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Key soil fertility determinants influencing rice yield in Malaysian paddy soils

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Abstract

Purpose

Soil fertility plays a crucial role in ensuring both the quality and quantity of agricultural crop production. However, determining the optimal parameters for regulating rice growth to enhance yield remains challenging, as the correlation between soil factors and rice yield has not been quantitatively assessed. The present work will examine the relationship between soil fertility and rice yield in Malaysia.

Methods

A Pearson correlation matrix heatmap was employed to quantitatively evaluate the relationships between soil chemical properties and rice yield of two paddy seed varieties, UiTM 1 and UiTM 5, cultivated across three regions in Perak, Kedah, and Johor. Furthermore, Principal Component Analysis (PCA) was utilised to elucidate the multivariate structure of soil fertility data and identify the dominant factors influencing yield variance.

Results

The results revealed that soil pH exhibited a stronger positive correlation with the yield of UiTM 5 ($r = 0.66$, $p<0.01$) compared to UiTM 1 ($r = 0.45$, p>0.05). In contrast, aluminium showed a stronger negative correlation with UiTM 5 (r = -0.87, p<0.01) than with UiTM 1 (r = -0.78, p<0.01), indicating a greater risk of aluminium toxicity in UiTM 5. The PCA identified two main components accounting for 78.2% of the total variance, suggesting that rice yield is strongly associated by the Soil Acidity and Cation Status Factor (PC2) rather than nitrogenous organic fertility alone. Among the five paddy fields studied, location A9 recorded the highest rice yields, with 9.29 mt/ha for UiTM 1 and 9.11 mt/ha for UiTM 5, which aligned with the optimal vector space for pH and cation exchange capacity in the PCA biplot. This superior performance may be attributed to the soil fertility at A9, which falls within the optimal critical range for rice cultivation.

Conclusion
The integration of correlation and multivariate analyses demonstrates that managing soil acidity and aluminium toxicity is a critical consideration for optimising productivity. Understanding these relationships provides valuable insights for improving soil management practices and enhancing rice production sustainability in Malaysia.

Keywords: Soil fertility; Rice; Rice Productivity; Paddy Field

1. Introduction

The Sustainable Development Goal "Zero Hunger" aims to eradicate hunger worldwide by 2030. However, since 2015, hunger and food insecurity have steadily increased due to a combination of factors, including the pandemic, conflict, climate change and widening inequalities [1]. In 2024, approximately 295 million people across 53 countries and territories were affected by acute food insecurity, reflecting an increase of nearly 14 million compared to the previous year, with the number of individuals experiencing extreme levels of hunger reaching its highest recorded level [2].

Rice is an important staple food, accounting for more than 50% of the world's food intake. Its crucial role in human nutrition has attracted much attention[3–5]. Eleven Asian countries account for around 87% of global rice production. Of these, eight countries alone are responsible for almost 35% of global rice exports[6], which emphasises the important role of rice as a staple food in the Asian diet.

In recent decades, sustainable initiatives across Southeast Asia have significantly increased rice production. The region has consistently generated a surplus, with rice production exceeding domestic demand, facilitating exports to other countries[7]. Despite economic progress over the past 40 years, food security remains fragile. Further, the global food crisis of 2008 and the recent COVID-19 pandemic have highlighted the urgent need for a stable, affordable, high-quality and sustainable food supply, especially for the poor. Therefore, a forward-looking vision for rice cultivation in Asia is crucial to guide future strategies and innovations[8].

Soil fertility plays a critical role in shaping the yield and quality of staple crops. [9]. One of the major challenges in rice production is low soil fertility, which is exacerbated by limited resources to improve it[10–12]. Soil quality is not a tangible technology that can be bought, but a guiding concept for informed land management decisions. While researchers largely agree on the key soil properties that influence soil functionality, they also emphasise that soil quality must be interpreted in the specific context of use and environment[13].

Multiple factors are recognised to affect rice production in Malaysia, and any adverse disturbance to these elements could provide considerable hurdles to the sector's sustainability. Key concerns include climate change, dependency on market forces, elevated production costs, restricted land availability, reliance on subsidies, and inadequate technology and infrastructure[14]. Soil fertility of paddy fields in Asian has been reported in several papers. Ladha et al.[11]reported a decline in rice and wheat yields in India, Nepal, China and Bangladesh and attributed this trend to changes in the quantity and quality of soil organic matter (SOM). These changes, which affect nutrient availability and soil structure, remain a major concern. Muon et al.[15] investigated soil fertility in Cambodian rice fields. In their work, they reported the influence of termite bioturbation on soil parameters that include the percentage (%) of carbon (C), nitrogen (N), clay, concentration of phosphorus (P), potassium (K), electrical conductivity (EC) and pH measurement. In addition, Iqbal et al.[16] also investigated soil fertility in rice fields and pointed out the importance of soil for the quality of rice. Oechaiyaphum et al.[17]conducted a study to enhance soil fertility in rice fields of Northeastern Thailand. The authors state soil organic carbon (SOC) is an essential indicator of soil quality and soil fertility. Zheng et al.[18] investigated paddy soil fertility characteristics, including SOM, total N, P, K and soil pH at different stages of rice cultivation. This research sheds light on how these important soil properties change over time and contribute to a deeper understanding of sustainable agricultural practises in rice fields.

Despite these available reports, research and studies evaluating the connection between soil quality of paddy fields and rice yield are scarce and remain significantly underdeveloped. Recently, Chen et al.[19] investigated the relationships between soil variables and common soil microbial communities on smallholder farms in the Danxia Mountain region of Guangdong Province, China. However, their study did not report on the direct effects of these variables on rice yield. In a more recent study, Sahoo et al.[20] used machine learning to predict rice yield gaps in eastern India, taking into account factors such as altitude, soil moisture, rainfall, temperature, soil temperature and evapotranspiration.

The relationship between crop yield and soil is highly complex, involving intricate interactions between physical and chemical properties. Simple linear functions are often inadequate to describe these relationships because intercorrelations among soil properties can lead to multicollinearity problems. Consequently, a multivariate approach is essential to capture the combined effects of interacting soil properties and to identify the underlying integrated gradients that define soil fertility status.

Therefore, this paper presents a comprehensive correlation analysis of soil physicochemical properties and their influence on rice yield in paddy fields across Perak, Kedah, and Johor regions. The significance of this study lies in its integrated evaluation of multiple soil fertility parameters across different paddy field locations within a consistent sampling period, allowing for robust spatial comparison. By elucidating soil-yield relationships using statistical analyses, the study provides valuable insights for improving site-specific soil fertility management and enhancing rice productivity in Malaysian paddy systems.

2. Material and methods

2.1. Study area and field management

Soil samples were collected from five paddy field sites located in Perak (Teluk Intan and Titi Serong), Kedah (Sanglang and Alor Setar), and Johor (Sungai Balang) (Table 1). The study was conducted in major paddy-growing regions across Peninsular Malaysia, including Kedah, Perak, and Johor, which represent distinct agro-climatic zones. Kedah and Perak are located in the northern part of the west coast of Peninsular Malaysia. Rainfall in Kedah and Perak follows a bimodal pattern typical of the north-western region of Peninsular Malaysia, with two periods of higher rainfall occurring during October–November and April–May[21]. Johor, situated in the southern part of Peninsular Malaysia, has experienced increasing occurrences of both floods and droughts due to alterations in rainfall distribution. A series of major flood events recorded in 2006 to 2020 are indicative of evolving climatic conditions associated with climate change[22].

