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Comparative analysis of Thai indigenous rice on growth, yield, and leaf nutrient under salinity conditions

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Salinity is one of the most detrimental environmental stresses, significantly
reducing rice yield and quality. Salinity tolerant varieties are crucial for rice
production in Southern Thailand. The objectives of this study were: 1) to
examine the response on growth, yield, and leaf nutrient composition of 10
indigenous rice varieties from Nakhon Si Thammarat Province under salinity
conditions, and 2) to identify varieties capable of surviving and producing yield
under saline conditions. The experiment was designed as a factorial arrangement
in a completely randomized design with two factors. The first factor was the
salinity level of irrigation water, consisting of 0.0%, 0.4%, and 0.8% salinity. The
second factor was the indigenous rice varieties, which included Dok Kha, Hom
Bon, Dawk Pa-yawm, Luk Lai, Leb Nok, Leuang, Banpeang, Chorlumpee, Sang
Yot (Tha Sala), and Sang Yot (Bang Khan). Significant differences were observed
across salinity levels and among rice varieties for most traits. All rice varieties
experienced substantial reductions in growth when exposed to higher salinity
levels. The principal component analysis revealed that rice varieties exhibited
varying responses in agronomic traits, yield traits, and leaf nutrients under
different salinity conditions. Based on their ability to survive in saline
environments and yield production, Luk Lai, Leb Nok, and Sang Yot (Bang
Khan) are recommended for farmers for future production on saline soils.

KEYWORDS

leaf nutrient composition, micro-XRF spectrometry, plant physiological response,
salinity stress, Thai indigenous rice

1 Introduction

Rice (*Oryza sativa* L.) is one of the world's most vital crops, feeding approximately half
of the global population. It holds immense global significance, providing over 21% of the
calories consumed by humans and up to 76% of the caloric intake in Southeast Asia
(Hussain et al., 2021; Mohidem et al., 2022). In Asia alone, more than 2 billion people

derive 80% of their energy from rice. Nutritionally, rice comprises 80% carbohydrates, 7-8% protein, 3% fat, and 3% fiber (Chaudhari et al., 2018). As one of the leading rice producers globally, Thailand harvested 19.5 million metric tons of rice in the 2021/22 market year, reflecting a 4% increase from the previous year. This growth was largely attributed to favorable seasonal rains that supported early planting and crop development (Foreign Agricultural Service, 2021). Thailand cultivates a diverse range of over 100 rice varieties, including hybrid, lowland, indigenous, and upland types.

Nakhon Si Thammarat Province is the largest rice-growing region in southern Thailand, accounting for approximately 27,671 hectares of rice cultivation—28.56% of the total rice-growing area in the southern region, which spans about 100,000 hectares (Office of Agricultural Economics, 2022). The primary rice-growing region in Nakhon Si Thammarat is the Pak Phanang River Basin, where indigenous rice has been cultivated for over a century (Summpunn et al., 2022). However, rice cultivation in this province has faced several challenges in recent years, including flooding during the rainy season, water shortages during the dry season, low soil fertility due to imbalanced nutrient management, and soil salinization from seawater intrusion.

Salinity is one of the most severe environmental stresses, significantly reducing agricultural productivity and quality worldwide. More than 20% of the world's arable land is affected by salinity, and this figure continues to grow due to both natural and anthropogenic factors (Hasanuzzaman and Fujita, 2022). Salt stress disrupts plant growth and development by increasing osmotic pressure and promoting the accumulation of harmful sodium ions. Similar to other abiotic stressors, salinity can impair plant development and reproduction, resulting in ion toxicity, oxidative and osmotic stress, nutrient and hormonal imbalances, and increased susceptibility to diseases (Zhao et al., 2021). In rice, salinity stress significantly impacts growth, development, and grain yield, making the enhancement of salt tolerance a critical strategy for meeting the rising global demand for food. Approximately 50% of irrigated soils are affected by sodium (Na^+) and chloride (Cl^-) ions, which are the primary contributors to salt toxicity. Plant responses to salinity are complex, involving ionic homeostasis, osmotic adjustment, reactive oxygen species scavenging, and nutrient balance, occurring at the organismic, cellular, and molecular levels (Liu et al., 2022).

The current study aims to 1) assess the response on growth, yield, and leaf nutrient composition of 10 indigenous rice varieties from Nakhon Si Thammarat Province under salinity conditions, and 2) identify varieties that can survive and produce yield under such conditions. The findings of this study will provide recommendations to rice farmers in salt-affected coastal areas of Thailand and offer valuable insights for breeders and researchers engaged in future breeding programs.

2 Materials and methods

2.1 Experimental details

The experiment was done at the greenhouse of School of Agricultural Technology and Food Industry (8°38'44.1"N 99° 54'04.7"E), Walailak University, Nakhon Si Thammarat Province. The investigation was arranged as a factorial experiment in a completely randomized design with 2 factors. The first factor was the salinity level of irrigation water including 1) 0.0% salinity (electrical conductivity (at 25°C): EC = 0.13 dS m^{-1}), 2) 0.4% salinity (EC = 1.42 dS m^{-1}), and 3) 0.8% salinity (EC = 2.85 dS m^{-1}). The second factor was indigenous rice varieties including 1) Dok Kha (V1), 2) Hom Bon (V2), 3) Dawk Pa-yawm (V3), 4) Luk Lai (V4), 5) Leb Nok (V5), 6) Leuang (V6), 7) Banpeang (V7), 8) Chorlumpee (V8), 9) Sang Yot (Tha Sala) (V9), and 10) Sang Yot (Bang Khan) (V10). There were 30 experimental units in all, with 10 replications per unit. The rice varieties were selected according to their popularity and planting areas. Rice seeds were sown in the 12-inch plastic plot with holes at the base to allow free drainage and clay loam soil from rice planting field in Nakhon Si Thammarat Province was used as a planting medium. Soil properties were clay = 38%, silt =27%, sand =35%, pH = 6.5, organic matter = 2.9%, EC = 0.18 dS m^{-1}, sodium absorption ratio = 6, exchangeable sodium percentage = 12.3%, total nitrogen = 0.38%, available phosphorus = 12.56 mg kg^{-1}, and exchangeable potassium = 192.12 mg kg^{-1}. A month following germination, rice seedlings were applied irrigation water with different salinity levels three times a day (8 am, 2 pm, and 5 pm), one litter at a time, using a drip irrigation system. Sodium chloride solution was used to regulate salinity. The water quality was pH = 7, electrical conductivity = 0.2 dS m^{-1}, total dissolve solid = 300 mg L^{-1}, sodium absorption ratio = 7.2, and temperature = 31°C. The experiment was conducted between January and April 2024. During the experiment, January was observed to be the highest rainfall, relative humidity, and lowest temperature at 137.2 mm, 86.3%, and 33.5°C, respectively, while April was lowest of rainfall, relative humidity, and highest temperature at 0.0 mm, 75.6%, and 38.4°C, respectively.

2.2 Dada collection and analysis

Data collection encompassed agronomic traits, yield traits, and nutrient accumulation in leaves. The agronomic traits were record at the first day of flowering stage (~60 days after planting) included plant height, stem diameter, leaf width, leaf length, tiller number, panicle number, and panicle length. The yield traits were assessed from mature panicle (~30 days after flowering) through seed count per panicle, percentage of viable seeds, seed weight per panicle, 1,000-seed weight, and seed yield per plant. Nutrient accumulation in mature leaves from flowering stage was analyzed using a micro-X-ray Fluorescence (micro-XRF) Spectrometer, model M4 Tornado (Bruker Co. Ltd.). Data variation was analyzed through ANOVA. The correlation coefficient and principal component analysis were performed using the psych and ggbiplot packages (Revelle, 2024; Vu et al., 2024). Mean comparisons were conducted using Duncan's multiple range test with the agricolae package (De Mendiburu, 2023), and significance levels reported at $p<0.05$ or $p<0.01$. All statistical analyses were done by R program version 4.2.3.

3 Results

3.1 Analysis of variance results

Analysis of variance for agronomic and yield traits of indigenous rice is presented in Table 1. Significant differences were observed across salinity levels for most traits, with the exception of panicle number. Among rice varieties, significant differences were also noted for most traits, except for plant height, stem diameter, leaf length, and 1,000-seed weight. A significant interaction between salinity levels and rice varieties was found for leaf width, tiller number, panicle number, panicle length, seeds per panicle, percentage of viable seeds, seed weight per panicle, and seed yield per plant. The coefficient of variation (CV) ranged from 7.49% to 38.24%, with the lowest and highest CVs observed for percentage of viable seeds and seed yield per plant, respectively.

Analysis of variance for leaf nutrient accumulation is presented in Table 2. All measured leaf nutrients—phosphorus, sulfur, chlorine, potassium, calcium, manganese, iron, and nickel—showed significant differences among salinity levels ($p<0.01$) and rice varieties ($p<0.01$). Additionally, a highly significant interaction between salinity levels and rice varieties was observed for all leaf nutrients ($p<0.01$).

