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Stratified soil nutrient contributions to rice leaf growth and stem development: a vertical heterogeneity perspective

Contribuições da estratificação de nutrientes no solo para o crescimento das folhas e o desenvolvimento do caule do arroz: uma perspectiva de heterogeneidade vertical

Chenyue Tian[1]; Yongxia Hou[2]*; Xiaoyang Wang[1]; Jianbing Wei[3]; Xueying Song[4]; Guojun Xing[5]

Highlights

Different effects of soil nutrients on rice morphology and physiology were assessed.
A "surface-middle-deep" correlation model was built for rice growth indicators.
Layered fertilization enhances rice growth: surface boosts leaf, deep supports stem.

Abstract

The vertical heterogeneity of soil nutrients significantly influences rice growth; however, its effects on leaf and stem development in the Liaohe Delta remain unclear. This study analyzed 35 rice fields in Panjin, China, and measured soil physicochemical properties (0–20 cm, 20–40 cm, and 40–60 cm) as well as rice morphological/physiological indicators (plant height, leaf length, stem thickness, and soluble sugar/protein). Principal component analysis (PCA) revealed three dominant components, which accounted for 75.97% of the variation, with leaf length, soluble sugar, and soluble proteins as key drivers. Multivariate regression revealed that 0–20 cm soil nitrogen (N) and phosphorus (P) promoted leaf growth and photosynthetic efficiency, whereas the 20–40 cm soil pH and water content regulated soluble sugar accumulation. Deep-layer (40–60 cm) organic matter and N improved the root environment and

[1] Graduate Students of Environmental Science and Engineering, College of Enviroment, Shenyang University, Shenyang City, Liaoning Province, China. E-mail: 3452936330@qq.com; 1798392558@qq.com
[2] Prof. Dr., College of Enviroment, Shenyang University, Shenyang City, Liaoning Province, China. Northeast Geological S&T Innovation Center of China Geological Survey, Shenyang City, Liaoning Province, China. E-mail: houyongxia@126.com
[3] Prof. Dr., College of Life Science and Bioengineering, Shenyang University, Shenyang City, Liaoning Province, China. E-mail: oliver1208@sina.com
[4] Prof. Dr., College of Enviroment, Shenyang University, Shenyang City, Liaoning Province, China. E-mail: songxy2046@163.com
[5] Shenyang No. 11 High School, Shenyang City, Liaoning Province, China. E-mail: 253290880@qq.com
* Author for correspondence

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enhanced the stem's mechanical strength. The study establishes a "surface-middle-deep" correlation model, demonstrating that stratified soil nutrients differentially affect rice growth. These findings provide a targeted fertilization strategy"surface layer for leaf promotion, deep layer for stem strengthening"to optimize nutrient management and improve rice productivity in the Liaohe Delta.
Key words: Rice plant. Soil quality. Principal Component Analysis. Multiple regression analysis.

Resumo

A heterogeneidade vertical dos nutrientes do solo influencia significativamente o crescimento do arroz, mas seus efeitos sobre o desenvolvimento das folhas e do caule no Delta do Liaohe ainda não estão claros. Este estudo analisou 35 campos de arroz em Panjin, China, medindo as propriedades físico-químicas do solo (0-20 cm, 20-40 cm, 40-60 cm) e indicadores morfológicos/fisiológicos do arroz (altura da planta, comprimento da folha, espessura do caule, açúcar solúvel/proteína). A análise de componentes principais (PCA) revelou três componentes dominantes que explicam 75,97% da variação, sendo o comprimento da folha, o açúcar solúvel e a proteína solúvel os principais fatores. A regressão multivariada mostrou que o nitrogênio (N) e o fósforo (P) do solo de 0-20 cm promoveram o crescimento das folhas e a eficiência fotossintética, enquanto o pH e o teor de água de 20-40 cm regularam o acúmulo de açúcar solúvel. A matéria orgânica e o N da camada profunda (40-60 cm) melhoraram o ambiente da raiz, aumentando a força mecânica do caule. O estudo estabelece um modelo de correlação "superfície-meio-profundo", demonstrando que os nutrientes estratificados do solo afetam diferencialmente o crescimento do arroz. Essas descobertas fornecem uma estratégia de fertilização direcionada - "camada superficial para promoção de folhas, camada profunda para fortalecimento do caule" - para otimizar o gerenciamento de nutrientes e melhorar a produtividade do arroz no Delta de Liaohe.
Palavras-chave: Planta de arroz. Qualidade do solo. Análise de componentes principais. Análise de regressão múltipla.

