6 and VT stages. At the V6 stage, Suwan 5819 and Suwan 5731 had significantly higher leaf Chl *a* and Chl *b* concentrations than Suwan 4452 and PAC 789. At the VT stage, all Suwan varieties had significantly higher Chl *a*, Chl *b* and total Chl concentrations than PAC 789.

Physiological parameters such as plant height, LAI and chlorophyll content can be used to measure maize's effective biomass production [21-23]. Suwan 5819 appeared to perform well in flooded paddy soil, as demonstrated by its superior growth (**Figure 2**(**A**)) and photosynthesis-related characteristics. However, it should be noted that there was no significant difference in the photosynthesis-related characteristics between Suwan 5819 and Suwan 5731. Overall, the new hybrid variety Suwan 5819 had the best performance in terms of growth and equally good performance with Suwan 5731 in term of photosynthesis-related characteristics.

Table 1 SPAD value, the concentration (µg cm^{-2}) of chlorophyll (Chl) *a*, Chl *b*, total Chl and Chl *a*/*b* ratio of fully developed leaf of maize varieties at the V6 and VT stages.

Varieties	SPAD value	Chl *a* (µg cm^{-2})	Chl *b* (µg cm^{-2})	Total Chl (µg cm^{-2})	Chl *a*/*b*
			V6 stage		
Suwan 4452	49.46 ± 4.76^{a}	53.27 ± 5.07^{b}	14.82 ± 1.47^{ab}	68.09 ± 6.53^{bc}	3.60 ± 0.05
Suwan 5819	53.49 ± 5.13^{a}	61.54 ± 4.27^{a}	16.87 ± 1.24^{a}	78.41 ± 5.52^{a}	3.65 ± 0.02
Suwan 5731	52.08 ± 2.51^{a}	60.93 ± 2.76^{a}	16.71 ± 0.92^{a}	77.64 ± 3.66^{ab}	3.65 ± 0.06
PAC 789	43.66 ± 2.26^{b}	49.54 ± 2.45^{b}	13.51 ± 0.41^{b}	63.05 ± 2.80^{c}	3.67 ± 0.11
			VT stage		
Suwan 4452	58.09 ± 2.68	64.05 ± 1.40^{a}	16.69 ± 0.19^{a}	80.78 ± 1.51^{a}	3.84 ± 0.07
Suwan 5819	59.43 ± 2.68	60.76 ± 0.90^{a}	16.08 ± 0.23^{a}	76.88 ± 1.00^{a}	3.78 ± 0.06
Suwan 5731	56.95 ± 3.06	63.01 ± 4.66^{a}	17.04 ± 0.98^{a}	80.09 ± 5.60^{a}	3.70 ± 0.10
PAC 789	56.74 ± 0.63	55.01 ± 2.95^{b}	14.41 ± 1.00^{b}	69.45 ± 3.94^{b}	3.82 ± 0.07

Note: Values are mean ± SD; means followed by different letters in the same column indicate differences according to LSD test at the 0.05 level; *, ** = significant at $p < 0.05$, 0.01, respectively.

Dry matter accumulation (DMA) of the maize varieties grown in paddy soil

The DMA of 4 parts of the maize plants—leaves, stems, tassels and grains—was studied in this research. All 4 varieties underwent the same measurement and test procedures. **Figure 3** shows the DMA of the maize plants' leaves (Leaves-DMA), stems (Stem-DMA), tassels (Tassel-DMA) and grains (Grain-DMA). The recorded data shows significant differences in Leaves-DMA, Stem-DMA and Tassel-DMA among the 4 maize varieties during the vegetative to reproductive stage (**Figures 3**(**A**) - **3**(**C**)). However, no significant differences were found in Grain-DMA (**Figure 3**(**D**)).