3.2 Agronomic traits of indigenous rice

The comparison of agronomic traits for indigenous rice varieties is presented in Table 3, while Figure 1 illustrated the rice characteristics at the vegetative stage under varying salinity levels. All rice varieties were drastically reduced in their growth when treated with higher salinity levels. On average, plant height across 10 rice varieties was greater at salinity levels of 0.0% (129.50 cm)

and 0.4% (125.13 cm) compared to 0.8% salinity (95.94 cm). The tallest variety, Hom Bon, reached 147.36 cm at 0.0% salinity, whereas the shortest variety, Dawk Pa-yawm, measured 63.20 cm at 0.8% salinity. At the 0.4% salinity level, plant height decreased by 2.71%, with Sang Yot (Bang Khan) showing the greatest reduction (-13.87%). In contrast, Luk Lai (8.65%), Leuang (3.78%), and Chorlumpee (10.56%) exhibited an increase in plant height. At the 0.8% salinity level, plant height decreased significantly by 20.65%, with Hom Bon (-26.23%) and Sang Yot (Bang Khan) (-26.98%) showing the highest percentage reductions compared to the 0.0% salinity level. Similarly, the average stem diameter was highest at 0.0% salinity (1.38 cm), followed by 0.4% (1.03 cm), with the smallest stem diameter recorded at 0.8% salinity (0.65 cm). Variety Leuang at 0.0% salinity exhibited the largest stem diameter (1.6 cm), while Dawk Pa-yawm at 0.8% salinity had the smallest (0.35 cm). At the 0.4% salinity level, stem diameter decreased by 22.78%, with Dawk Pa-yawm (-32.91%) and Leuang (-33.97%) recording the largest reductions. At the 0.8% salinity level, stem diameter further decreased by 48.29%, with Dawk Pa-yawm (-57.09%) and Banpeang (-58.57%) showing the highest percentage decreases relative to the 0.0% salinity.

Leaf width was also influenced by salinity, with the average leaf width being largest at 0.0% salinity (1.65 cm). The leaf widths at 0.4% and 0.8% salinity were 1.17 cm and 1.04 cm, respectively. At the 0.4% salinity level, leaf width declined by 26.48%, with Dok Kha (-34.98%), Dawk Pa-yawm (-34.34%), and Sang Yot (Bang Khan) (-39.73%) having the greatest reductions. Similarly, at the 0.8% salinity level, leaf width decreased by 31.59%, with Dok Kha (-39.91%), Dawk Pa-yawm (-40.03%), and Sang Yot (Bang Khan) (-37.68%) showing the largest decline compared to the 0.0% salinity. Variety Sang Yot (Bang Khan) at 0.0% salinity exhibited the widest leaf (2.06 cm), while Dawk Pa-yawm at 0.8% salinity had the narrowest (0.62 cm). In terms of leaf length, the average at 0.0% (95.62 cm) and 0.4% salinity (91.17 cm) was longer than at 0.8%

TABLE 1 Analysis of variance of agronomic and yield traits of indigenous rice planted under different salinity levels.

Sources	Salinity (a) MS	Varieties (b) MS	a x b MS	MS Error	CV (%)
Plant height	16,638.10**	608.00	569.30	382.60	16.74
Stem diameter	6.53**	0.14**	0.05	0.04	20.57
Leaf width	5.25**	0.24**	0.14*	0.07	20.82
Leaf length	7,270.20**	261.10	265.80	222.70	19.33
Tiller number	820.05**	644.5**	24.38*	13.09	17.29
Panicle number	1.48	153.83**	110.73*	22.88	32.70
Panicle length	183.00**	35.77**	32.45*	7.58	11.42
Seed per panicle	14,863.80**	4,417.00**	11,890.00**	259.90	11.51
Good seed percentage	6707.40**	240.70**	997.90**	37.50	7.49
Seed weight per panicle	11.70**	5.54**	1.52**	0.31	37.40
1,000 seed weight	710.75**	141.45**	14.92	4.91	16.00
Seed yield per plant	1438.29**	809.08**	593.38**	45.51	38.24

[ns]not significant difference, *,**significant at $p<0.05$ and 0.01, respectively.

TABLE 2 Analysis of variance of leaf nutrients of indigenous rice planted under different salinity levels using micro-XRF Spectrometer.

Sources	Salinity (a) MS	Varieties (b) MS	a × b MS	MS Error	CV (%)
P	6.74**	0.91**	1.21**	0.001	5.90
S	6.97**	0.69**	0.20**	0.01	5.24
Cl	718.17**	75.24**	30.65**	0.73	5.29
K	269.73**	100.27**	94.95**	7.00	5.03
Ca	328.85**	30.07**	55.25**	0.45	5.32
Mn	15.88**	7.48**	10.40**	0.05	5.47
Fe	0.01**	0.01**	0.005**	0.001	5.49
Ni	0.01**	0.001**	0.001**	0.001	5.14

**significant at $p<0.01$.

TABLE 3 Mean comparison on agronomic traits of indigenous rice planted under different salinity levels.

Salinity levels	Varieties	Plant height (cm)	Stem diameter (cm)	Leaf width (cm)	Leaf length (cm)	Tiller number (no.)
0.0%	Dok Kha	132.26 ± 19.92[abc]	1.27 ± 0.16[a-f]	1.88 ± 0.16[ab]	87.58 ± 13.59[a-d]	14.40 ± 0.89[h-k]
	Hom Bon	147.36 ± 8.62[a]	1.33 ± 0.18[a-e]	1.72 ± 0.46[a-d]	92.78 ± 32.93[ab]	14.00 ± 1.00[h-k]
	Dawk Pa-yawm	140.36 ± 4.39[ab]	1.36 ± 0.16[a-d]	1.84 ± 0.11[abc]	95.62 ± 5.04[a]	13.00 ± 0.71[ijk]
	Luk Lai	130.54 ± 6.77[abc]	1.37 ± 0.45[a-d]	1.52 ± 0.16[b-f]	91.88 ± 7.55[ab]	24.00 ± 4.47[b-f]
	Leb Nok	127.20 ± 5.72[abc]	1.22 ± 0.23[a-f]	1.38 ± 0.13[b-g]	85.56 ± 4.14[a-d]	28.20 ± 3.27[abc]
	Leuang	121.44 ± 6.87[a-d]	1.60 ± 0.07[a]	1.70 ± 0.25[a-e]	81.90 ± 3.64[a-d]	27.80 ± 3.11[abc]
	Banpeang	118.14 ± 11.10[a-d]	1.53 ± 0.16[ab]	1.54 ± 0.11[b-f]	78.60 ± 11.69[a-d]	27.20 ± 1.10[a-d]
	Chorlumpee	118.74 ± 11.81[a-d]	1.45 ± 0.20[abc]	1.52 ± 0.13[b-f]	84.04 ± 11.42[a-d]	32.60 ± 2.88[a]
	Sang Yot, (Tha Sala)	127.52 ± 4.72[abc]	1.35 ± 0.21[a-e]	1.38 ± 0.08[b-g]	88.12 ± 5.57[a-d]	28.40 ± 1.82[abc]
	Sang Yot (Bang Khan)	131.42 ± 6.99[abc]	1.28 ± 0.29[a-f]	2.06 ± 0.11[a]	88.98 ± 8.06[a-d]	20.40 ± 5.59[d-h]
	Average	**129.50 ± 12.49[A]**	**1.38 ± 0.24[A]**	**1.65 ± 0.28[A]**	**87.51 ± 12.93[A]**	**23.00 ± 7.29[A]**
0.4%	Dok Kha	127.84 ± 10.49[a-c]	1.06 ± 0.11[c-i]	1.22 ± 0.50[d-g]	88.28 ± 8.15[a-d]	14.60 ± 2.30[h-k]
	Hom Bon	128.10 ± 6.47[a-c]	0.95 ± 0.15[e-k]	1.32 ± 0.37[d-g]	85.56 ± 3.12[a-d]	16.20 ± 1.79[g-j]
	Dawk Pa-yawm	128.86 ± 10.79[a-c]	0.90 ± 0.11[f-k]	1.20 ± 0.47[d-g]	90.42 ± 6.53[abc]	13.20 ± 3.35[ijk]
	Luk Lai	140.92 ± 24.95[ab]	1.12 ± 0.35[c-h]	1.22 ± 0.13[d-g]	83.68 ± 19.09[a-d]	28.60 ± 4.39[ab]
	Leb Nok	119.50 ± 11.70[a-d]	1.04 ± 0.15[c-i]	1.02 ± 0.31[fgh]	80.98 ± 8.41[a-d]	28.60 ± 2.70[ab]
	Leuang	126.08 ± 22.52[a-c]	1.06 ± 0.12[c-i]	1.10 ± 0.38[fgh]	73.32 ± 9.49[a-d]	24.80 ± 2.28[b-e]
	Banpeang	113.82 ± 6.59[a-d]	1.05 ± 0.06[c-i]	1.12 ± 0.08[fgh]	75.96 ± 6.57[a-d]	27.80 ± 2.28[abc]
	Chorlumpee	131.28 ± 32.80[a-c]	1.17 ± 0.27[b-g]	1.22 ± 0.15[d-g]	72.04 ± 7.79[a-d]	29.00 ± 2.00[ab]
	Sang Yot, (Tha Sala)	122.06 ± 2.95[a-d]	1.02 ± 0.19[d-j]	1.10 ± 0.07[fgh]	77.72 ± 7.98[a-d]	27.40 ± 1.82[abc]
	Sang Yot (Bang Khan)	112.80 ± 11.17[a-d]	0.89 ± 0.14[f-k]	1.24 ± 0.22[d-g]	73.20 ± 6.35[a-d]	25.00 ± 7.00[b-e]
	Average	**125.13 ± 17.11[A]**	**1.03 ± 0.19[B]**	**1.17 ± 0.29[B]**	**80.12 ± 10.50[A]**	**23.52 ± 6.77[A]**