Introduction

Rice is the second-largest food crop in the world, supporting over half the world's population (Gao et al., 2024). With the advancement of the social economy and optimization of the dietary structure, consumer demand for rice quality is increasingly stringent (Bu et al., 2022). Rice growth is significantly influenced by the production environment, and there are significant differences in rice production under different soil nutrient conditions. Exploring the relationship between rice growth and soil nutrients in rice-producing areas is important for guiding rational fertilization in paddy fields and improving rice quality.

Organic matter, nitrogen, phosphorus, and K in the soil affect rice quality (Ali et al., 2021; Jiaying et al., 2022; Liu et al., 2024; Wang et al., 2023; Ye, 2021; Zhang et al., 2023). Among the three major elements (nitrogen, phosphorus, and potassium), nitrogen had the greatest effect on rice quality, followed by potassium and phosphorus. Rational application of nitrogen fertilizer can improve the photosynthetic efficiency of rice leaves and increase their sugar and starch content, thereby enhancing rice quality (Wang et al., 2023). The application of magnesium fertilizer to soil has been shown to enhance the nitrogen absorption capacity of rice and improve the utilization rate of nitrogen fertilizer (Ali et al., 2021). Even when the magnesium content in the soil was relatively high, nitrogen uptake by rice roots remained at a consistently high level. In addition, K promotes protein synthesis in rice grains, increases the accumulation of photosynthetic products, and influences both the taste and nutritional quality of rice (Ye, 2021).

Recent studies have emphasized the role of vertical heterogeneity in soil nutrient distribution during crop development. Layered soil properties contribute to sustainable nutrient cycling (Lal, 2008). Moreover, rice root systems have been shown to respond spatially to stratified nutrients (Hong-bo et al., 2013; Wang et al., 2022). These insights align with previous findings on how interactions among N, P, and K influence plant morphological development (Fageria, 2001).

As soils have certain regional characteristics, it is more practical to examine the relationship between soil conditions and rice in a specific region. Accordingly, this study focused on rice field soils formed under the climatic conditions of Panjin City. We aimed to address the issue of uneven rice growth and quality in Panjin City's paddy fields caused by the vertical distribution heterogeneity of soil nutrients. By elucidating the regulatory effects of different soil layers on the key growth indicators of rice, we propose targeted fertilization management strategies to optimize regional rice production and achieve scientific soil fertilization.

Materials and Methods

Materials

Panjin City, Liaoning Province, is located in the estuary of the Liaohe River. It is rich in water resources, has a humid climate, and has fertile soil, making it suitable for rice cultivation (Wang et al., 2022). Based on the locations of the second soil census, information on Panjin soil types, and the overall map of Panjin, 35 rice fields planted with the Yanfeng 47 variety were selected from Panlong County (14 rice fields, numbered 1–14), Dawa District (19 rice fields, numbered 15–33), and Xinglongtai District (two rice fields, numbered 34 and 35), following the principle of relatively uniform spatial distribution. The specific distribution of the sampling points is shown in Figure 1. Soil samples were collected in mid-April 2024 before rice planting. A diagonal sampling pattern was established in each paddy field to ensure spatial coverage. Five representative points were systematically positioned at the diagonal intersections and midpoints. Surface debris (vegetation and stones) was removed prior to sampling. At each point, the soil pits were excavated using a stainless-steel excavation shovel to extract samples from three depths (0-20 cm, 20-40 cm, 40-60 cm). For each stratum, subsamples from all five points were homogenized to form a single composite sample per depth layer per field, ensuring representative characterization. The samples were immediately sealed in pre-labeled bags to document the field ID, coordinates, depth, and collection date. The soil in the same layer from the same rice field was mixed, placed in a sealed bag, and marked with a serial number. The soil samples were air-dried, impurities were removed, ground, sieved through a 10-mesh sieve, and stored for testing. From mid to late October 2024, during the rice maturity period, rice samples were collected at the corresponding soil collection points. Ten rice paddies were sampled from each field. The samples were bagged, labeled properly, and promptly returned to the laboratory for measurement.