There were no significant differences in Leaves-DMA among the varieties at the V6 and PM stages, but significant differences in Leaves-DMA were found at the VT and R3 stages (**Figure 3**(**A**)). At the VT stage, Suwan 5819 had significantly the highest Leaves-DMA measurements. Expressed as a percentage of difference, at the VT stage, Suwan 5819 had a greater Leaves-DMA than Suwan 4452, Suwan 5731 and PAC 789 by 53.1, 62.0 and 63.9 %, respectively. However, at the R3 stage, Suwan 4452 and Suwan 5819 had significantly greater Leaves-DMA than PAC 789 (**Figure 3**(**A**)).

Significant differences in Stem-DMA among the 4 maize varieties were found at the VT and PM stages, but not at the V6 and R3 stages. At the VT stage, Suwan 5819 had a significantly higher Stem-DMA than Suwan 4452, Suwan 5731 and PAC 789 by 29.3, 38.2 and 74.8 %, respectively. But, at the PM stage, Suwan 4452 had a significantly higher Stem-DMA than Suwan 5819, Suwan 5731 and PAC 789 by 64.3, 32.6 and 62.0 %, respectively (**Figure 3**(**B**)).

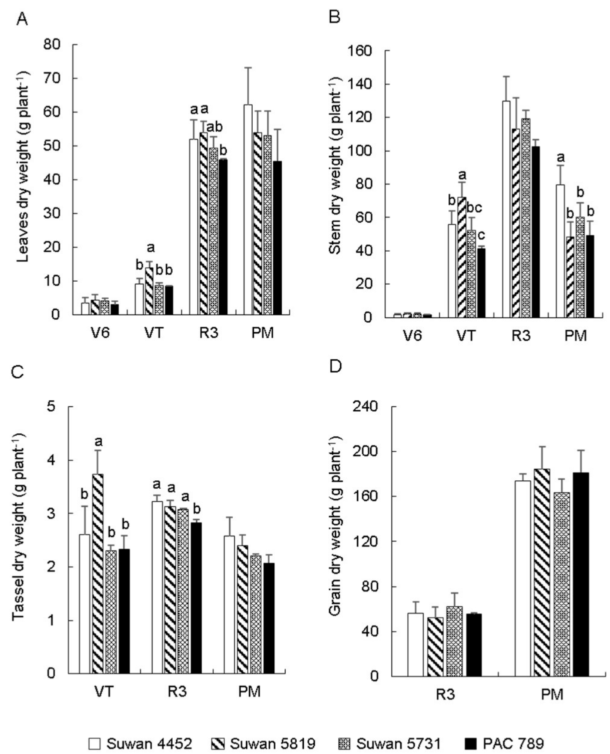

Figure 3 Dry matter accumulation (DMA) in leaves (A), stem (B), tassel (C) and grain (D) of 4 maize varieties (Suwan 4452, Suwan 5819, Suwan 5731 and PAC 789) at different growth stages. Data represent the mean ± standard deviation (error bar) of 3 independent biological replicates. Different letters above bar graph indicate differences according to LSD tests at the 0.05 level.

For Tassel-DMA, significant differences in Tassel-DMA were found among the maize varieties at the VT and R3 stages, but not at the PM stage. At the VT stage, Suwan 5819 had a significantly higher Tassel-DMA than Suwan 4452, Suwan 5731and PAC 789 by 43.5, 62.2 and 60.1 %, respectively. However, at the R3 stage, all Suwan varieties had significantly higher Tassel-DMA than PAC 789 (**Figure 3**(**C**)).

Figure 4 shows the dry matter (DM) partitioning of the 4 maize varieties. The total aboveground biomass accumulation at the PM stage for Suwan 4452, Suwan 5731, Suwan 5819 and PAC 789 was approximately 27.7, 24.0, 23.5 and 23.2 t ha^{-1}, respectively. The rate of leaf and stem dry weight production of Suwan 4452, Suwan 5731, Suwan 5819 and PAC 789 from V6 to VT was 142, 190, 130 and 108 kg ha^{-1} d^{-1}, respectively, and from VT to R3 was 278, 192, 256 and 235 kg ha^{-1} d^{-1}, respectively (**Figure 4**).