TABLE 3 Continued

Salinity levels	Varieties	Plant height (cm)	Stem diameter (cm)	Leaf width (cm)	Leaf length (cm)	Tiller number (no.)
0.8%	Dok Kha	87.00 ± 50.87[de]	0.48 ± 0.29[lm]	0.88 ± 0.50[gh]	65.50 ± 37.10[a-e]	8.80 ± 5.22[kl]
	Hom Bon	108.40 ± 20.39[a-d]	0.68 ± 0.12[i-m]	1.34 ± 0.24[c-g]	68.24 ± 16.34[a-e]	9.80 ± 2.49[jkl]
	Dawk Pa-yawm	63.20 ± 58.61[e]	0.35 ± 0.32[m]	0.62 ± 0.58[h]	41.66 ± 38.76[e]	5.80 ± 5.54[l]
	Luk Lai	113.50 ± 6.69[a-d]	0.90 ± 0.41[f-k]	1.02 ± 0.13[fgh]	77.34 ± 4.05[a-d]	23.20 ± 3.03[b-f]
	Leb Nok	105.90 ± 14.59[bcd]	0.72 ± 0.10[h-m]	0.98 ± 0.08[gh]	71.44 ± 10.39[a-d]	17.60 ± 1.67[f-i]
	Leuang	98.34 ± 15.67[cde]	0.74 ± 0.09[h-l]	1.16 ± 0.11[fg]	65.04 ± 13.68[b-e]	21.40 ± 4.51[c-g]
	Banpeang	97.98 ± 9.65[cde]	0.62 ± 0.11[j-m]	1.18 ± 0.13[efg]	65.88 ± 11.43[a-e]	22.60 ± 4.16[b-g]
	Chorlumpee	92.8 ± 17.41[cde]	0.78 ± 0.13[g-l]	0.96 ± 0.24[gh]	60.00 ± 13.10[de]	24.80 ± 2.95[b-e]
	Sang Yot, (Tha Sala)	97.08 ± 12.97[cde]	0.67 ± 0.06[i-m]	0.94 ± 0.11[gh]	63.90 ± 10.88[b-e]	18.40 ± 2.88[e-i]
	Sang Yot (Bang Khan)	95.24 ± 15.34[cde]	0.59 ± 0.16[klm]	1.28 ± 0.16[d-g]	60.30 ± 14.41[cde]	10.20 ± 7.89[jkl]
	Average	**95.94 ± 28.44[B]**	**0.65 ± 0.24[C]**	**1.04 ± 0.33[B]**	**63.93 ± 20.34[B]**	**16.26 ± 7.77[B]**
F-test		**	**	**	**	**

The values show the mean ± standard deviation. Different small letters indicate statistically significant differences among the variety at different salinity levels and capital letters indicate statistically significant differences among salinity levels within the same column. ** significance at $p<0.01$, the underline values are the highest value in each column.
Bold values are the average values of 10 rice varieties of each salinity level.

salinity (63.93 cm). The longest leaf was observed in Dawk Pa-yawm at 0.0% salinity (95.62 cm), while the shortest was also in Dawk Pa-yawm at 0.8% salinity (41.66 cm). At the 0.4% salinity level, leaf length decreased by 6.14%, with Chorlumpee (-13.10%) and Sang Yot (Bang Khan) (-17.23%) showing the highest percentage reductions, while Dok Kha (2.60%) and Hom Bon (9.49%) exhibited slight increases in leaf length. At the 0.8% salinity level, leaf length decreased by 19.27%, with Chorlumpee

(-27.01%), Sang Yot (Tha Sala) (-27.40%), and Sang Yot (Bang Khan) (-31.24%) recording the largest reductions compared to the 0.0% salinity.

Finally, tiller number was highest at 0.0% (23.00) and 0.4% salinity (23.52), compared to 16.26 at 0.8% salinity. Variety Chorlumpee at 0.0% salinity had the highest tiller number (32.60), while Dawk Pa-yawm at 0.8% salinity had the lowest (5.80). At the 0.4% salinity level, tiller number increased by

FIGURE 1
Indigenous rice characteristics at vegetative stage (1 month old) planted under different salinity levels. Left: 0.0% salinity, middle: 0.4% salinity, and right: 0.8% salinity.

4.97%, with Hom Bon (16.72%), Luk Lai (19.84%), and Sang Yot (Bang Khan) (27.36%) showing the greatest increases, while Leuang (-9.31%) and Chorlumpee (-10.39%) recorded reductions. However, at the 0.8% salinity level, tiller number decreased markedly by 27.01%, with Leb Nok (-36.50%), Sang Yot (Tha Sala) (-34.85%), and Sang Yot (Bang Khan) (-42.50%) showing the highest percentage decreases relative to the 0.0% salinity.

3.3 Yield traits of indigenous rice

The comparison of yield traits for indigenous rice varieties is shown in Table 4. At 0.8% salinity, all rice varieties experienced dehydration and died during the flowering stage. At 0.4% salinity, only varieties Luk Lai, Leb Nok, and Sang Yot (Bang Khan) survived. Across all yield traits, the average performance of the 10 varieties was higher at 0.0% salinity compared to 0.4%, with the exception of panicle number, where no significant difference was observed between the two salinity levels. The highest panicle numbers were recorded for Luk Lai (18.20), Leb Nok (16.60), Leuang (20.60), and Sang Yot (Bang Khan) (20.20) at 0.0% salinity, and for Leb Nok (18.00) and Sang Yot (Bang Khan) (21.00) at 0.4% salinity. The lowest panicle numbers were observed in Banpeang (6.80) and Chorlumpee (6.60) at 0.0% salinity, and in Luk Lai (6.00) at 0.4% salinity.

At 0.0% salinity, Leb Nok exhibited the longest panicle length (27.94 cm), while the shortest was recorded for Sang Yot (Bang Khan) (15.70 cm) at 0.4% salinity. The highest number of seeds per panicle was observed in Sang Yot (Bang Khan) (198.44) at 0.0% salinity, whereas the lowest was also from Sang Yot (Bang Khan) (53.00) at 0.4% salinity. Sang Yot (Bang Khan) recorded the highest percentage of viable seeds (94.08%) at 0.0% salinity, while the lowest percentage (37.76%) was also seen in Sang Yot (Bang Khan) at 0.4% salinity. The heaviest seed weight per panicle was noted in Hom Bon (3.91 g) at 0.0% salinity, with the lowest in Sang Yot (Bang Khan) (0.23 g) at 0.4% salinity. Sang Yot (Bang Khan) achieved the highest 1,000-seed weight (23.60 g) at 0.0% salinity, while the lowest weight (2.00 g) was observed in Luk Lai at 0.4% salinity. In terms of seed yield per plant, Dok Kha (34.42 g), Hom Bon (42.09 g), and Sang Yot (Bang Khan) (39.63 g) at 0.0% salinity had the highest yields, while the lowest yield was recorded in Luk Lai (2.36 g) at 0.4% salinity.

At the 0.4% salinity level, panicle number decreased by 8.49%, with Luk Lai exhibiting the highest reduction (-65.07%). In contrast, Leb Nok (24.03%) and Sang Yot (Bang Khan) (15.56%) showed increases in panicle number. Panicle length decreased by 23.91%, with Sang Yot (Bang Khan) (-23.91%) recording the greatest reduction, followed by Luk Lai (-16.57%) and Leb Nok (-13.15%). The number of seeds per panicle declined by 34.39%, with Sang Yot (Bang Khan) (-73.77%) showing the largest decrease, followed by Luk Lai (-40.30%). Conversely, Leb Nok recorded an increase of 10.00% in seeds per panicle. The percentage of good seeds decreased by 33.60%, with Sang Yot (Bang Khan) (-59.87%) showing the greatest reduction, followed by Luk Lai (-26.60%) and Leb Nok (-14.33%). Seed weight per panicle dropped by 59.14%, with Sang

Yot (Bang Khan) (-89.54%) having the highest percentage reduction, followed by Luk Lai (-50.09%) and Leb Nok (-37.80%). The 1,000-seed weight decreased by 60.30%, with Luk Lai (-73.49%) showing the largest reduction, followed by Sang Yot (Bang Khan) (-56.71%) and Leb Nok (-50.71%). Seed yield per plant declined by 57.97%, with Sang Yot (Bang Khan) (-88.38%) exhibiting the highest percentage decrease, followed by Luk Lai (-75.55%) and Leb Nok (-9.81%).

3.4 Leaf nutrient analysis using micro-XRF

Figure 2 shows the leaf nutrient levels of indigenous rice planted under different salinity conditions, while Table 5 presents the mean comparison of these nutrient levels. The average leaf phosphorus content across 10 varieties was highest at 0.0% salinity (1.66%), compared to 0.4% and 0.8% salinity (0.82% and 0.86%, respectively). Variety Sang Yot (Bang Khan) recorded the highest phosphorus percentage at 0.0% salinity (2.70%), while the lowest was observed in Sang Yot (Tha Sala) at 0.8% salinity (0.25%). For leaf sulfur, the highest average percentage was at 0.0% salinity (2.14%), with the lowest at 0.4% salinity (1.27%). Luk Lai at 0.0% salinity exhibited the highest sulfur content (2.88%), while the lowest was seen in Dok Kha (0.86%) and Banpeang (0.84%) at 0.4% salinity, as well as Dok Kha at 0.8% salinity (0.86%).