These sites span a broad latitudinal range (approximately 1.9-6.3° N) and represent contrasting agro-ecological conditions, management histories, and soil environments typical of Malaysian lowland rice systems. The total sampled area across all sites was approximately 0.5 acres. Although relatively small in spatial extent, the selected fields were chosen to capture variability in soil chemical properties and yield performance under real-world farmer-managed conditions rather than controlled experimental plots. Mean daily temperatures across sites ranged from 27.59 to 29.64 °C, while the number of days with rainfall (≥ 1.0 mm) varied markedly among locations, from 138 to 263 days per year, reflecting differences in regional climate and water availability.

All paddy fields were managed under conventional flooded rice cultivation systems. Irrigation was primarily supplied through gravity-fed canal networks managed by local agricultural authorities, supplemented by rainfall during the main growing season. Fertilization practices followed standard regional recommendations and typically involved split applications of nitrogen (N), phosphorus (P), and potassium (K) fertilizers. However, the exact fertilizer rates, timing, and formulations varied among sites according to local management practices and farmer decision-making.

Cropping history at all sites consisted predominantly of continuous rice cultivation, with one to two cropping cycles per year depending on water availability and regional planting schedules. No recent land-use conversion or major soil amendment (e.g., large-scale liming or organic matter incorporation) was reported at the time of sampling. These variations in management history and fertilization regimes were not experimentally imposed but represent inherent field-level differences, which were accounted for in the interpretation of soil–yield relationships. To improve transparency and reproducibility, key site characteristics, climatic variables, and available management information are summarised in Table 1.

Climate data for each study site were retrieved from publicly accessible databases (Weather and Climate), which generate location-specific estimates using data from nearby meteorological stations combined with interpolated datasets. These data represent long-term monthly averages and were used to characterise the overall climatic conditions of the study areas. In the absence of site-specific climate data for Sungai Balang, Batu Pahat was selected as the closest representative location due to its geographical proximity and comparable climatic conditions. Likewise, as no direct climate data were available for Titi Serong, Parit Buntar was used as the nearest representative site based on similar proximity and climatic characteristics.

Table 1. Location and climatic characteristics of selected paddy field sites.

[a]Sample [b]Sampling month	Location	[a]Longitude [b]Latitude	Temperature for daily mean °C	Number of days with rainfall (≥ 1.0 mm)	Reference
[a]A4 [b]September	Teluk Intan, Perak	4°05'55.5"N 101°02'48.5"E	29.64	263.43 days (72.17%)	[23]

[a]A5 [b]September	Titi Serong, Perak	5°06'18.4"N 100°27'36.4"E	27.59	245.18 days (67.17%)	[24]
[a]A6 [b]September	Ayer Hitam, Kedah	6°20'27.7"N 100°15'37.4"E	29.28	187.04 days (51.24%)	[25]
[a]A7 [b]September	Sg. Balang, Johor	1.903367 N, 102.748348 E	28.90	138.05 days (37.82%)	[26]
[a]A9 [b]October	Alor Setar, Kedah	6°03'33.1"N 100°26'35.5"E	28.96	191.47 days (52.46%)	[27]

2.2. Collection and treatment of soil samples

No experimental treatments were imposed at any of the study sites. Instead, this study was designed as an observational field investigation in which differences among sites reflect inherent soil physicochemical properties and site-specific management practices, rather than controlled or experimentally manipulated treatments. Each paddy field therefore represents a distinct field condition shaped by long-term soil formation processes, cropping history, fertilization regimes, irrigation practices, and local environmental factors.

Prior to sample collection, formal permission was obtained from the respective landowners/farmers and local agricultural authorities, and all sampling activities were conducted with their consent and cooperation. The soil samples were taken from the surface layer using a hand auger and a depth is 20 cm from the land surface. Using the X method of sample collection, few effective sample points were collected (Figure 1). At all sampling points, the researchers adhered to the following rules: 1) the distance from each points are approximately 2.0 meters among points; 2) the total collected samples were mixed within 24 hours to avoid random errors; 3) the longitude and latitude coordinates of the center of the quadrat were recorded using smartphones; and 4) Large amount of soil samples was reduced to small quadrant of samples. The protocol of the sample collection was followed Luo et al. [28] and Tenedero & Surtida,[29] with slight modifications. The collected soil samples were poured onto the plastic sheet, mixed thoroughly, and dried under the air drying and avoiding direct sunlight. To aid in the drying process, the soil samples were broken down into smaller portions, and unwanted materials like stones, roots, and pebbles were manually removed. The samples were then subjected to quartering by thoroughly mixing and dividing them into four equal parts. Two opposite quarters were discarded, and the remaining portions were mixed again. This procedure was repeated until one kilogram representative sample was obtained. The soil samples were ground and passed through a 2-mm sieve following the method suggested by[30]. Then the samples were sent to a professional laboratory to measure their soil parameters. The sample collection is shown in Figure 2.

2.3 Soil samples analysis

The soil characteristics, including dry matter and water content, were assessed using the gravimetric method (ISO 11465). The pH was determined through water and potassium chloride extraction at a 1:5 ratio (NEN-ISO 10390). Particle size distribution, to indicate the percentage of clay, was measured via laser diffraction (In-house procedure based on ISO 11277:2009 and NEN 5753:2006). Total carbon (C) and nitrogen (N) content were analysed using the DUMAS method (NEN-EN 16168:2012), while organic carbon was determined by dry combustion through instrumental analysis (NEN-EN 15936:2012). The levels of potassium, calcium, magnesium and CEC were analysed via Hexamminecobalt trichloride extraction using ICP-MS (ISO 23470:2007). Total aluminium (Al), total iron (Fe), phosphorus (P), were quantified using X-ray fluorescence spectrometry, pelletised samples (ISO 18227:2014). All soil sample analyses were performed by Soil Analytic Sdn. Bhd. (Serdang, Malaysia) and the methods were followed in accordance with their established laboratory protocols and referenced standards.

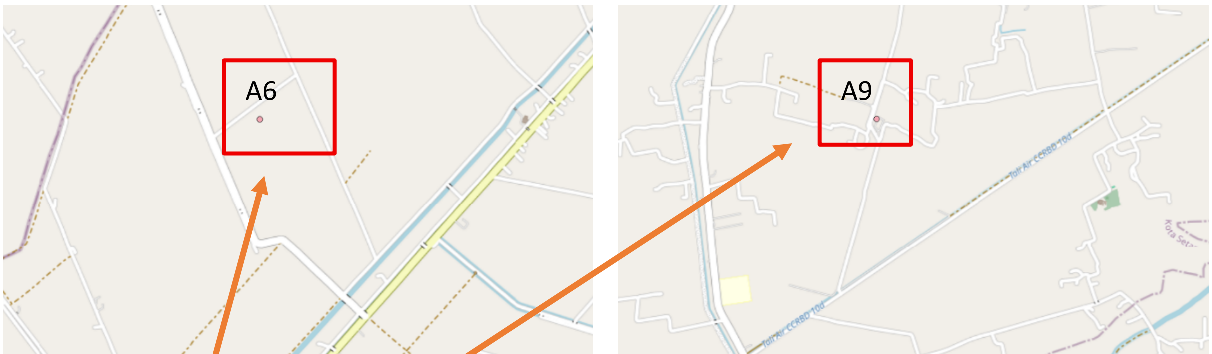


Figure 1. Location of the study sites in Peninsular Malaysia and detailed views of the five paddy fields (A4, A5, A6, A7, and A9). All map panels are presented at a uniform scale of 1:15,000. The maps were generated using QGIS Desktop (version 3.34 LTR; https://qgis.org) with base map data from OpenStreetMap (© OpenStreetMap contributors).