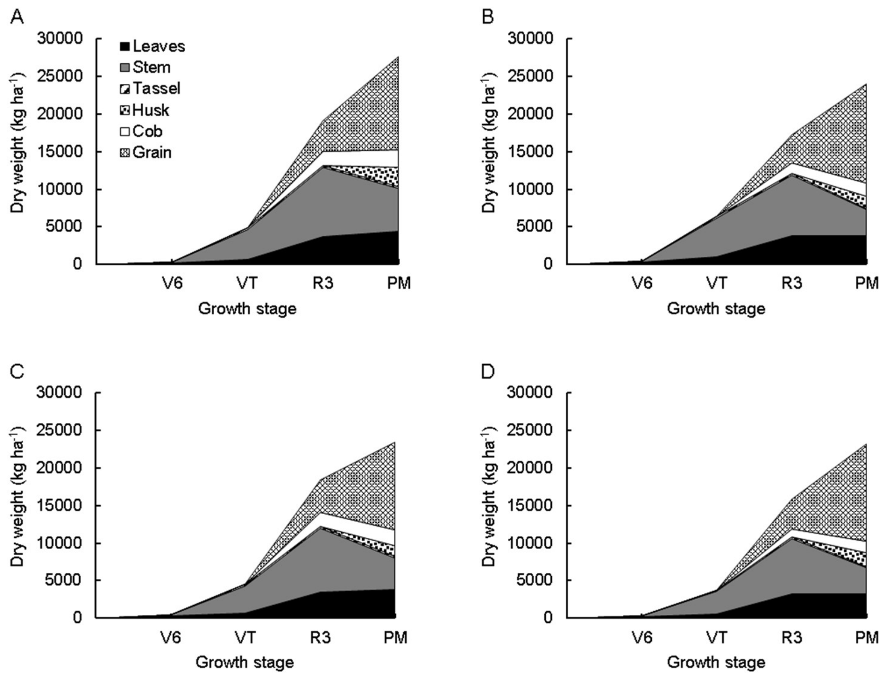

Figure 4 Partitioning of dry weight (kg ha^{-1}) of Suwan 4452 (A), Suwan 5819 (B), Suwan 5731 (C) and PAC 789 (D) grown in paddy soil at different growth stages.

This experiment observed significant differences in the DMA of the 4 maize varieties at the VT stage that can be attributed directly to the plants' heights. The new hybrid variety Suwan 5819 showed greater development than the other varieties, as indicated by its height (**Figure 2**(**A**)), and as a result, it produced significantly more leaf and stem DMA (**Figure 3**). According to Machado *et al.* [24], 90 % of variations in the total dry matter of maize can be attributed to plant height. Suwan 5819 had strong growth characteristics, photosynthesis-related parameters and higher DMA production in paddy field conditions with clay textured soil. However, no significant differences were observed in the grain yield of these maize varieties (**Figure 5**). This suggests that the assimilate partitioning mechanism may play an important role in determining grain yield under these conditions. Suwan 5819 may have directed more assimilates towards leaf and stem growth, at the expense of grain development. This hypothesis is consistent with our observation that there were no significant differences in grain yield between the maize varieties, despite the differences in growth. Beside the assimilate partitioning mechanism, Inthong [25], found that maize varieties grown in paddy soil did not show significant differences in grain yield and yield components, but their yield performance appeared to depend on the clay content of the soil. Clay soil has a high water-holding capacity, which can cause waterlogging and reduce oxygen availability for the roots, leading to poor root development and reduced nutrient uptake. Additionally, the high clay content can affect soil structure, making it compact and limiting root growth. Therefore, it is important to consider the clay content of soil when selecting maize varieties for cultivation in paddy fields. In this study, the clay content of the experimental site was found to be relatively high at 44 %, which falls outside the optimal range of 20 - 40 % for maize yield [26]. This suggests potential yield risks for maize cultivation in this region. However, further research is needed to confirm the optimal clay content for maize growth in paddy fields and to determine the mechanisms by which clay content affects yield performance.