The average leaf chlorine content was highest at 0.4% salinity (20.67%) and lowest at 0.0% salinity (10.96%). The highest chlorine percentage was recorded in Dok Kha at 0.4% and 0.8% salinity (27.66% and 27.88%, respectively), with the lowest observed in Dok Kha at 0.0% salinity (9.84%). In terms of potassium, the average leaf content was highest at 0.8% salinity (55.85%) and lowest at 0.4% salinity (49.96%). Luk Lai (63.40%) and Sang Yot (Tha Sala) (63.22%) at 0.8% salinity exhibited the highest potassium levels, while Sang Yot (Bang Khan) at 0.4% salinity had the lowest (40.64%). The average calcium content in leaves was highest at 0.0% salinity (15.63%) and lowest at 0.8% salinity (9.07%). Dok Kha recorded the highest calcium percentage at 0.0% salinity (23.40%), while the lowest percentages were observed in Dok Kha (5.05%) and Luk Lai (6.26%) at 0.8% salinity.

Leaf manganese levels were higher at 0.0% and 0.4% salinity (4.42% and 4.50%, respectively) compared to 0.8% salinity (3.20%). The highest manganese content was found in Dok Kha (8.07%) and Sang Yot (Bang Khan) (7.39%) at 0.0% salinity, while the lowest was in Dok Kha at 0.4% salinity (1.55%) and Luk Lai (1.46%) and Sang Yot (Tha Sala) (1.60%) at 0.8% salinity. For leaf iron, the average content was highest at 0.0% salinity (0.09%) and lowest at 0.4% salinity (0.10%). Hom Bon exhibited the highest iron percentage at 0.0% salinity (0.23%), while Chorlumpee had the lowest at 0.4% salinity (0.03%). Lastly, the average nickel content in leaves was higher at 0.0% and 0.8% salinity (both 0.09%) than at 0.4% salinity (0.06%). Luk Lai at 0.8% salinity had the highest nickel percentage (23.40%), while the lowest was observed in Hom Bon at 0.4% salinity (0.05%).

Figure 3 illustrates the correlation plot among leaf nutrients of indigenous rice grown under different salinity levels, based on

TABLE 4 Mean comparison on yield traits of indigenous rice planted under different salinity levels.

Salinity levels	Varieties	Panicle number (no.)	Panicle length (cm)	Seed per panicle (no.)	Good seed percentage (%)	Seed weight per panicle (g)	1,000-seed weight (g)	Seed yield per plant (g)
0.0%	Dok Kha	12.40 ± 3.21[ab]	28.02 ± 3.95[a]	169.40 ± 10.45[abc]	86.12 ± 2.14[a-d]	3.17 ± 1.33[ab]	23.60 ± 2.07[a]	34.42 ± 9.45[a]
	Hom Bon	11.60 ± 4.10[ab]	22.78 ± 1.43[a-d]	164.60 ± 6.23[bcd]	79.59 ± 12.74[bcd]	3.91 ± 0.76[a]	20.80 ± 2.28[ab]	42.09 ± 4.69[a]
	Dawk Pa-yawm	13.40 ± 3.21[ab]	23.36 ± 2.31[a-d]	153.20 ± 14.17[b-e]	88.14 ± 6.57[abc]	1.37 ± 0.49[cd]	18.80 ± 3.11[bc]	11.65 ± 6.06[bcd]
	Luk Lai	18.20 ± 4.87[a]	25.02 ± 5.92[a-d]	179.20 ± 25.99[ab]	73.98 ± 11.00[d]	0.89 ± 0.29[d]	10.40 ± 4.34[ef]	11.46 ± 4.28[bcd]
	Leb Nok	16.60 ± 7.16[a]	27.94 ± 2.39[a]	136.46 ± 12.98[de]	91.85 ± 2.20[ab]	1.08 ± 0.18[d]	12.20 ± 0.84[de]	13.19 ± 2.62[bc]
	Leuang	20.60 ± 5.94[a]	21.37 ± 3.12[cd]	128.04 ± 26.96[ef]	88.79 ± 5.06[abc]	0.98 ± 0.32[d]	10.20 ± 1.64[ef]	15.66 ± 6.46[b]
	Banpeang	6.80 ± 1.92[b]	21.62 ± 1.96[bcd]	97.58 ± 29.56[f]	89.14 ± 2.89[abc]	0.89 ± 0.28[d]	11.00 ± 3.39[de]	5.50 ± 2.43[bcd]
	Chorlumpee	6.60 ± 1.14[b]	25.40 ± 0.89[a-d]	97.80 ± 6.50[f]	82.80 ± 2.17[a-d]	0.86 ± 0.05[d]	10.20 ± 1.30[ef]	7.72 ± 0.90[bcd]
	Sang Yot, (Tha Sala)	19.20 ± 7.26[a]	25.94 ± 1.40[abc]	143.40 ± 7.67[cde]	87.83 ± 7.28[abc]	1.32 ± 0.73[cd]	15.20 ± 0.84[cd]	16.03 ± 10.50[b]
	Sang Yot (Bang Khan)	20.20 ± 7.60[a]	27.20 ± 2.66[ab]	198.44 ± 9.70[a]	94.08 ± 1.99[a]	2.24 ± 0.35[bc]	20.80 ± 1.10[ab]	39.63 ± 13.84[a]
	Average	**14.56 ± 6.82**	**24.28 ± 3.58[A]**	**146.81 ± 35.38[A]**	**81.71 ± 8.24[A]**	**1.48 ± 1.17[A]**	**13.85 ± 5.45[A]**	**17.46 ± 4.58[A]**
0.4%	Dok Kha	ND	ND	ND	ND	ND	ND	ND
	Hom Bon	ND	ND	ND	ND	ND	ND	ND
	Dawk Pa-yawm	ND	ND	ND	ND	ND	ND	ND
	Luk Lai	6.00 ± 0.01[b] (-65.07)	20.00 ± 0.01[de] (-16.57)	105.00 ± 6.01[f] (-40.30)	53.33 ± 5.01[e] (-26.60)	0.41 ± 0.01[d] (-50.09)	2.00 ± 0.01[g] (-73.49)	2.36 ± 0.01[d] (-75.55)
	Leb Nok	18.00 ± 3.01[a] (24.03)	24.20 ± 0.01[a-d] (-13.15)	150.00 ± 7.01[b-e] (10)	78.67 ± 4.01[cd] (-14.33)	0.66 ± 0.01[d] (-37.80)	6.00 ± 0.01[fg] (-50.71)	11.53 ± 0.01[bcd] (-9.81)
	Leuang	ND	ND	ND	ND	ND	ND	ND
	Banpeang	ND	ND	ND	ND	ND	ND	ND
	Chorlumpee	ND	ND	ND	ND	ND	ND	ND
	Sang Yot, (Tha Sala)	ND	ND	ND	ND	ND	ND	ND
	Sang Yot (Bang Khan)	21.00 ± 2.01[a] (15.56)	15.70 ± 0.01[e] (-42.01)	53.00 ± 5.01[g] (-73.77)	37.74 ± 7.01[f] (-59.87)	0.23 ± 0.01[d] (-89.54)	9.00 ± 0.01[ef] (-56.71)	4.12 ± 0.01[cd] (-88.38)
	Average	**15.00 ± 6.87 (-8.49)**	**19.97 ± 3.68[B] (-23.91)**	**102.67 ± 42.04[B] (-34.39)**	**56.58 ± 17.82[B] (-33.60)**	**0.43 ± 0.19[B] (-59.14)**	**5.67 ± 3.04[B] (-60.30)**	**6.00 ± 4.21[B] (-57.97)**
F-test		**	**	**	**	**	**	*