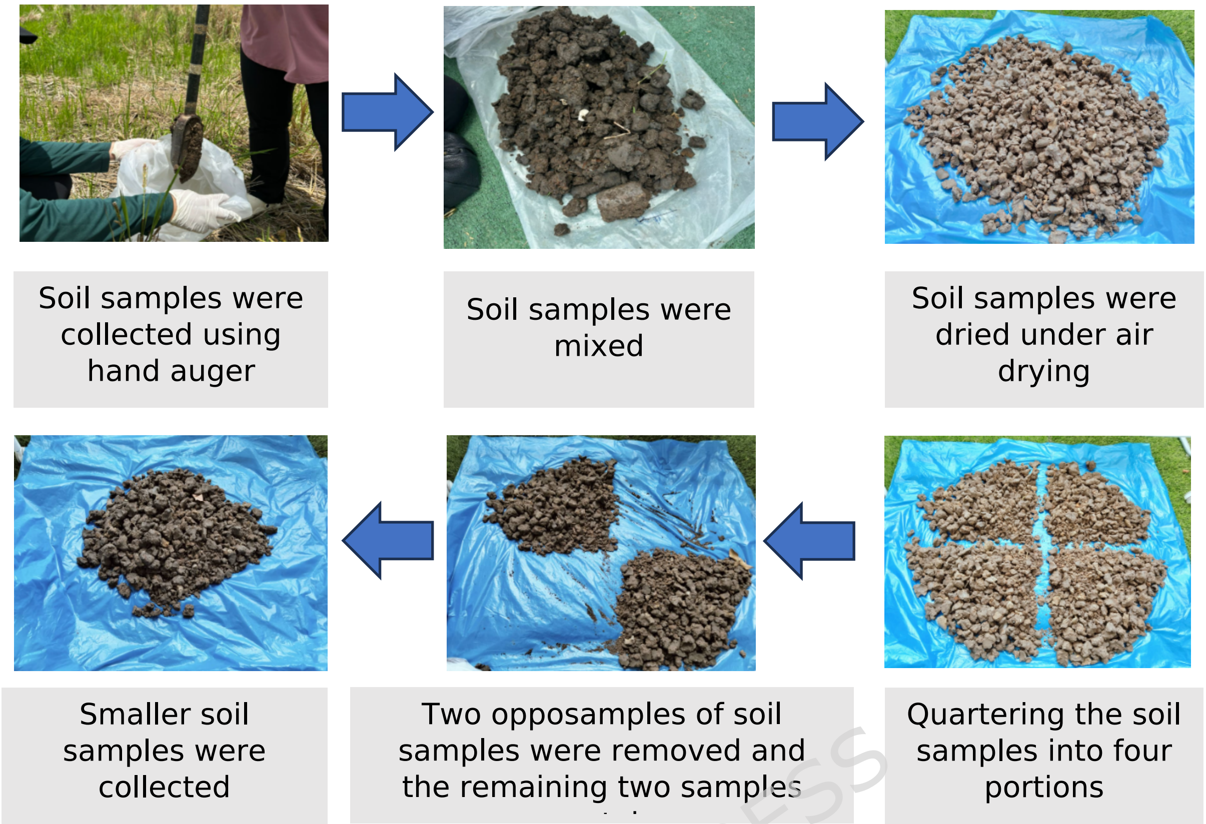


Figure 2. Sample collection and quartering process[31].

2.4 Rice Planting Experiment

Two rice lines developed by Universiti Teknologi MARA (UiTM) were used in this study. UiTM 1 is an advanced mutant line developed through gamma-ray irradiation, whereas UiTM 5 was developed using marker-assisted backcrossing. Both lines are classified at Technology Readiness Level (TRL) 6.

2.5 Germination, transplanting, and rice yield

The seeds will initially be sown in trays containing soil to promote germination. After three weeks, the seedlings will be transplanted into the designated block using a randomised complete block design (RCBD), with three seedlings per hill. Each block will measure 2m x 2m, consisting of 8 hills by 8 hills. Each row of blocks will serve as a replicate, with 3 blocks representing 3 replicates. The plants in the first replicate will be randomly arranged in block 1, and the same process will be followed for replicates 2 and 3. Agronomic traits related to rice productivity were evaluated to assess their association with yield per hill. Grains harvested from each hill were cleaned, sun-dried, and weighed to determine the yield per hill.

2.6 Statistical analysis

Descriptive statistics, including mean, standard deviation (SD), and coefficient of variation (CV), were computed for all measured soil chemical properties across the five study areas (A4, A5, A6, A7, and A9). These parameters provided insights into the central tendency and variability of soil pH, cation exchange capacity (CEC), soil moisture (SM), total aluminium (Al), total Iron (Fe), calcium exhange (Ca^{2+}), magnesium exchange (Mg^{2+}) and potassium exchange (K^{+}). In addition, organic matter (OM), organic carbon (OC), phosphorus (P), nitrogen (N), and potentially mineralizable nitrogen (PMN) and percentage of clay were determined. Statistical significance was determined at the 95% confidence level ($p < 0.05$).

To explore the relationships between rice yield and soil chemical properties, Pearson correlation analysis was conducted. Statistical significance was evaluated at both the 95% and 99% confidence levels ($\alpha = 0.05$ and 0.01, respectively). This analysis aimed to identify key soil parameters that significantly influence rice productivity. Furthermore, Principal Component Analysis (PCA) was performed to elucidate the multivariate relationships and underlying structures within the soil fertility data. The PCA allowed for the identification of major factors contributing to the variance in soil properties and their collective influence on rice yield.

All statistical analyses were performed using R software (version 4.4.3). Pearson correlation coefficients were calculated using the psych package, while hierarchical partitioning was conducted with the hier.part package. Data visualization and graphical outputs were generated using the ggplot2 package to enhance interpretability and presentation of the results.

3. Results

3.1 Soil physicochemical properties

Table 2 shows the summary of soil physicochemical in different paddy field. The results indicate significant differences ($p < 0.05$) across all measured parameters among the study areas. Soil pH values ranged from slightly acidic to near neutral, with A6 exhibiting the highest mean pH (6.13). The highest mean cation exchange capacity (CEC), a critical indicator of soil fertility, was highest in A7 (192.00 $mmol^{+}/kg$) followed by A6 (186.67 $mmol^{+}/kg$), indicating a greater capacity to retain essential nutrients in these areas. In contrast, A4 recorded the lowest mean CEC (80.67 $mmol^{+}/kg$), potentially limiting nutrient retention. The highest mean soil moisture (SM) was most pronounced in A7 (36.77%). Sample A5 contain the highest mean total Aluminium (Al) (111.87 g/kg) and Iron (Fe) (53.47 g/kg), which could pose toxicity risks to plants.

Soil fertility at each sample (A4, A5, A6, A7 and A9) was assessed using the critical range thresholds (see Table 2). The results show that all samples have low soil pH, except for A6. The CEC is in the acceptable range at all paddy field, indicating that the soil is well able to bind important nutrients. Consequently, the exchangeable calcium and magnesium content is high in all paddy field. Amount of K are adequate at paddy field A4 and A5 and elevated at A6, A7 and A9. However, the consistently high total Fe content at all paddy field raises concerns about possible Fe toxicity. In addition, most paddy field have a high percentage of clay, except for A9. These results will serve as a basis for further analyses regarding the yield performance of rice.

Table 2: Summary of soil physicochemical properties in different paddy field.