Nutrient accumulation in the plant parts of maize varieties grown in paddy soil

The nutrient accumulation of the plant parts of the 4 maize varieties was analyzed at different growth stages. When comparing all 4 varieties at the V6 stage, Suwan 5819 had the greatest N, P and K accumulation in its leaves, but the data did not significantly differ from the other varieties (**Table 2**).

At the VT stage, Suwan 5819 had the highest levels of accumulation in leaves-N, stem-N and tassel-N, but only its leaves-N accumulation was significantly higher than Suwan 4452 (47.5 %), Suwan 5731 (52.0 %) and PAC 789 (59.4 %). Suwan 5819 had significantly higher levels of leaves-P, stem-P and tassel-P accumulation than Suwan 4452, Suwan 5731 and PAC 789. Suwan 5819's leaves-P accumulation was significantly higher than Suwan 4452 (60.9 %), Suwan 5731 (85.0 %) and PAC 789 (105.6 %). Suwan 5819's stem-P accumulation was significantly greater than Suwan 5731 (57.9 %), Suwan 4452 (76.5 %) and PAC 789 (82.9 %). Suwan 5819's tassel-P accumulation was significantly greater than Suwan 4452 (51.9 %), PAC 789 (64.0 %) and Suwan 5731 (105.0 %) (**Table 2**).

Analysis of K accumulation in the plant parts of the 4 Suwan varieties revealed that Suwan 5819 had significantly higher levels of leaves-K accumulation than PAC 789 (50.0 %), Suwan 4452 (57.0 %) and Suwan 5731 (90.6 %). Suwan 5819's tassel-K accumulation was also significantly higher than Suwan 4452 (39.1 %), PAC 789 (43.1 %) and Suwan 5731 (75.9 %) (**Table 2**).

At the R3 stage, all Suwan varieties had significantly greater leaves-P accumulation than PAC 789. However, analysis of all 4 Suwan varieties revealed no significant differences in the levels of grain-nutrient accumulation (**Table 2**).

At the PM stage, only the grain of the 4 varieties was analyzed. The results of the analysis at the PM stage were similar to the R3 stage-there were no significant differences in the levels of grain-N, grain-P and grain-K accumulation (**Table 2**).

During the VT, R3 and PM stages, significant differences in nutrient accumulation were found among the maize varieties. Suwan 5819 had the highest accumulation of N, P and K in leaves, the highest P accumulation in stem, and the highest P and K accumulation in tassel (**Table 2**). The differences in macronutrient accumulation in maize are likely due to the increased dry matter and yields production [27,28]. Suwan 5819 had the highest leaf, stem and tassel DMA at the VT stage (**Figure 3**), indicating that its enhanced DMA may lead to higher nutrient accumulation in plant parts than the other Suwan and commercial varieties at the VT stage.

Table 2 Total nitrogen (N), phosphorus (P) and potassium (K) accumulation in plant parts of 4 maize varieties grown in paddy soil at different growth stages.

Varieties	**V6 stage**	**VT stage**			**R3 stage**		**PM stage**
	Leaves	**Leaves**	**Stem**	**Tassel**	**Leaves**	**Grain**	**Grain**
				N accumulation (kg ha^{-1})			
Suwan 4452	2.82	5.35^{b}	9.19	1.75	24.64	21.66	59.77
Suwan 5819	3.81	7.89^{a}	10.76	2.46	21.29	17.90	50.87
Suwan 5731	2.85	5.19^{b}	8.10	1.48	22.34	24.06	50.80
PAC 789	2.12	4.95^{b}	6.73	1.52	19.38	21.40	56.76
				P accumulation (kg ha^{-1})			
Suwan 4452	0.20	0.46^{b}	0.85^{b}	0.27^{b}	2.68^{a}	4.75	10.25
Suwan 5819	0.36	0.74^{a}	1.50^{a}	0.41^{a}	2.73^{a}	3.59	13.07
Suwan 5731	0.27	0.40^{b}	0.95^{b}	0.20^{b}	2.78^{a}	4.11	8.97
PAC 789	0.16	0.36^{b}	0.82^{b}	0.25^{b}	2.14^{b}	3.74	8.33
				K accumulation (kg ha^{-1})			
Suwan 4452	2.41	3.86^{b}	13.80	1.05^{ab}	20.88	10.18	17.05
Suwan 5819	4.56	6.06^{a}	23.41	1.46^{a}	19.96	7.73	19.48
Suwan 5731	4.18	3.18^{b}	13.18	0.83^{b}	19.10	9.16	14.83
PAC 789	2.84	4.04^{b}	11.93	1.02^{b}	20.22	8.53	16.65