The values show the mean ± standard deviation and the numbers in parentheses indicate the percentage difference compared to the 0.0% salinity level. Different small letters indicate statistically significant differences among the variety at different salinity levels and capital letters indicate statistically significant differences between salinity levels within the same column. *,** significant at $p < 0.05$ and 0.01, respectively. ND has no data.
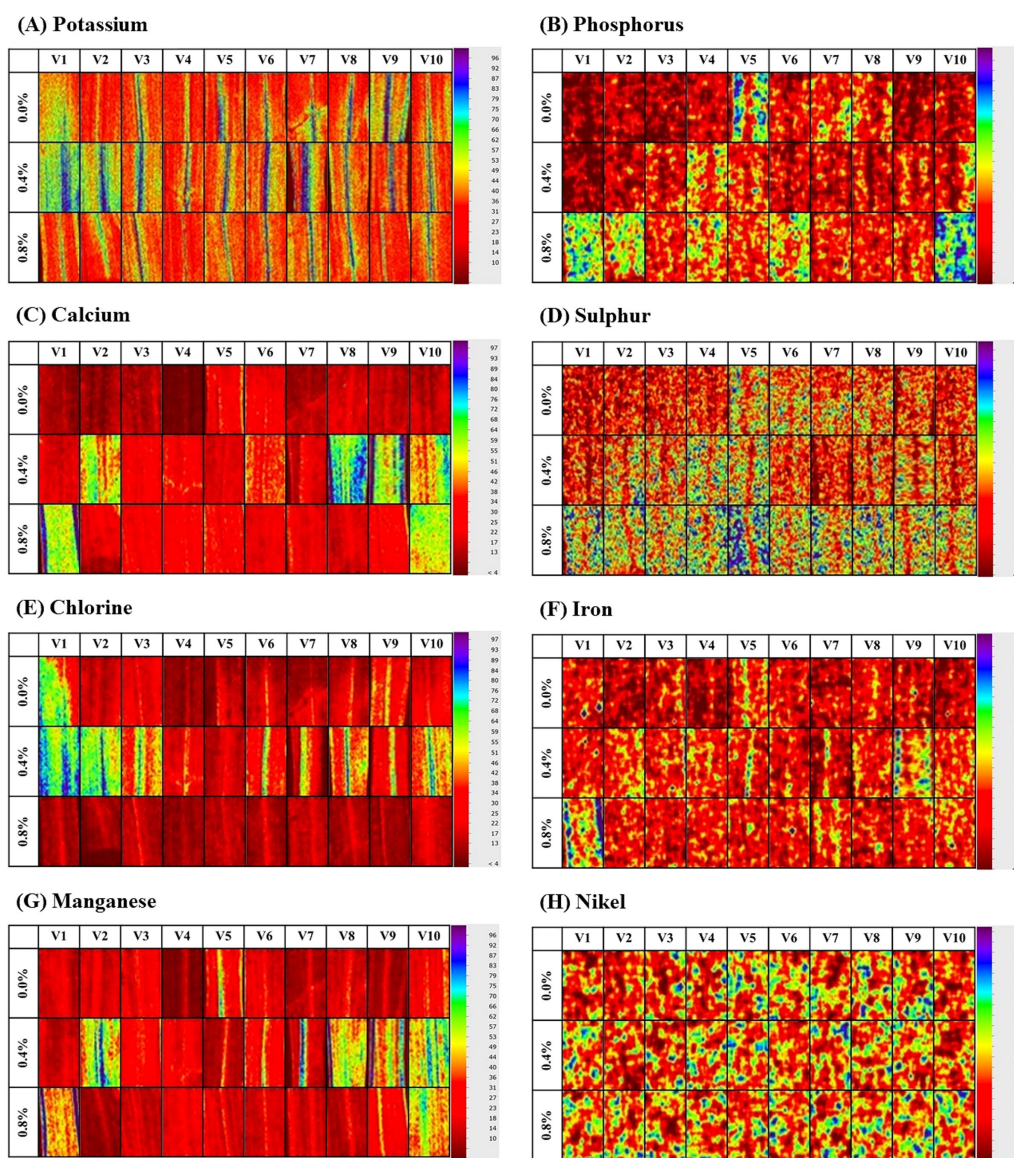Bold values are the average values of 10 rice varieties of each salinity level.

FIGURE 2
Leaf nutrients of indigenous rice planted under different salinity levels. **(A–H)** are potassium, phosphorus, calcium, sulfur, chlorine, iron, manganese, and nickel, respectively. V1: Dok Kha, V2: Hom Bon, V3: Dawk Pa-yawm, V4: Luk Lai, V5: Leb Nok, V6: Leuang, V7: Banpeang, V8: Chorlumpee, V9: Sang Yot, (Tha Sala), and V10: Sang Yot (Bang Khan).

Pearson's correlation coefficient. A strong positive correlation was observed between calcium and manganese (0.84***), phosphorus and sulfur (0.68***), and sulfur and nickel (0.54***). Conversely, a strong negative correlation was found between potassium and manganese (-0.77***), chlorine and sulfur (-0.76***), calcium and potassium (-0.65***), and chlorine and phosphorus (-0.61***).

3.5 Principal component analysis

The biplots for the first two principal components of indigenous rice agronomic traits, yield traits, and leaf nutrients are illustrated in Figures 4-6. The biplot for agronomic traits revealed that the first two principal components accounted for 50.0% and 22.3% of the variation, respectively. The cluster at 0.0% salinity is positioned on the left side of the y-axis, aligning with traits such as stem diameter, plant height, leaf length, and leaf width. In contrast, the 0.8% salinity cluster is located on the right side of the y-axis, showing an inverse relationship with most agronomic traits. Varieties Hom Bon, Luk Lai, and Sang Yot (Bang Khan) at 0.0% salinity were dominant in plant height, leaf length, and leaf width, while Leuang, Chorlumpee, Sang Yot (Tha Sala), and Sang Yot (Bang Khan) at 0.0% salinity, along with Luk Lai at 0.4% salinity, were dominant in stem diameter. Varieties Banpeang and Chorlumpee at 0.0% salinity, as well as Luk Lai, Leb Nok, and Chorlumpee at 0.4% salinity, were dominant in tiller number.

TABLE 5 Mean comparison on leaf nutrients of indigenous rice planted under different salinity levels.

Salinity levels	Varieties	P (%)	S (%)	Cl (%)	K (%)	Ca (%)	Mn (%)	Fe (%)	Ni (%)
0.0%	Dok Kha	2.27±0.11^{bc}	1.89±0.09^{fg}	9.84±0.49^{k}	43.51±2.18^{ghi}	<u>23.40±1.17^{a}</u>	<u>8.07±0.40^{a}</u>	0.20±0.01^{b}	0.07±0.00^{ij}
	Hom Bon	2.09±0.10^{d}	2.14±0.11^{cd}	9.94±0.50^{jk}	53.92±2.70^{b-f}	12.96 ±0.65^{g-j}	1.91±0.10^{no}	<u>0.23±0.01^{a}</u>	0.08±0.00^{gh}
	Dawk Pa-yawm	0.92±0.05^{h}	1.87±0.09^{fg}	11.70±0.59^{h-k}	57.96±2.90^{abc}	14.16 ±0.71^{gh}	3.11±0.16^{jk}	0.12±0.01^{fg}	0.08±0.00^{gh}
	Luk Lai	2.07±0.10^{d}	<u>2.88±0.14^{a}</u>	10.84±0.54^{ijk}	49.29±2.46^{d-g}	17.41±0.87^{d}	5.03±0.25^{de}	0.20±0.01^{b}	0.10±0.01^{cd}
	Leb Nok	1.06±0.05^{gh}	2.47±0.12^{b}	11.11±0.56^{h-k}	54.24±2.71^{b-e}	15.81±0.79^{ef}	3.75±0.19^{f-i}	0.11±0.01^{gh}	0.09 ±0.00^{d-g}
	Leuang	2.14±0.11^{cd}	2.00±0.10d^{ef}	10.92±0.55^{ijk}	53.70±2.68^{b-f}	12.21 ±0.61^{ijk}	3.24±0.16^{ijk}	0.09±0.00^{ij}	0.09 ±0.00^{d-g}
	Banpeang	1.25±0.06^{f}	1.93±0.10^{efg}	11.90±0.60^{g-k}	57.24±2.86^{abc}	12.73 ±0.64^{hij}	3.29±0.16^{ijk}	0.19±0.01^{b}	0.08±0.00^{h}
	Chorlumpee	0.94±0.05^{h}	2.25±0.11^{c}	11.20±0.56^{h-k}	58.25±2.91^{abc}	11.51 ±0.58^{jkl}	2.85±0.14^{kl}	0.08±0.00^{jkl}	0.09 ±0.00^{e-h}
	Sang Yot, (Tha Sala)	1.15±0.06^{fg}	2.16±0.11^{cd}	10.49±0.52^{ijk}	47.38±2.37^{fgh}	14.51 ±0.73^{fg}	5.14±0.26^{de}	0.08±0.00^{kl}	0.12±0.01^{ab}
	Sang Yot (Bang Khan)	<u>2.70±0.14^{a}</u>	1.81±0.09^{fgh}	11.65±0.58^{h-k}	43.54±2.18^{ghi}	21.58±1.08^{b}	7.83±0.39^{a}	0.05±0.00^{m}	0.10 ±0.00^{def}
	Average	**1.66±0.64^{A}**	**2.14±0.33^{A}**	**10.96±0.82^{C}**	**51.90±5.85^{B}**	**15.63 ±3.95^{A}**	**4.42±2.02^{A}**	**0.13±0.06^{A}**	**0.09±0.01^{A}**
0.4%	Dok Kha	0.34±0.02^{mno}	0.86±0.04^{n}	<u>27.66±1.38^{a}</u>	56.84±2.84^{abc}	6.40±0.32^{qr}	1.55±0.08^{o}	0.11±0.01^{gh}	0.06±0.00^{ij}
	Hom Bon	0.61±0.03^{ijk}	1.21±0.06^{klm}	24.60±1.23^{b}	47.64±2.38^{e-h}	12.74 ±0.64^{hij}	5.28±0.26^{d}	0.07±0.00^{l}	0.05±0.00^{m}
	Dawk Pa-yawm	0.94±0.05^{h}	1.29±0.06^{jkl}	24.26±1.21^{b}	51.68±2.58^{c-f}	9.64 ±0.48^{mno}	3.53 ±0.18^{g-j}	0.14±0.01^{e}	0.05 ±0.00^{lm}
	Luk Lai	1.76±0.09^{e}	2.09±0.10^{cde}	17.76±0.89^{de}	47.45±2.37^{fgh}	13.4±0.67^{ghi}	3.90 ±0.19^{fgh}	0.15±0.01^{d}	0.08±0.00^{gh}
	Leb Nok	1.22±0.06^{f}	1.83±0.09^{fgh}	12.53±0.63^{ghi}	58.18±2.91^{abc}	10.32 ±0.52^{lmn}	2.44 ±0.12^{lm}	0.17±0.01^{c}	0.10±0.00^{de}
	Leuang	0.51±0.03^{jkl}	1.07±0.05^{m}	19.20±0.96^{cd}	52.12±2.61^{c-f}	13.39 ±0.67^{ghi}	4.11±0.21^{f}	0.05±0.00^{m}	0.06±0.00^{jkl}
	Banpeang	0.58±0.03^{i-l}	0.84±0.04^{n}	17.94±0.90^{de}	59.43±2.97^{ab}	7.99±0.40^{p}	4.16±0.21^{f}	0.07±0.00^{l}	0.06±0.00^{jk}
	Chorlumpee	0.43±0.02^{lmn}	1.09±0.05^{lm}	20.96±1.05^{c}	43.05±2.15^{ghi}	20.05±1.00^{c}	6.29±0.31^{c}	0.03±0.00^{n}	0.05 ±0.00^{klm}
	Sang Yot, (Tha Sala)	0.73±0.04^{i}	1.33±0.07^{jk}	16.75±0.84^{e}	42.59±2.13^{hi}	20.82 ±1.04^{bc}	7.06±0.35^{b}	0.12±0.01^{fg}	0.07±0.00^{i}
	Sang Yot (Bang Khan)	1.06±0.05^{gh}	1.12±0.06^{lm}	25.07±1.25^{b}	40.64±2.03^{i}	16.34 ±0.82^{de}	6.73±0.34^{bc}	0.05±0.00^{m}	0.06±0.00^{jk}
	Average	**0.82±0.42^{B}**	**1.27±0.389^{C}**	**20.67±4.59^{A}**	**49.96±6.86^{C}**	**13.11 ±4.69^{B}**	**4.50±1.77^{A}**	**0.10±0.04^{C}**	**0.06±0.02^{B}**
0.8%	Dok Kha	0.31±0.02^{no}	0.86±0.04^{n}	<u>27.88±1.39^{a}</u>	53.10±2.66^{b-f}	5.05±0.25^{r}	1.94±0.10^{no}	0.13±0.01^{ef}	0.06±0.00^{ijk}
	Hom Bon	0.48±0.02^{klm}	1.21±0.06^{klm}	18.91±0.95^{d}	51.64±2.58^{c-f}	8.37±0.42^{op}	3.49±0.17^{hij}	0.10±0.00^{hi}	0.09 ±0.00^{fgh}
	Dawk Pa-yawm	0.33±0.02^{mno}	1.06±0.05^{m}	18.40±0.92^{de}	53.52±2.68^{b-f}	7.85±0.39^{pq}	4.02±0.20^{fg}	0.12±0.01^{fg}	0.09 ±0.00^{e-h}
	Luk Lai	0.71±0.04^{i}	1.33±0.07^{jk}	12.01±0.60^{g-j}	<u>63.40±3.17^{a}</u>	6.26±0.31^{r}	1.46±0.07^{o}	0.14±0.01^{de}	<u>0.12±0.01^{a}</u>