Area	Item	pH	CEC (mmol+/kg)	SM	Al (g/kg)	Fe (g/kg)	Ca^{2+} (mmol+/kg)	Mg^{2+} (mmol+/kg)	Clay (%)	OM (%)	OC (g/kg)	P (mg/kg)	N (g/kg)	PMN (mg N/kg)	K^{+} (mmol+/kg)
A4	Max	5.40	88.00	23.00	106.80	43.10	36.60	19.80	59.00	3.50	20.20	6.40	2.40	88.30	2.20
	Min	5.20	75.00	20.00	103.50	35.00	25.40	12.70	54.00	3.20	18.80	2.60	2.00	74.00	1.70
	Mean	5.27	80.67	21.90	105.53	40.37	30.90	17.17	57.33	3.37	19.63	4.10	2.20	81.27	1.97
	SD	0.12	6.66	1.65	1.78	4.65	5.60	3.89	2.89	0.15	0.74	2.02	0.20	7.15	0.25
	CV (%)	2.19	8.25	7.54	1.69	11.51	18.13	22.65	5.04	4.54	3.75	49.33	9.09	8.80	12.80
A5	Max	5.50	115.00	25.10	115.20	58.00	56.50	27.20	54.00	4.30	24.70	25.80	2.50	92.00	2.50
	Min	5.30	87.00	21.10	107.90	48.90	36.70	15.70	47.00	3.70	21.60	13.30	2.30	85.80	2.30
	Mean	5.43	105.33	23.07	111.87	53.47	45.17	21.63	51.00	3.97	22.93	17.63	2.40	88.13	2.40
	SD	0.12	15.89	2.00	3.69	4.55	10.21	5.76	3.61	0.31	1.59	7.08	0.10	3.37	0.10
	CV (%)	2.13	15.08	8.67	3.30	8.51	22.60	26.62	7.07	7.70	6.95	40.13	4.17	3.83	4.17
A6	Max	6.20	210.00	22.00	91.10	42.90	130.20	59.30	45.00	4.10	23.50	68.10	2.30	85.70	5.80
	Min	6.00	169.00	17.90	71.60	36.50	102.30	34.90	37.00	3.20	18.70	31.80	1.90	68.70	5.20
	Mean	6.13	186.67	20.17	83.17	39.00	114.97	48.20	42.33	3.77	21.83	45.03	2.13	78.77	5.43
	SD	0.12	21.08	2.08	10.25	3.42	14.13	12.35	4.62	0.49	2.72	20.05	0.21	8.92	0.32
	CV (%)	1.88	11.29	10.33	12.32	8.77	12.29	25.62	10.91	13.10	12.44	44.52	9.76	11.33	5.92
A7	Max	5.50	232.00	42.50	109.20	44.10	89.40	81.20	54.00	11.80	68.50	0.60	5.00	198.00	3.80
	Min	5.10	169.00	31.00	97.60	34.60	45.80	59.60	49.00	7.50	43.60	0.30	3.30	126.00	2.30
	Mean	5.33	192.00	36.77	102.20	38.07	60.93	69.03	51.00	10.03	58.20	0.43	4.40	172.67	3.20
	SD	0.21	34.77	5.75	6.16	5.24	24.67	11.06	2.65	2.25	13.00	0.15	0.95	40.46	0.79
	CV (%)	3.90	18.11	15.64	6.03	13.78	40.49	16.02	5.19	22.43	22.33	35.25	21.68	23.43	24.80
A9	Max	5.90	117.00	20.60	64.00	27.40	51.60	23.10	31.00	4.50	26.00	25.20	2.30	88.40	3.10
	Min	5.70	102.00	18.70	59.50	26.00	43.70	21.30	30.00	4.00	23.40	20.40	2.10	80.00	3.00
	Mean	5.77	109.67	19.70	61.20	26.83	47.10	22.00	30.67	4.20	24.43	22.33	2.20	83.37	3.07
	SD	0.12	7.51	0.95	2.44	0.74	4.06	0.96	0.58	0.26	1.38	2.53	0.10	4.44	0.06
	CV (%)	2.00	6.84	4.84	3.99	2.75	8.63	4.38	1.88	6.30	5.65	11.34	4.55	5.33	1.88
	Significance	*P*<0.001	*P*<0.001	*P*<0.001	*P*<0.001	*P*<0.001	*P*<0.001	*P*<0.001	*P*<0.001	*P*<0.001	*P*<0.001	*P*<0.001	*P*<0.001	*P*<0.001	*P*<0.001

Note: SD was standard deviation, CV was coefficient of variation ^{a}Sample Location, ^{b}Organic matter, ^{c}Phosphorus, ^{d}Total N, ^{e}Potassium, ^{f}Calcium, ^{g}Magnesium, ^{h}Organic carbon, ^{i}Potentially Mineralizable Nitrogen, ^{j} Cation Exchange Capacity

Table 3: Soil fertility ratings and rice yield (mt/ha) of five paddy fields.

Parameter	Unit	Critical range (low-high)	Paddy field				
			A4	A5	A6	A7	A9
pH (water)	pH Value	6.0-7.2	5.27	5.43	6.13	5.33	5.77
Cation Exchange Capacity	mmol+/kg	75-200	80.67	105.33	186.67	192.00	109.67
Soil moisture	%	10-30	21.90	23.07	20.17	36.77	19.70
Total Aluminium	g/kg	94-115	105.53	111.87	83.17	102.20	61.20
Total Iron	g/kg	5-8	40.37	53.47	39.00	38.07	26.83
Calcium (exch.)	mmol+/kg	15-25	30.90	45.17	114.97	60.93	47.10
Magnesium (exch.)	mmol+/kg	4.5-10	17.17	21.63	48.20	69.03	22.00
Clay	%	20-40	57.33	51.00	42.33	51.00	30.67
Organic matter	%	2.9-6.2	3.37	3.97	3.77	10.03	4.20
Organic Carbon	g/kg	17-50	19.63	22.93	21.83	58.20	24.43
Phosphorus	mg/kg	20-40	4.10	17.63	45.03	0.43	22.33
Total Nitrogen	g/kg	1-2	2.20	2.40	2.13	4.40	2.20
Potentially Mineralizable Nitrogen	mg N/kg	22-32	81.27	88.13	78.77	172.67	83.37
Potassium (exch.)	mmol+/kg	1.5-3	1.97	2.40	5.43	3.20	3.07
Rice yield (UiTM 1)	mt/ha	-	5.33	4.55	6.78	4.94	9.29
Rice yield (UiTM 5)	mt/ha	-	4.91	4.36	7.75	5.52	9.11

Low; Adequate; High

Actual measured soil properties were first obtained from laboratory analyses. These quantitative values are presented in Table 4, while Table 3 summarises the soil fertility status using categorical classes (Low, Adequate, High) based on critical ranges provided by Soil Analytic Sdn. Bhd. (Serdang, Malaysia). The highest rice yield was recorded at site A9 for both UiTM 1 (9.29 mt/ha) and UiTM 5 (9.11 mt/ha), indicating optimal conditions for paddy productivity at this site. Interestingly, the high total Fe content in A9 did not appear to have a negative effect on yield, possibly due to balancing factors such as adequate P, SOC, clay content and SM. In addition, adequate CEC likely contributed to higher availability of important cations such as K, Ca and Mg. Site A6 also performed strongly, especially at UiTM 5 (7.75 mt/ha), indicating that adequate pH, SOM, CEC and SM created favourable conditions for rice growth. In contrast, A5 recorded the lowest yield. Since the soil fertility parameters did not show any critical anomalies, the lower productivity might be attributed to other factors such as rice diseases or sub-optimal rice field management practises.

3.2 The correlation analysis between soil chemical properties and rice yields

A Pearson correlation analysis of rice varieties of UiTM 1 and UiTM 5 were conducted to determine the relationship between selected soil fertility indicators and rice yield (Figure 3 and Figure 4). The correlation matrix of

UiTM 1 reveals several significant associations that highlight the influence of soil physicochemical properties on paddy productivity in the studied fields. Among the measured parameters, soil pH showed a moderate positive correlation with rice yield ($r=0.45$, $p>0.05$), although it was not statistically significant. Statistical analysis indicates that as soil pH increases from 5.1 to 6.2, rice yield also tends to increase. In contrast, rice variety of UiTM 5 exhibited a stronger and statistically significant positive correlation ($r=0.66$, $p<0.01$), indicating that higher pH towards 6.2 promotes paddy growth and contributes significantly to the yield. Acid sulphate soils are characterised by the presence of pyrite (an iron sulphide mineral) or its oxidation byproducts, which develop under prolonged waterlogged conditions. The accumulation of H^+ ions relative to OH^- ions in the soil solution leads to a pH below 4 in these soils. Acid sulphate soils commonly exhibit phosphorus deficiency, which limits rice growth [32].