Note: Values are mean ± SD; means followed by different letters in the same column indicate differences according to LSD test at the 0.05 level; *, ** = significant at $p < 0.05$, 0.01, respectively.

Yield and yield components of maize varieties grown in paddy soil

Table 3 shows the correlation coefficients for the relationship between grain yield and yield components in the 4 maize varieties (Suwan 4452, Suwan 5819, Suwan 5731 and PAC 789). For the 4 varieties, there was a positive correlation between ear diameter and ear length ($r = 0.78^{**}$). Grain yield correlated positively with ear diameter ($r = 0.75^{**}$) and ear length ($r = 0.58^{*}$). The number of rows correlated positively with ear diameter ($r = 0.45^{*}$) and ear tip ($r = 0.68^{*}$).

Table 3 Pearson correlation coefficients (*r*) for the relationships of yield and yield components of 4 maize varieties (Suwan 4452, Suwan 5819, Suwan 5731 and PAC 789).

	Grain yield	Ear diameter	Ear length	Cob weight	Ear tip	Number of rows	100-kernel weight
Grain yield	1.00						
Ear diameter	0.75^{**}	1.00					
Ear length	0.58^{*}	0.78^{**}	1.00				
Cob weight	0.18	0.08	0.18	1.00			
Ear tip	–0.18	0.24	0.46	0.19	1.00		
Number of rows	0.13	0.45^{*}	0.22	–0.04	0.68^{*}	1.00	
100-kernel weight	0.42	0.25	0.33	–0.23	–0.45	–0.52	1.00

Note: * and ** = significant correlation at the 0.05 and 0.01 probability level, respectively.

The grain yield of 4 Suwan cultivars was examined and presented in **Figure 5**. The highest grain yield was found for PAC 789, with a yield of 13.71 t ha^{-1}, while the lowest yield was found for Suwan 5819, with a yield of 12.25 t ha^{-1}. Although PAC 789 had the highest yield, statistical analysis showed that there was no significant difference in grain yield among the Suwan varieties. These results suggest that while PAC 789 may have slightly higher yield potential, all 3 Suwan cultivars could be viable options for farmers looking to maximize their maize yield. While the grain yield is an important factor, the study suggests that other growth parameters such as photosynthetic-related characteristics, DMA and nutrient accumulation at the vegetative stage are also critical for selecting maize varieties that can adapt to varying environmental conditions. As demonstrated by Suwan 5819's superior growth performance, these factors are essential to maximize maize yield and should be taken into account when selecting cultivars.

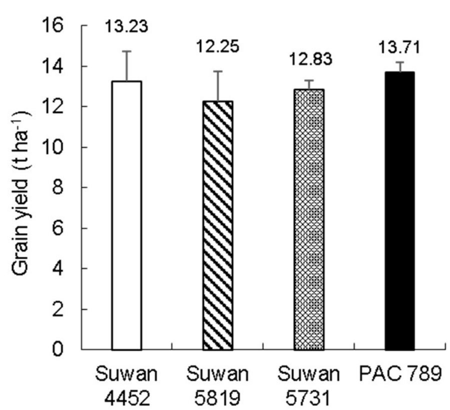

Figure 5 Grain yield of 4 maize varieties (Suwan 4452, Suwan 5819, Suwan 5731 and PAC 789) grown in paddy soil at Chon Daen district, Phetchabun province, Thailand. Data represent mean ± standard deviation (error bar).