(Continued)

TABLE 5 Continued

Salinity levels	Varieties	P (%)	S (%)	Cl (%)	K (%)	Ca (%)	Mn (%)	Fe (%)	Ni (%)
	Leb Nok	2.34 ± 0.12^b	1.74 ± 0.09^{gh}	$12.03\pm0.60^{g-j}$	$52.44\pm2.62^{c-f}$	12.14 ± 0.61^{ijk}	5.17 ± 0.26^d	0.14 ± 0.01^{de}	0.07 ± 0.00^{ij}
	Leuang	0.64 ± 0.03^{ij}	1.64 ± 0.08^{hi}	13.83 ± 0.69^{fg}	56.34 ± 2.82^{bc}	14.14 ± 0.71^{gh}	4.12 ± 0.21^f	0.07 ± 0.00^l	0.09 ± 0.00^{fgh}
	Banpeang	1.85 ± 0.09^e	1.77 ± 0.09^{gh}	13.20 ± 0.66^{fgh}	57.76 ± 2.89^{abc}	8.92 ± 0.45^{nop}	2.28 ± 0.11^{mn}	0.09 ± 0.00^{ijk}	0.11 ± 0.01^{bc}
	Chorlumpee	1.04 ± 0.05^{gh}	1.48 ± 0.07^{ij}	14.76 ± 0.74^f	54.85 ± 2.74^{bcd}	10.71 ± 0.54^{klm}	3.31 ± 0.17^{ijk}	0.11 ± 0.01^g	0.10 ± 0.01^{cd}
	Sang Yot, (Tha Sala)	0.25 ± 0.01^o	1.15 ± 0.06^{klm}	18.76 ± 0.94^{de}	63.22 ± 3.16^a	7.80 ± 0.39^{pq}	1.60 ± 0.08^o	0.10 ± 0.00^{hi}	0.08 ± 0.00^h
	Sang Yot (Bang Khan)	0.65 ± 0.03^{ij}	1.17 ± 0.06^{klm}	18.64 ± 0.93^{de}	$52.20\pm2.61^{c-f}$	$9.40\pm0.47^{m-p}$	4.65 ± 0.23^e	0.02 ± 0.00^n	0.09 ± 0.00^{fgh}
	Average	$\mathbf{0.86\pm0.67^B}$	$\mathbf{1.34\pm0.30^B}$	$\mathbf{16.84\pm4.70^B}$	$\mathbf{55.85\pm4.82^A}$	$\mathbf{9.07\pm2.63^C}$	$\mathbf{3.20\pm1.27^B}$	$\mathbf{0.10\pm0.03^B}$	$\mathbf{0.09\pm0.02^A}$
F-test		**	**	**	**	**	**	**	**

The values show the mean ± standard deviation. Different small letters indicate statistically significant differences among the variety at different salinity levels and the capital letters indicate statistically significant differences between salinity levels within the same column. ** significance at $p<0.01$, the underline values are the highest value in each column.
Bold values are the average values of 10 rice varieties of each salinity level.

For yield traits, the biplot indicated that the first two principal components explained 54.1% and 15.9% of the variation. Most of the points within the 0.0% salinity cluster are situated on the right side of the y-axis, correlating with traits such as panicle length, seeds per panicle, good seed percentage, seed weight per panicle, 1,000-seed weight, and seed yield per plant. In contrast, the 0.4% salinity cluster is located on the left side of the y-axis, with an opposite relationship to most yield traits. Varieties Luk Lai, Leb Nok, Leuang, and Sang Yot (Tha Sala) at 0.0% salinity were dominant in panicle number, while varieties Dok Kha, Hom Bon, and Sang Yot (Bang Khan) at 0.0% salinity dominated traits such as panicle length, seeds per panicle, good seed
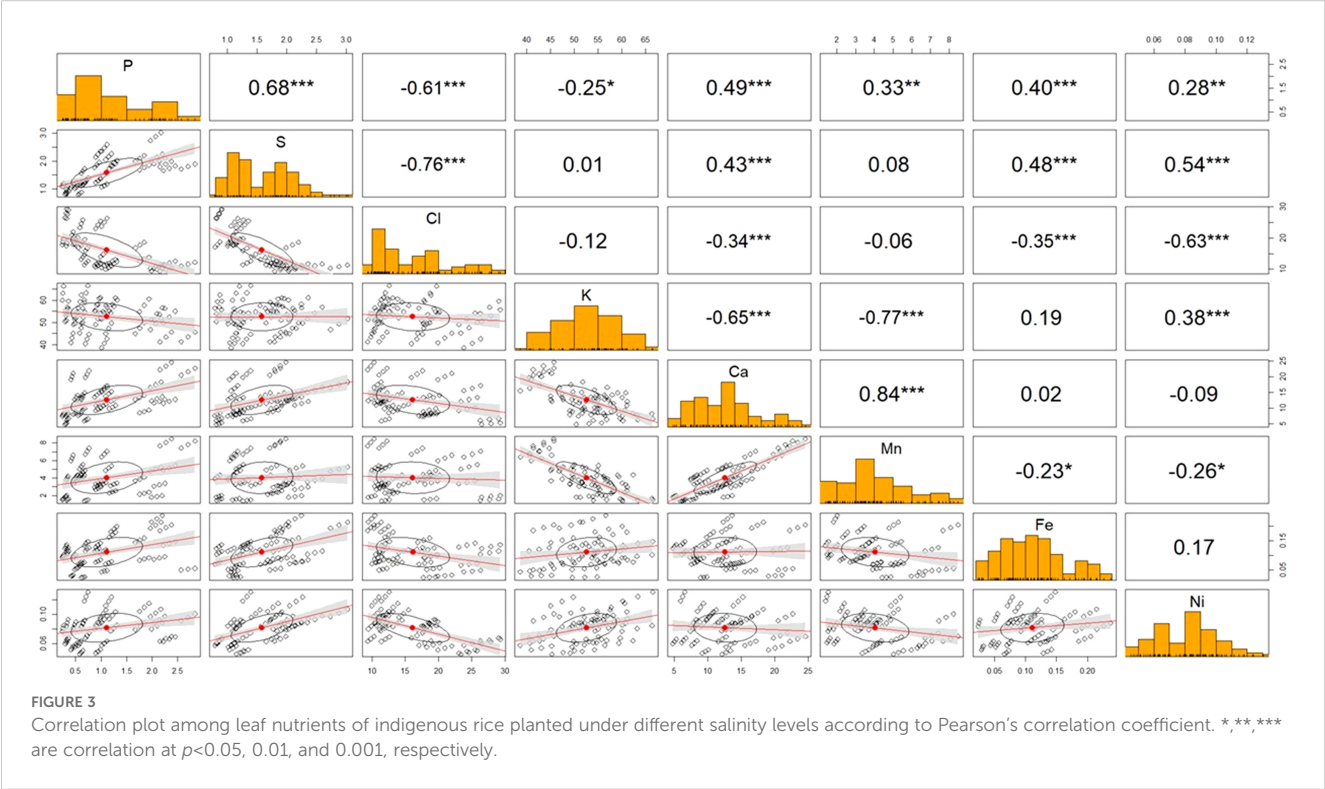