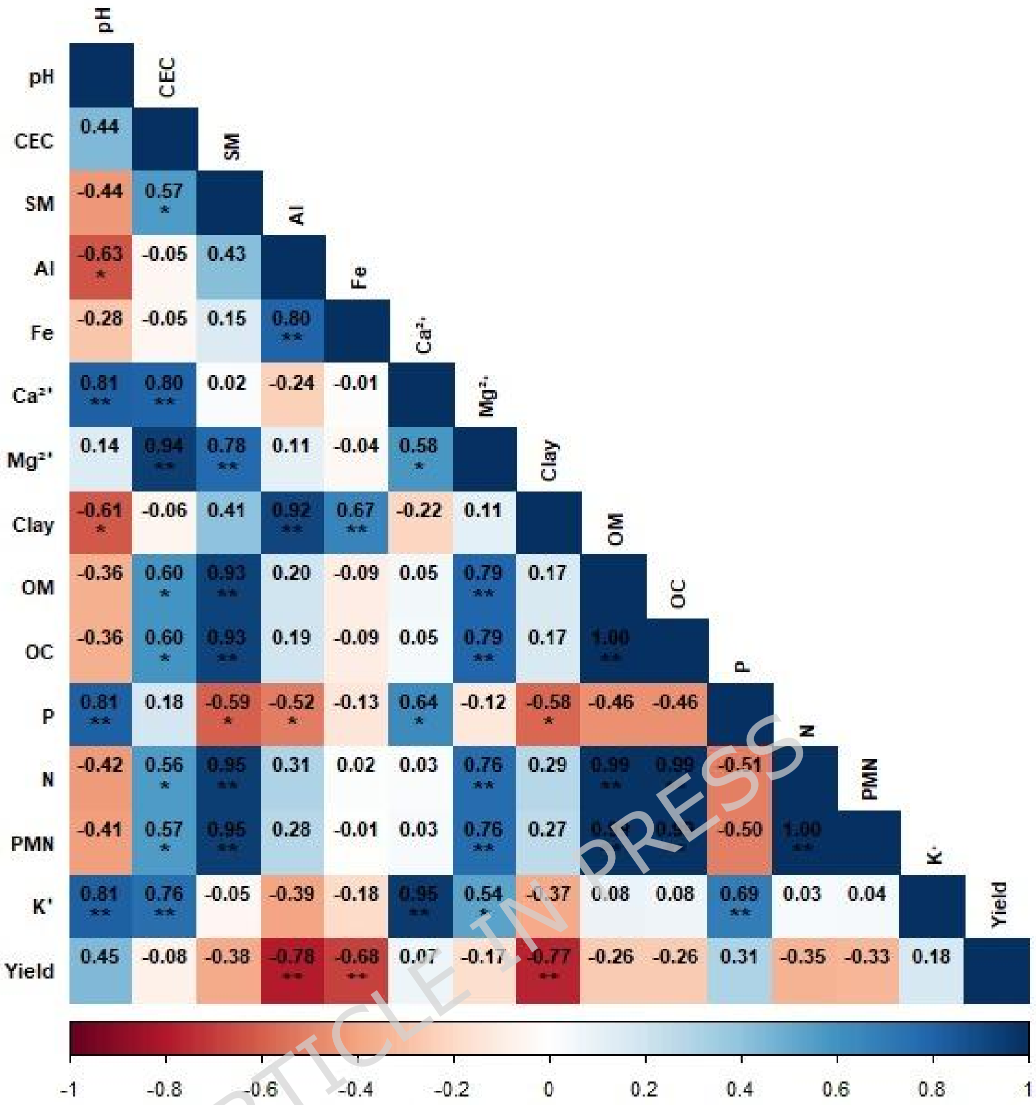
In contrast to pH, a number of soil parameters showed strong negative correlations with rice yield. One of the parameters is Al which has a relationship with pH. In this study, an increase of total Al from 59.50 to 115.20 demonstrated a decrease in rice yield. Notably, Al content demonstrated strong inverse relationship to rice yield for seed UiTM 1 ($r=-0.78$, $p<0.01$), indicating that higher levels of exchangeable Al can severely inhibit plant growth and root development. Seed UiTM 5 showed a stronger negative correlation with rice yield ($r=-0.87$, $p<0.01$), indicating a greater sensitivity to growth conditions. In contrast, Seed UiTM 1 demonstrated higher resilience to total Al stress.

In the Pearson correlation matrix, total Al has a moderate negative correlation with P ($r=-0.52$, $p<0.01$) indicates the presence of Al^{3+} decrease the available phosphate in a soil. At pH 4.5, Al^{3+} ions form sparingly soluble Al–phosphate complexes, which significantly reduce phosphorus availability to crop plants according to the reaction $Al^{3+}+H_2PO_4-\rightarrow AlPO_4 +2H^+$ [33] which aligns with Hsu et al. [34] whose discuss phosphate fixation via Al^{3+} in acid soils. A soil is considered as deficient in available P when it is less than 5 $mgkg^{-1}$ [35, 36] therefore location A7 suffered greatly by insufficient P in a soil.

In the present work, CEC exhibited strong positive correlation with K^+ ($r = 0.76$), Ca^{2+} ($r = 0.80$) and Mg^{2+} ($r = 0.94$), all significant at $p<0.01$. This indicates a significant capability of the soil to assist the exchange of the cation in the soil. In the analysis, CEC has a moderate positive correlation to an OM and OC ($r=0.60$** both). Our findings revealed comparable correlations between CEC and SOC fractions to those reported by Kim et al. [37] who examined the relationship in paddy fields in South Korea. In their study, CEC showed moderate positive correlations with three SOC fractions, with correlation coefficients of $r=0.68$, $r=0.47$, and $r=0.67$, respectively. These results suggest that the influence of SOC on CEC is consistent across different paddy soil conditions. However, CEC showed a very weak and non-significant correlation with rice yield for seed UiTM 1 (r=-0.08, p>0.05) and seed UiTM 5 (r=0.14, p>0.05), suggesting that higher CEC values (55 to 232 $mmol^+/kg$) might be associated with a slight decrease in rice yield, although the relationship appears negligible.

SOM exhibited the strongest positive correlation to SOC (r=1.00), N (r=0.99) and PMN (r=0.98), all highly significant (p<0.01). However, SOM exhibited a weak and non-significant correlation with rice yield for both UiTM 1 (r=-0.26, p>0.05) and UiTM 5 (r=-0.17, p>0.05). This finding contrasts with the review by Zhang et al. [38] which reported that the management of mineral N and SOM resulted in yield increases of 412% and 8.7%, respectively. The discrepancy may be explained by variations in agroecological conditions, since Zhang's study was conducted in China, whereas our investigation focused on Malaysian paddy fields.