Soil chemical properties in the root zone of maize varieties at VT and PM stages

At the VT stage, the tests performed to determine soil pH and exchangeable K in the root zone of the 4 maize varieties showed significant differences (**Table 4**). The soil pH in the root zone of Suwan 5819 (5.08) was the least acidic, compared to Suwan 4452 (4.58), PAC 789 (4.61) and Suwan 5731 (4.75).

Exchangeable K (expressed as mg kg^{-1}) was highest in the root zone of PAC 789 (75.61), compared to the exchangeable K found in the root zones of the other varieties: Suwan 5819 (47.19), Suwan 4452 (48.68) and Suwan 5731 (52.62). The other tested soil chemical properties ranged from 0.15 - 0.21 dS m^{-1} for soil EC, 1.70 - 1.90 % for soil OM and 9.06 - 19.45 mg kg^{-1} for available P (**Table 4**).

At the PM stage, no significant differences were found in some selected soil chemical parameters in the root zone paddy soils of the 4 maize varieties. At the PM stage, the root zone soil chemical properties ranged from 4.98 - 5.57 for soil pH, 0.15 - 0.20 dS m^{-1} for soil EC, 2.72 - 2.97 % for soil OM, 13.96 - 19.90 mg kg^{-1} for available P, and 116.52 - 182.50 mg kg^{-1} for exchangeable K (**Table 4**).

Table 4 Some selected soil chemical properties at the 0 - 20 cm depth (root zone) of paddy soil at the VT and PM stages.

Varieties	Soil pH 1:1 (dH_2O)	Soil EC 1:5 (dS m^{-1})	Soil OM (%)	Avai. P (mg kg^{-1})	Exch. K (mg kg^{-1})
	VT stage				
Suwan 4452	4.59 ± 0.14[b]	0.17 ± 0.01	1.70 ± 0.04	9.06 ± 3.51	48.68 ± 12.39[b]
Suwan 5819	5.09 ± 0.36[a]	0.15 ± 0.02	1.81 ± 0.17	9.29 ± 0.51	47.19 ± 2.65[b]
Suwan 5731	4.75 ± 0.20[b]	0.18 ± 0.02	1.84 ± 0.07	13.69 ± 10.72	52.62 ± 5.35[b]
PAC 789	4.61 ± 0.10[b]	0.21 ± 0.04	1.90 ± 0.26	19.45 ± 13.53	75.61 ± 11.60[a]
	PM stage				
Suwan 4452	5.57 ± 0.96	0.15 ± 0.05	2.73 ± 0.36	19.90 ± 15.69	116.52 ± 38.29
Suwan 5819	5.15 ± 0.31	0.20 ± 0.06	2.97 ± 0.39	15.38 ± 15.02	182.50 ± 38.02
Suwan 5731	4.98 ± 0.14	0.18 ± 0.04	2.72 ± 0.16	13.96 ± 6.94	116.58 ± 57.75
PAC 789	5.22 ± 0.16	0.16 ± 0.01	2.96 ± 0.22	14.77 ± 11.88	174.54 ± 75.88

Note: Values are mean ± SD; means followed by different letters in the same column indicate differences according to LSD test at the 0.05 level; EC = electrical conductivity; OM = organic matter; Avai. P = available phosphorus; Exch. K = exchangeable potassium.

Before planting, the soil pH in the experimental field was moderately acidic at 5.80. During maize cultivation, the root-zone soil pH of the 4 maize varieties at the VT and PM stages ranged from 4.61 to 5.08 and 4.98 to 5.57, respectively. At the VT stage, significant differences were observed in the root-zone soil pH of the 4 maize varieties, with Suwan 5819 showing the least acidic condition compared to the other varieties (**Table 4**). The release of H^+ or OH^- from root cells to maintain electro-neutrality at the soil-root interface in response to cation or anion uptake by plant roots in the rhizosphere can result in acidification or alkalization of the surrounding soil [29-32]. The significant accumulation of N, P and K in plant parts at the VT stage by Suwan 5819 may have contributed to high cation or anion uptake by roots, leading to H^+ or OH^- release into the soil and contributing to the observed root-zone soil pH level in this variety. However, further research is needed to confirm the cation/anion uptake ratio by roots in this variety.