FIGURE 3
Correlation plot among leaf nutrients of indigenous rice planted under different salinity levels according to Pearson's correlation coefficient. *,**,*** are correlation at $p<0.05$, 0.01, and 0.001, respectively.
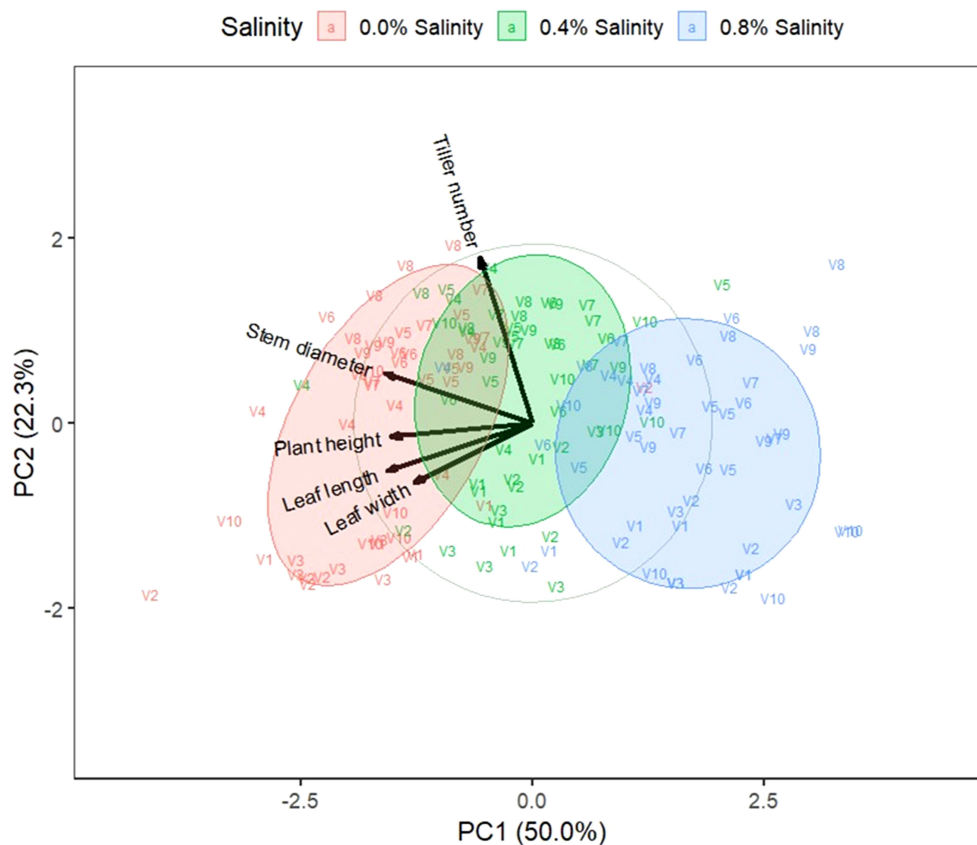
FIGURE 4
Biplot on the first two principal components of indigenous rice agronomic traits. 0.0%, 0.4%, and 0.8% are salinity levels. V1: Dok Kha, V2: Hom Bon, V3: Dawk Pa-yawm, V4: Luk Lai, V5: Leb Nok, V6: Leuang, V7: Banpeang, V8: Chorlumpee, V9: Sang Yot, (Tha Sala), and V10: Sang Yot (Bang Khan).

percentage, seed weight per panicle, 1,000-seed weight, and seed yield per plant.

The biplot for leaf nutrients revealed that the first two principal components accounted for 41.0% and 33.4% of the variation. The 0.0% salinity cluster was associated with calcium, phosphorus, sulfur, iron, and nickel, while the 0.4% salinity cluster was aligned with potassium, and the 0.8% salinity cluster corresponded with chlorine and manganese. Varieties Dok Kha and Sang Yot (Bang Khan) at 0.0% salinity were dominant in calcium, while Luk Lai at 0.0% salinity was dominant in phosphorus and sulfur. Varieties Hom Bon, Leb Nok, Leuang, and Banpeang at 0.0% salinity, Leb Nok at 0.4% salinity, and Chorlumpee at 0.8% salinity dominated in iron and nickel. Luk Lai at 0.8% salinity was dominant in potassium, and varieties Dawk Pa-yawm, Leuang, and Banpeang at 0.4% salinity, along with Hom Bon, Dawk Pa-yawm, and Sang Yot (Bang Khan) at 0.8% salinity, dominated in chlorine.

4 Discussion

Salt stress is one of the major constraints in agricultural soils, significantly reducing growth and productivity in rice and other crops. Several complex processes in rice, including cell wall modifications, cytoskeletal modulation, gene regulation, stress defense mechanisms, ion homeostasis, salt sensing, and ROS signaling, are involved in the plant's response to salt stress (Hasan et al., 2023). In this study, we found that the agronomic traits, yield characteristics, and leaf nutrient profiles of ten indigenous rice varieties from Nakhon Si Thammarat were influenced by varying salinity levels. Specifically, stem diameter and leaf length were significantly reduced at 0.4% salinity, while plant height, leaf length, and tiller number were notably reduced at 0.8% salinity.

In terms of yield traits, all rice varieties subjected to 0.8% salinity exhibited severe dehydration and perished during the flowering stage, whereas only the rice varieties Luk Lai, Leb Nok, and Sang Yot (Bang Khan) survived at 0.4% salinity. According to Sari et al. (2019), several traits such as flag leaf length, tiller number per plant, panicle number per plant, days to flowering, panicle length, number of filled grains per panicle, spikelet fertility, grain weight per panicle, and 1,000-grain weight are strongly correlated with grain yield. When these traits are affected by salinity stress, rice is unable to produce normal yields. Furthermore, Ninsuwan et al. (2013) examined the salt tolerance of Thai native rice seedlings and improved varieties using 103 mM NaCl. They found that the survival rate differed among rice varieties and that all tested varieties displayed distinct visual symptoms following salinity stress.
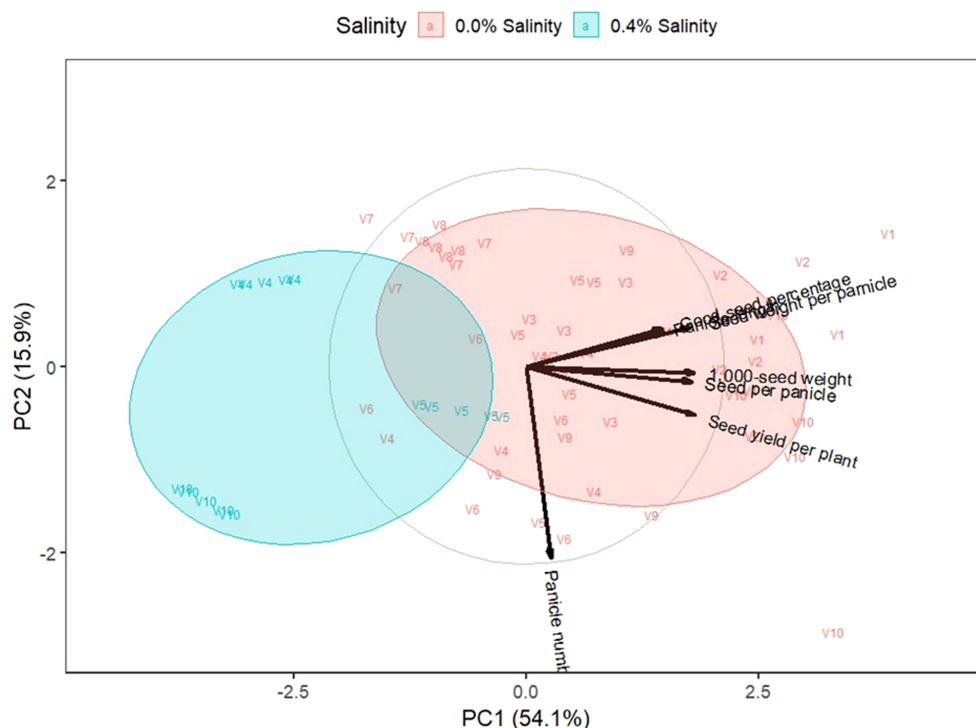
FIGURE 5
Biplot on the first two principal components of indigenous rice yield traits. 0.0% and 0.4% are salinity levels. V1: Dok Kha, V2: Hom Bon, V3: Dawk Pa-yawm, V4: Luk Lai, V5: Leb Nok, V6: Leuang, V7: Banpeang, V8: Chorlumpee, V9: Sang Yot, (Tha Sala), and V10: Sang Yot (Bang Khan).