In the present analysis, total N showed the strongest correlation with PMN (r=1.00, p<0.01). This highlights the importance of assessing N as a key indicator for evaluating soil fertility, as agreed by Liu et al. [39]. Besides, Hirzel et al. [40] investigated the role of PMN in relation to rice production and nitrogen requirements in two paddy rice soils in Chile. In their work, one of the soils, namely Quella, with a pH of 6.02, showed a strong linear relationship between soil available nitrogen and grain yield (R^2=0.89), suggesting that available N is a crucial factor for plant growth and productivity.



	pH	CEC	SM	Al	Fe	Ca^{2+}	Mg^{2+}	Clay	OM	OC	P	N	PMN	K^+	Yield
pH															
CEC	0.44														
SM	-0.44	0.57 *													
Al	-0.63 *	-0.05	0.43												
Fe	-0.28	-0.05	0.15	0.80 **											
Ca^{2+}	0.81 **	0.80 **	0.02	-0.24	-0.01										
Mg^{2+}	0.14	0.94 **	0.78 **	0.11	-0.04	0.58 *									
Clay	-0.61 *	-0.06	0.41	0.92 **	0.67 **	-0.22	0.11								
OM	-0.36	0.60 *	0.93 **	0.20	-0.09	0.05	0.79 **	0.17							
OC	-0.36	0.60 *	0.93 **	0.19	-0.09	0.05	0.79 **	0.17	1.00 **						
P	0.81 **	0.18	-0.59 *	-0.52 *	-0.13	0.64 *	-0.12	-0.58 *	-0.46	-0.46					
N	-0.42	0.56 *	0.95 **	0.31	0.02	0.03	0.76 **	0.29	0.99 **	0.99 **	-0.51				
PMN	-0.41	0.57 *	0.95 **	0.28	-0.01	0.03	0.76 **	0.27	0.99 **	0.99 **	-0.50	1.00 **			
K^+	0.81 **	0.76 **	-0.05	-0.39	-0.18	0.95 **	0.54 *	-0.37	0.08	0.08	0.69 **	0.03	0.04		
Yield	0.45	-0.08	-0.38	-0.78 **	-0.68 **	0.07	-0.17	-0.77 **	-0.26	-0.26	0.31	-0.35	-0.33	0.18	

Figure 3. *Pearson correlation matrix heatmap illustrating the relationships between soil chemical properties and rice yield for paddy seed* ***UiTM 1****. Parameters include pH, cation exchange capacity (CEC), soil moisture (SM), aluminium (Al), iron (Fe), calcium (Ca^{2+}), magnesium (Mg^{2+}), clay content, organic matter (OM), organic carbon (OC), phosphorus (P), nitrogen (N), potentially mineralizable nitrogen (PMN), potassium (K^+), and yield. The color gradient represents correlation strength, ranging from -1 (strong negative, red) to +1 (strong positive, blue). Statistically significant correlations are denoted by asterisks:***$p < 0.05$*, ***$p < 0.01$.

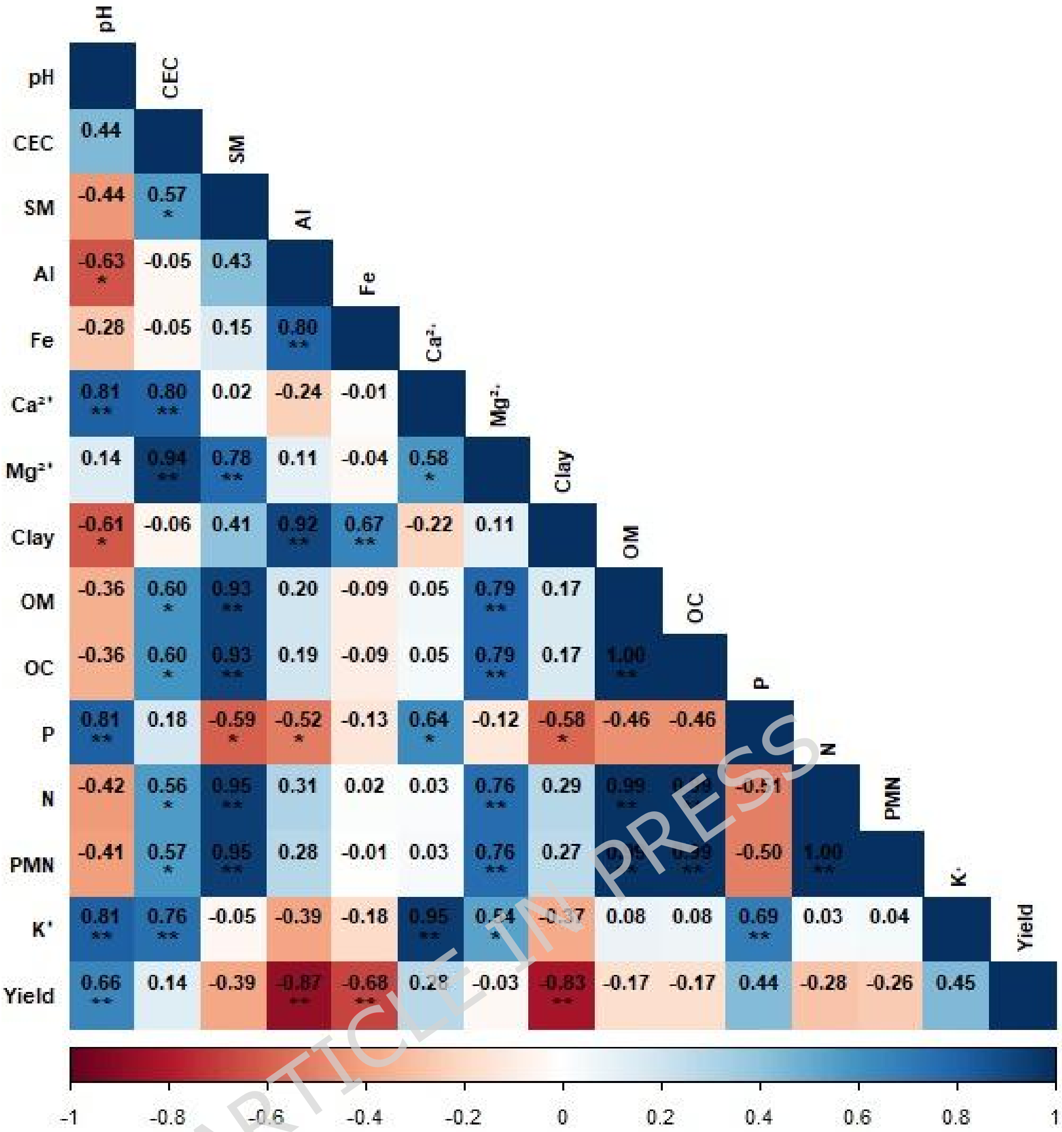


Figure 4. *Pearson correlation matrix heatmap illustrating the relationships between soil chemical properties and rice yield for paddy seed* ***UiTM 5****. Parameters include pH, cation exchange capacity (CEC), soil moisture (SM), aluminium (Al), iron (Fe), calcium (Ca^{2+}), magnesium (Mg^{2+}), clay content, organic matter (OM), organic carbon (OC), phosphorus (P), nitrogen (N), potentially mineralizable nitrogen (PMN), potassium (K^+), and yield. The color gradient represents correlation strength, ranging from -1 (strong negative, red) to +1 (strong positive, blue). Statistically significant correlations are denoted by asterisks:* $*p < 0.05$, $**p < 0.01$.

3.3 Multivariate Analysis: Principal Component Analysis (PCA)

To provide a more comprehensive understanding of the complex multivariate relationships between soil fertility properties and rice yield, a Principal Component Analysis was conducted. This analysis effectively captured 78.2% of the total variance through the first two principal components, which are detailed in Table 4 and visualised in the PCA Biplot (Figure 5).

The first component, PC1, accounts for 45.5% of the total variance and represents the Soil Organic Fertility Factor. It is characterised by high positive loadings for soil moisture (SM, 0.99), organic matter (OM, 0.93), organic carbon (OC, 0.93), total nitrogen (N, 0.97) and potentially mineralizable nitrogen (PMN, 0.96). This axis reflects the basal organic matrix of the soil, contributing to the overall soil fertility status rather than acting as an immediate yield-limiting factor in the studied regions.