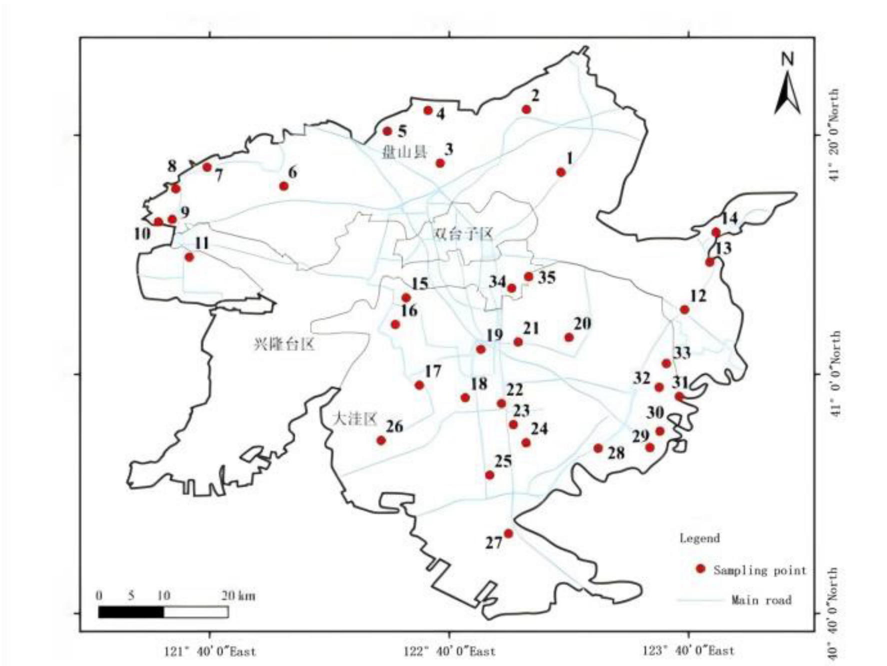

Figure 1. Distribution of sampling points.

Determination of rice indicators

The plant height and leaf length were measured using a tape measure. The basal stem diameter of the rice was measured using Vernier calipers. The soluble sugar content of the leaves was determined using the anthrone colorimetric method (Guo et al., 2019). The soluble protein content in the leaves was determined using the Coomassie Brilliant Blue method (Bradford, 1976). The organic matter content of the leaves was determined using the potassium dichromate external heating method (Song et al., 2023).

Determination of soil indicators

pH value and electrical conductivity (EC) were determined using standardized aqueous extraction methods. Soil pH, indicating acidity/alkalinity, was measured by mixing air-dried soil with distilled water at a 1:2.5 ratio, agitating, and allowing it to settle for 30 min before recording stable readings from the supernatant using a potentiometric electrode. Electrical conductivity, reflecting soluble salt content (μS cm^{-1}), was determined using the same pretreatment at a soil-water ratio of 1:5, with measurements taken directly from the aqueous extract using an EC probe. The soil water content was measured with reference to the methods in soil agrochemical analysis. Organic matter was determined using the potassium dichromate external heating method, with the units expressed as grams per kilogram (g kg^{-1}). Total nitrogen was determined using the Kjeldahl method, with soil samples digested in concentrated sulfuric acid in the presence of K_2SO_4 and $CuSO_4{\cdot}5H_2O$ catalyst. Results are expressed in grams per kilogram (g kg^{-1}). Total potassium was measured after oxidation of soil samples by heating with nitric acid (HNO_3) and perchloric acid ($HClO_4$). Silicates and other minerals were decomposed using hydrofluoric acid (HF). After that, heating is continued to remove residual acidic substances, and the residue is dissolved in hydrochloric acid (HCl) to release potassium ions, which are finally determined by flame photometry. The unit of total potassium content is grams per kilogram (g kg^{-1}). Total phosphorus was determined by fusing soil samples with sodium hydroxide (NaOH) to convert phosphorus-containing minerals and organic phosphorus compounds in the soil into soluble orthophosphate, which was then measured using the molybdenum-antimony anti-colorimetric method (Bao, 2000). Results were expressed in grams per kilogram (g kg^{-1}).