Quantification of N-fixing, phosphate-solubilizing and K-solubilizing bacteria in the root zone of the maize varieties

Table 5 shows the quantitative estimation of soil microbial bacteria abundance in the root zone of 4 maize varieties (Suwan 4452, Suwan 5819, Suwan 5731 and PAC 789) at the VT stage. No significant differences were observed in the total viable count in the root zone among the varieties.

PAC 789 had the highest total viable count on the N-free, phosphate- and K-containing medium among the varieties. Its total viable count on the N-free medium was higher than those of Suwan 5819 (4 %), Suwan 4452 (35 %) and Suwan 5731 (35 %). The total viable count on the phosphate-containing medium in the root zone of PAC 789 and Suwan 4452 was higher than that in Suwan 5819 and Suwan 5731. On the K-containing medium, the total viable count in the root zone of PAC 789 was higher than those of Suwan 4452 (33 %), Suwan 5819 (22 %) and Suwan 5731 (22 %).

The number of N-fixing, phosphate-solubilizing and K-solubilizing bacteria were determined by counting the clear zones in the selective media. At the VT stage, there were no significant differences in the number of these bacteria in the root zone of the 4 maize varieties (**Table 5**). PAC 789 had the highest number of N-fixing and K-solubilizing bacteria in its root zone. The abundance of N-fixing bacteria in the root zone of PAC were higher than those of Suwan 4452 (167 %), Suwan 5819 (158 %) and Suwan 5731 (122 %). The abundance of K-solubilizing bacteria in the root zone of PAC 789 were greater than those of Suwan 4452 (33 %), Suwan 5819 (22 %) and PAC 789 (22 %). The abundance of phosphate-solubilizing bacteria in the root zone of PAC 789 was similar to that of Suwan 5819 (0.40×106 CFU g^{-1}), which was higher than that in the root zone of Suwan 4452 and Suwan 5731 (**Table 5**).

Table 5 Quantitative estimation of soil microbial bacteria in the root zone of 4 maize varieties (Suwan 4452, Suwan 5819, Suwan 5731 and PAC 789) at the VT stage.

Varieties	Total viable count on N-free medium (10^6 CFU g^{-1})	Total viable count on phosphate-containing medium (10^6 CFU g^{-1})	Total viable count on K-containing medium (10^6 CFU g^{-1})	N-fixing bacteria (10^6 CFU g^{-1})	Phosphate-solubilizing bacteria (10^6 CFU g^{-1})	K-solubilizing bacteria (10^6 CFU g^{-1})
Suwan 4452	6.67 ± 2.89	5.33 ± 0.58	7.00 ± 2.65	2.00 ± 1.00	0.37 ± 0.06	0.10 ± 0.00
Suwan 5819	8.67 ± 2.31	4.76 ± 1.53	7.67 ± 2.08	2.07 ± 2.57	0.40 ± 0.00	0.47 ± 0.32
Suwan 5731	6.67 ± 2.08	5.00 ± 1.73	7.67 ± 2.08	2.40 ± 1.97	0.33 ± 0.06	0.43 ± 0.29
PAC 789	9.00 ± 1.73	5.33 ± 2.08	9.33 ± 1.15	5.33 ± 1.53	0.40 ± 0.17	0.60 ± 0.26

Note: Values are mean ± SD; N = nitrogen; K = potassium.