The second component, PC2, explains 32.7% of the variance and represents the Soil Acidity and Cation Status Factor. This component shows strong positive loadings for soil pH (0.78), cation exchange capacity (CEC, 0.83) and exchangeable bases such as potassium (K^+, 0.92), (Mg^{2+}, 0.66) and calcium (Ca^{2+}, 0.85). Conversely, it exhibits a significant negative loading for exchangeable aluminium (Al, -0.60). PC2 represents an integrated soil acidity and cation status gradient, where the chemical environment is modulated by the interplay between pH, buffering capacity and toxic elements, providing multivariate evidence of associations rather than definitive cause effect relationships.

Regarding the relationship with rice yield, the Figure 5 biplot reveals that yield is positioned in the upper-left quadrant and shows a close vector alignment with pH, and available phosphorus (P). Such an alignment suggests that higher pH levels and available pH status are the key associative factors of productivity in these acid sulphate soils.

In contrast, the vector for aluminium (Al) is oriented in the opposite direction to the rice yield vector along the PC2 axis. This 180° spatial arrangement provides robust multivariate evidence of the antagonistic relationship between Al-toxicity and rice productivity. While PC1 contributes to the general soil profile, the variance in rice yield is more significantly explained by the acidity-related variables captured in PC2. These findings justify the prioritization of liming and soil acidity management to alleviate Al-stress and enhance yield for both UiTM 1 and UiTM 5 varieties.

Table 4. Component loadings of soil chemical properties and rice yield.

Soil Properties	**PC1**	**PC2**
pH	-0.57*	**0.78****
Cation Exchange Capacity (CEC)	0.49	**0.83****
Soil Moisture (SM)	**0.99****	0.13
Exchangeable Aluminium (Al)	0.57*	**-0.60***
Iron (Fe)	0.24	-0.46
Calcium (Ca^{2+})	-0.06	**0.85****
Magnesium (Mg^{2+})	**0.73****	**0.66***
Clay	0.55*	**-0.58***
Organic Matter (OM)	**0.93****	0.30
Organic Carbon (OC)	**0.93****	0.30
Available Phosphorus (P)	**-0.66***	**0.56***
Total Nitrogen (N)	**0.97****	0.22
Potentially Mineralizable Nitrogen (PMN)	**0.96****	0.23
Potassium (K^+)	-0.12	**0.92****
Rice Yield	**-0.53***	**0.51**

*Note: Bold values indicate strong factor loadings (> |0.50|). Significance levels for correlations: *p<0.05, **p<0.01.*

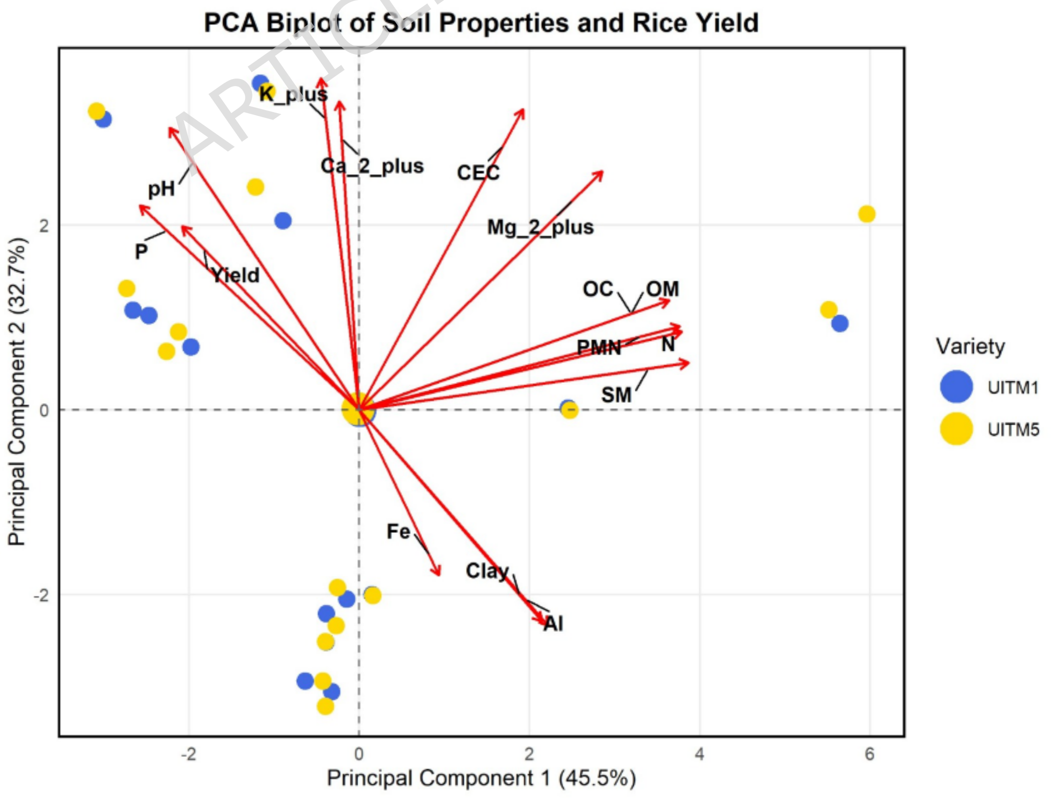


Figure 5. *PCA biplot illustrating the relationships between soil chemical properties and rice yield for UiTM 1 and UiTM 5 varieties.*

4.0 Discussion

The influence of soil physicochemical properties on rice yield was quantified to identify the correlation between pH, Al, CEC, and OM and rice yield. The analysis was quantitatively evaluated and is discussed herein based on the Pearson correlation matrix heatmap and further elucidated through Principal Component Analysis (PCA) to capture the multivariate nature of the soil fertility data.

As nutrient availability to plants is highly dependent on soil pH, this parameter represents one of the most important chemical properties of soil [41]. Supriyadi et al. [42] examined paddy fields in Merauke, Indonesia, where the soil pH was reported to range between 4.9 to 5.8. A past study by Choi et al. [43] has reported a similar pH range (5.5–6.6) in paddy soils in the central region of Sejong, Korea, where satisfactory rice yields were achieved. Also, Azura et al. [44] in her work, she observed rice root length increased significantly with rising soil pH, where pH 3.0 shows the lowest root length compared to pH 6.0. This might be because the optimum range of pH for rice cultivation is 5.5 to 7.0 [45, 46]. Extremely low pH levels may be unsuitable for rice growth, as demonstrated by Abdul Halim et al. [47] who observed poor rice performance in acid sulphate soil with a very low pH of 3.76. According to a recent study by Nishigaki et al. [48] the pH of paddy soils in Madagascar’s central highlands ranged from 4.4 to 6.6, with a mean value of 5.3, which is remarkably similar to the pH levels observed in the present paddy soils.

In comparison to the soil from other countries, Yanai et al.[49], reported Thai paddy soil exhibited a moderately acidic pH of 5.77 accompanied by a relatively high CEC of 13.8 cmol kg^{-1}reflecting a strong ability of the soil to retain and exchange nutrient cations. In contrast, soils reported from Azerbaijan showed a higher pH value of 7.62 and an organic matter content of 1.66% [50]. Although CEC values were not explicitly reported for the Azerbaijan soils, the relatively low organic matter content suggests a reduced contribution of organic colloids to cation retention, potentially influencing nutrient dynamics differently from those observed in Thai paddy fields. Supporting these observations, Prakongkep et al.[51] reported that OC content in Thai paddy soils decreased with depth, with mean values of 8.0 ± 3.0 g kg^{-1} in the topsoil and 2.1 ± 1.8 g kg^{-1} in the subsoil. Soil pH followed a similar depth-related trend, averaging 6.0 ± 1.0 in the topsoil and increasing slightly to 6.4 ± 1.1 in the subsoil. Likewise, Nguyen et al.[52] demonstrated the paddy soils of the Mekong River Delta exhibited a generally acidic to slightly acidic pH range (3.7–6.8), with a median value of 4.9 and a mean of 5.0.