The detrimental effects of salinity—such as soil compaction, osmotic stress from reduced water availability, nutrient deficiencies due to impaired uptake of essential elements like calcium, phosphorus, potassium, and nitrogen, and ion toxicity—further inhibit rice growth (Razzaq et al., 2020). Factors such as the intensity and duration of salt exposure, the growth stage of the plant, and the susceptibility of the rice variety are key determinants of the extent to which rice production and quality are reduced by salt stress. For example, grain yield in salt-sensitive rice varieties has been reported to decrease by 52.5–67.7% compared to tolerant varieties under 3-6% irrigated salinity. Furthermore, increases in salt concentration have been shown to decrease nitrogen uptake by 20.6–50.8%, reduce seed protein content by 6.66–8.15%, and lower amylose content by 17.74–25.48% (Li et al., 2023).

The use of micro-XRF spectrometry provided valuable insights into the nutrient status and compartmentalization in the leaves of indigenous rice varieties grown under different salinity conditions. Micro-XRF spectrometry is a well-established, non-destructive analytical technique for both qualitative and quantitative elemental analysis, making it suitable for *in vivo* plant studies (Rodrigues et al., 2018). This method is effective for timely plant nutrition monitoring, offering highly accurate, cost-effective analysis for multiple elements simultaneously ($R^2 > 0.99$) with no significant variation between certified and measured values at a 99% confidence level (Rallos et al., 2023).

In this study, micro-XRF spectrometry revealed that leaf contents of phosphorus, sulfur, calcium, manganese, iron, and nickel decreased significantly with increasing salinity levels, while chlorine and potassium levels increased. Potassium, the third most essential macronutrient, plays a crucial role in physiological and metabolic processes such as stomatal movement, enzyme activation, photosynthesis, osmoregulation, and stress resistance (Praveen and Singh, 2024). Hom Bon, Chorlumpee, Sang Yot (Tha Sala), and Sang Yot (Bang Khan) had increased calcium and manganese accumulation at 0.4% salinity, and Dok Kha and Sang Yot (Bang Khan) had increased calcium and manganese accumulation at 0.8% salinity. Calcium is considered to be essential for improving plants' ability to tolerate stress. Calcium acts as a secondary messenger in a variety of stress signal transduction pathways, including drought, salinity, cold, heat and heavy metal stress. It greatly aids in reducing abiotic stress, whether used alone or in combination with exogenous plant hormones (Gupta et al., 2023). By enhancing ionic and osmotic homeostasis by reducing Na^+ influx and raising water status, respectively, manganese assisted the plants in partially recovering from the chlorosis and growth inhibition. By raising the levels of phenolic compounds, flavonoids, and ascorbate as well as the activities of catalase, superoxide dismutase, dehydroascorbate reductase, and monodehydroascorbate reductase in the salt-treated seedlings, exogenous Mn administration enhanced reactive oxygen species detoxification (Rahman et al., 2016). Chloride accumulation in rice leaves tended to increase at 0.4% salinity levels and decrease at 0.8% salinity level. Chloride ions, a key micronutrient, support water use efficiency, photosynthesis, and stomatal regulation, and are essential cofactors in photosynthetic light reactions and electron transport within the chloroplast (Wang et al., 2020).
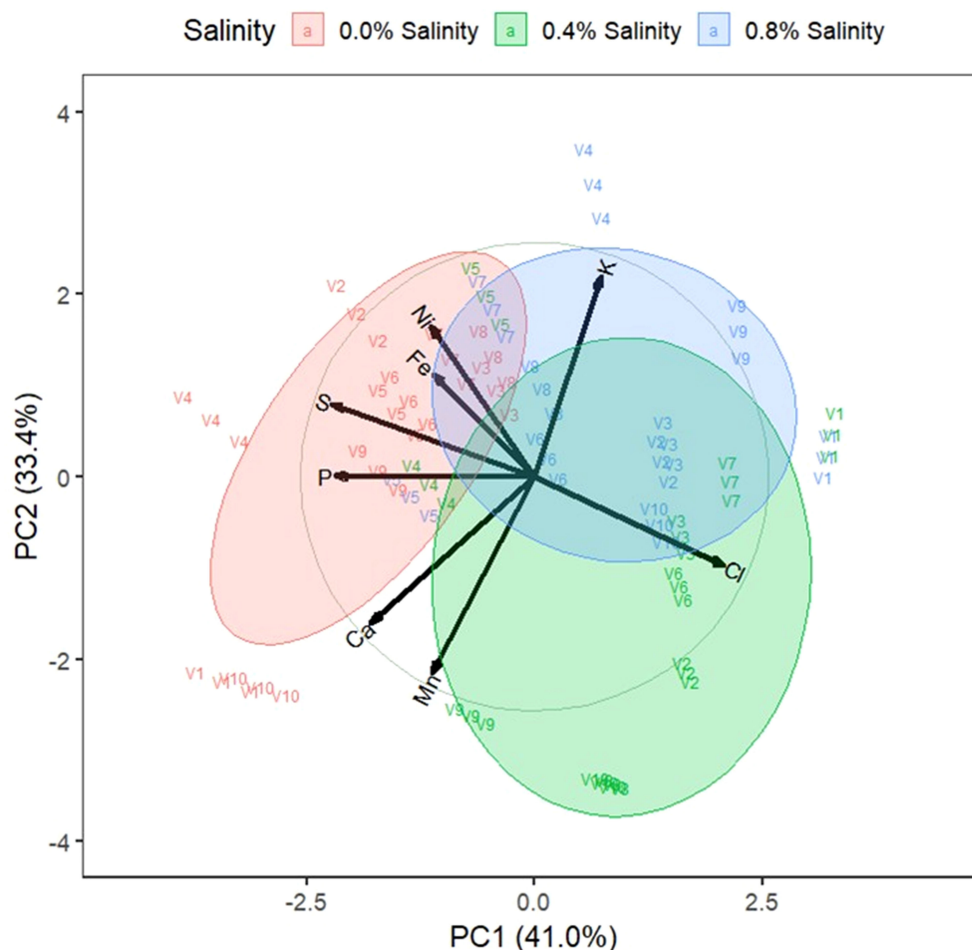
FIGURE 6
Biplot on the first two principal components of indigenous rice leaf nutrient. 0.0%, 0.4%, and 0.8% are salinity levels. V1: Dok Kha, V2: Hom Bon, V3: Dawk Pa-yawm, V4: Luk Lai, V5: Leb Nok, V6: Leuang, V7: Banpeang, V8: Chorlumpee, V9: Sang Yot, (Tha Sala), and V10: Sang Yot (Bang Khan).

The correlation analysis revealed several strong positive relationships among leaf nutrients, including calcium and manganese, phosphorus and sulfur, and sulfur and nickel. Conversely, strong negative correlations were observed between potassium and manganese, chlorine and sulfur, calcium and potassium, and chlorine and phosphorus. These findings suggest that variations in certain leaf nutrients can significantly influence the levels of other correlated nutrients (Khomphe et al., 2022; Khomphet, 2024).

Principal component analysis (PCA) effectively distinguished the indigenous rice varieties based on agronomic traits, yield characteristics, and leaf nutrient content. PCA is a valuable tool for cluster analysis and is widely used to measure the contribution of each component to the total variance (Popet et al., 2023). The results of PCA for agronomic traits indicated that increasing salinity levels reduced plant height, stem diameter, leaf width, leaf length, and tiller number. PCA for yield traits showed that salinity levels negatively impacted panicle length, seed per panicle, good seed percentage, seed weight per panicle, 1,000-seed weight, and seed

yield per plant, although panicle number remained unaffected. PCA for leaf nutrients revealed that higher salinity levels reduced phosphorus, sulfur, calcium, iron, and nickel content in the leaves, while chlorine and potassium levels increased.

Based on their performance under salinity stress, the indigenous rice varieties Luk Lai, Leb Nok, and Sang Yot (Bang Khan) are recommended for further cultivation in saline soils. All three rice varieties survived, exhibited high levels of certain growth characteristics, such as the tiller number, and were able to produce a yield in saline soil. Additionally, these varieties hold potential as valuable genetic resources for future rice breeding programs aimed at improving salinity tolerance.

5 Conclusions

There were significant differences among rice varieties and salinity levels for most of growth and yield traits, and leaf nutrient. Higher saline levels at 0.4 and 0.8% significantly

inhibited the development of all varieties of rice. Rice varieties responded differently to varied salinity conditions in terms of growth, yield traits, and leaf nutrients, according to the principal component analysis. The high level of potassium, chlorine, and manganese was observed in the rice leaves under salinity conditions. The indigenous varieties of rice Luk Lai, Leb Nok, and Sang Yot (Bang Khan) are suggested for farmers to plant in the future on saline soils due to their capacity to thrive in salty conditions and produce well. The field experiment is suggested for further study.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

Author contributions

TK: Conceptualization, Formal Analysis, Funding acquisition, Methodology, Project administration, Supervision, Visualization, Writing – original draft, Writing – review & editing. YZ: Validation, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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