Figure 6 shows the relative abundance of bacteria in the root zone of Suwan 4452, Suwan 5819, Suwan 5731 and PAC 789 at the VT stage. Overall, the root zone of the 4 maize varieties was heavily occupied by N-fixing bacteria. The highest relative abundance of N-fixing bacteria was found in the root zone of PAC 789 (84 %), and the highest relative abundance of phosphate-solubilizing and K-solubilizing bacteria was detected in the root zone of Suwan 4452 (15 %) and Suwan 5891 (16 %), respectively.

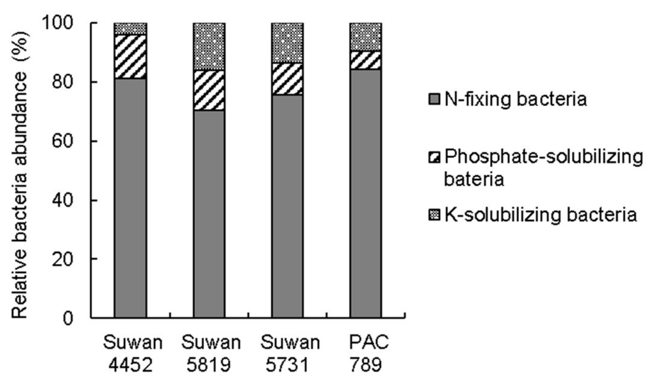

Figure 6 Relative bacteria abundance (%) in root zone soil of Suwan 4452, Suwan 5819, Suwan 5731 and PAC 789 at VT stage.

The rhizosphere is the zone of soil surrounding a plant root where the biology and chemistry of the soil are influenced by the roots of crops [33]. The bacteria living in this zone play a role in improving the nutrient status of host plants by increasing the availability of nutrients [34]. In this study, there were no statistically significant differences in the quantitative determination of bacteria in the root zone among the maize varieties at the VT stage. Overall, the number of N-fixing, phosphate-solubilizing and K-solubilizing bacteria in the root zone of PAC 789 was higher than that in the root zones of the 3 Suwan varieties (**Table 5**). While the effect of genotype on soil bacteria was not found to be statistically significant in this study, previous research by Aira *et al.* [35], Bouffaud *et al.* [11] and Peiffer *et al.* [12], has shown that the bacterial community structure of the rhizosphere in maize can be influenced by the host genotype. In this study, we observed that the relative abundance of bacteria differed among the maize varieties, with PAC 789 having the highest number of N-fixing bacteria, Suwan 4452 having the highest number of phosphate-solubilizing bacteria, and Suwan 5819 having the highest number of K-solubilizing bacteria. These findings suggest that the different maize varieties may select for specific bacterial communities in the rhizosphere, consistent with the notion that the host genotype can shape the bacterial community structure in this environment. However, we acknowledge that the effect of genotype on soil bacteria was not statistically significant in this study.

Conclusions

Our evaluation of different hybrid maize varieties grown in paddy soil after rice harvest during the dry season revealed that Suwan 5819 exhibited significantly higher plant height, estimated LAI and DMA yield than the other tested varieties at the VT stage. However, there were no significant differences in overall grain yield among all 4 varieties. Regarding soil properties, we found that the root zone of Suwan 5819 had less acidic conditions than the other varieties. Meanwhile, PAC 789 had the highest counts of N-fixing and K-solubilizing bacteria in the root zone soil, but there was no significant difference in bacterial count compared to the Suwan varieties.

Our findings suggest that selecting maize varieties with favourable agronomic characteristics and root zone soil properties is crucial for achieving optimal yields in paddy soil after rice harvest during the dry season. Suwan 5819 and PAC 789 may be suitable maize varieties for cultivation in such conditions.

Although our study only includes 1 year of field experiments, we acknowledge that longer-term studies and experiments conducted at different locations are needed to confirm and validate our findings. Future studies could investigate the stability and consistency of our results across multiple years and locations to provide a more comprehensive understanding of the agronomic characteristics and soil properties of different hybrid maize varieties grown in paddy soil after rice harvest during the dry season. However, our study contributes valuable insights into the growth and development of maize in paddy soil and provides a foundation for further research in this area.

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