However, excessively high soil pH levels may negatively affect rice yield. The effect of higher pH (7,8, and 9) on yields and nutrient absorption of rice has been reported by Huang et al.[53]. According to their analysis using stepwise regression analysis results, the main factor influencing rice grain yield was soil pH, which has a highly significant and negative impact on grain production. Likewise, Liu et al.[54] investigated rice yield in saline-sodic paddy fields with soil pH ranging from 8.28 to 9.9. Pearson correlation analysis revealed a moderate negative correlation between soil pH and rice yield (r = -0.45), indicating that alkaline-sodic conditions, characterised by high concentrations of CO_3^{2-} and HCO_3^-, may inhibit rice productivity. Also, Huang et al.[53] observed the rice grain yield and shoot weight significantly decreased with increasing soil pH (7-9) planted in a greenhouse. Even though the literature advocates the importance of pH in influencing rice yield in paddy soils, the strength of this relationship is relatively weak (seed UiTM 1) and moderate (seed UiTM 5), suggesting that soil pH alone may not be the primary factor influencing yield in this study.

The complexity of these interactions is further clarified by the PCA results, where soil pH was found to have a strong positive loading (0.78) on PC2. The PCA biplot (Figure 5) illustrates that the vector for rice yield is closely aligned with the pH vector along the PC2 axis, which accounts for 32.7% of the total variance. This multivariate alignment suggests that while pH is a critical driver, its influence is intrinsically linked to the overall cation status and the mitigation of acidity-related stresses, rather than acting as an isolated variable.

The toxicity of Al is regarded as another important parameter to be considered. According to Panhwar et al.[55], Al toxicity is the primary cause of the stagnant root growth, especially in acidic soils where the presence of Al^{3+} hinder cell division and cell elongation leading to problem to roots growths[56]. This is well supported by few researchers at low pH, soil contains high concentrations of Al^{3+} which can be toxic to plants. The effects of aluminium on rice growth were investigated by Panhwar et al.[55] who reported that high concentrations of Al significantly inhibited seedling development, leading to reductions in plant height, root volume, and dry biomass. Chang et al.[57] investigated the effects of aluminium exposure on several hybrid rice cultivars. In the control group (without Al treatment), no significant changes in root activity were observed. However, after 12 days of aluminium exposure, a substantial reduction in root vigour was recorded. The cultivars (Yangdao 6, Wuyunjing 7 and Longjing 9) exhibited decreases in root activity of 83.7%, 35.0% and 45.3%, respectively. Al dissolves into its soluble form, Al^{3+}, in soils with a pH below 5.0. Even at micromolar concentrations, Al^{3+} in acidic soils can exert toxic effects on plants and significantly disrupt the metabolic processes of soil microbial communities[58–60].

In the present study, the antagonistic relationship between Aluminium and yield is robustly supported by both Pearson correlation and PCA. Aluminium showed strong negative correlations with yield for both UiTM 1 (r=-0.78) and UiTM 5 (r=-0.87). This is visualised in the PCA biplot (Figure 5), where the vector for Al is oriented in the opposite direction (180°) to the rice yield vector along the PC2 axis. Furthermore, Al exhibited a significant negative loading (-0.60) on PC2, suggesting that Al-toxicity is a dominant multivariate factor limiting productivity in these acid sulphate soils. This spatial arrangement in the PCA provides strong evidence that Al-stress is the primary force counteracting the positive effects of pH and base cations on yield.

The naturally occurring acid sulphate soils, which are 50% world's potent agricultural lands. The soil is rich in pyrite (an iron sulphide mineral) or its oxidation byproducts, which develop under prolonged waterlogged conditions. The process produces the accumulation of H^+ ions in the soil solution leads to a pH below 4 in these soils[61]. To overcome the excessive H^+ and low pH in a paddy soil, liming is a common agronomic practice to raise the pH of acidic paddy soils. Increasing soil pH above 5 facilitates the precipitation of soluble aluminium as gibbsite [$Al(OH)_3$], thereby reducing aluminium toxicity[62].

CEC refers to the soil’s capacity to retain and exchange positively charged ions, plays a crucial role in maintaining soil fertility[63]. Chong et al. [35] reported that the application of calcium silicate in paddy soils of Sabah, Malaysia improved soil pH, available P, CEC, and reduced exchangeable Al. The rise in CEC was attributed to the significant increase in soil pH and the abundance of negatively charged sites, thereby enhancing nutrient retention and buffering capacity of the soil.

This role of CEC is corroborated by PCA Table 4, where CEC showed a high positive loading (0.83) on PC2, alongside exchangeable bases such as K^+ (0.92) and Ca^{2+} (0.85). Although the direct correlation between CEC and yield was statistically weak, the multivariate analysis reveals that CEC is a major component of the Soil Acidity and Cation Status Factor (PC2). The close grouping of CEC, pH and Yield in the PCA biplot suggests that a higher cation exchange capacity indirectly supports yield by stabilizing the soil's buffering capacity and base saturation.

Soils enriched with acidic OM generally contain higher levels of humic substances, which are abundant in functional groups such as carboxylic (COOH) and phenolic (OH) groups. These groups contribute to the development of negative surface charges on humus particles as soil pH increases, thereby improving the soil’s capacity to supply nutrients to plants[64, 65]. Consequently, the accumulation of organic inputs from decomposed plant residues in the upper soil layer enhances the retention of base cations primarily due to the high cation exchange capacity of organic matter[66]. Interestingly, PCA identified Organic Matter (OM) and

Total Nitrogen (N) as the dominant variables in PC1 (explaining 45.5% of variance), with loadings of 0.93 and 0.97, respectively. However, the orientation of the PC1 axis relative to the yield vector suggests that while organic inputs significantly define the soil's nitrogenous fertility, they are not the immediate limiting factors for yield compared to the acidity-related variables captured in PC2.

5.0 Conclusions

This study demonstrates that soil fertility parameters, particularly pH and aluminium content, play a decisive role in influencing the yield performance of the two rice varieties, UiTM 1 and UiTM 5. Among all sites, paddy field A9 recorded the highest yields, producing 9.29 mt/ha for UiTM 5 and 9.11 mt/ha for UiTM 1, under soil conditions of pH 5.7–5.9 with aluminium levels between 59.50–64.00 g/kg. In contrast, A5 produced the lowest yields, with 4.36 mt/ha for UiTM 5 and 4.55 mt/ha for UiTM 1, despite having a comparable pH range (5.3–5.5). The markedly higher aluminium concentration at A5 (107.90–115.20 g/kg), nearly double that of A9, strongly indicates aluminium toxicity as the main limiting factor. Collectively, these findings highlight that the productivity of both UiTM 1 and UiTM 5 is highly sensitive to aluminium concentration. The findings are based on site-specific field observations and may be exposed to different climate changes and various environment factors, which may limit broader generalisation to other rice-growing regions. Future research could expand the spatial and temporal coverage to include additional paddy fields and growing seasons, as well as incorporate controlled experimental approaches to further validate the influence of key soil fertility factors on rice yield performance.

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Declarations

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Conflicts of Interest / Competing Interests

On behalf of all authors, the corresponding author declares that there are no conflicts of interest.

Availability of Data and Material

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

Use of Artificial Intelligence (AI)

The authors used AI-based tools (Gemini and ChatGPT) to assist in language refinement, rephrasing, and drafting support. All scientific content, interpretations, and conclusions were critically reviewed and validated by the authors. The authors take full responsibility for the accuracy, originality, and integrity of the manuscript.