Data analysis methods

Principal Component Analysis (PCA) was applied to address the issues of high dimensionality and potential multicollinearity among rice growth indicators, including plant height, leaf length, stem diameter, leaf organic matter, soluble sugar, and soluble protein. Prior to the analysis, all variables were subjected to zero-mean standardization and unit variance standardization to eliminate biases caused by different measurement scales (e.g., stem diameter measured in millimeters and soluble sugar measured as a percentage). A comprehensive evaluation system for rice growth was constructed by selecting principal components (PCs) with eigenvalues >1 and cumulative variance ≥70%. Key growth indicators were identified based on the initial factor-loading matrix, laying the foundation for subsequent regression analysis.

This study further adopted multiple regression analysis to quantify the correlation between the three key rice growth indicators (identified via PCA) and 21 layered soil variables (three soil layers × seven indicators: water content, pH, electrical conductivity, organic matter, total nitrogen, total phosphorus, and total potassium). The partial correlation coefficient, t-test value, and p-value were used to assess the strength, direction, and significance of the correlations between the soil variables and rice indicators, respectively. The reliability of the model was verified using the coefficient of determination (R2), standardized estimation error, and Durbin (DW) value (with a target value of approximately 2 to avoid residual autocorrelation).

Data organization and chart visualization were performed using Microsoft Excel 2019. Statistical analyses, including PCA and multiple regression analysis, were conducted using SPSS software version 26.0, and graphical illustrations were generated using Origin 2022 software.

Results

Comparison of rice indicators in different paddy fields

The plant height of rice in different paddy fields ranged from 62.83 to 100.52 cm, the leaf length ranged from 28.8 to 44.5 cm, and the stem diameter ranged from 47.73 to 92.06 mm. Among them, rice in Paddy Field 14 was the tallest, with the longest leaves, and rice in Paddy Field 30 had the thickest stem (Figure 2).

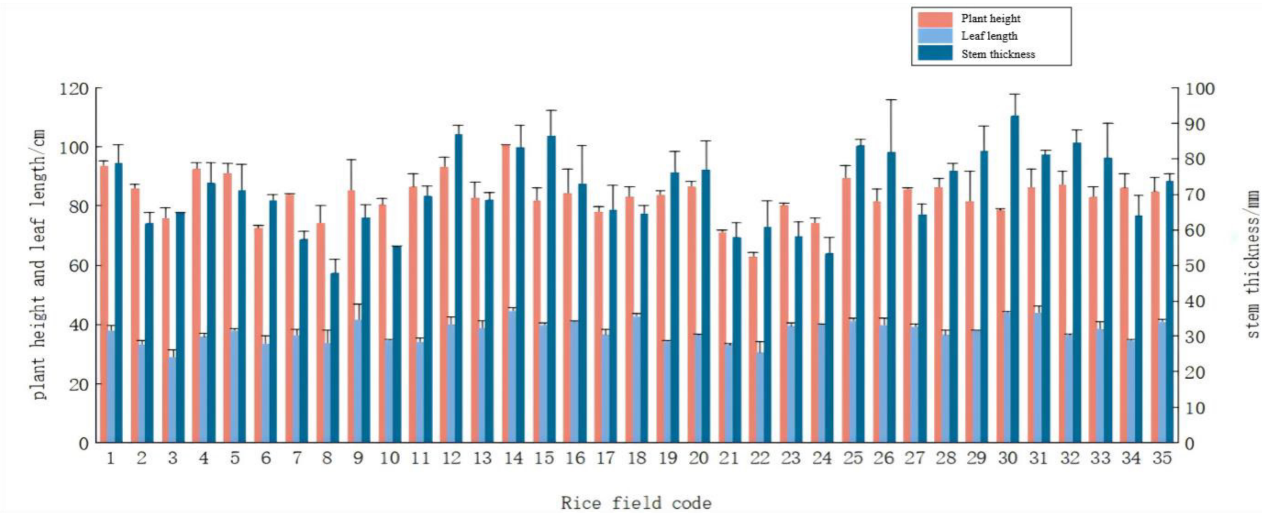

Figure 2. Rice plant height, leaf length and stem thickness in different rice fields.

As shown in Figure 3, the organic matter content of leaves in the paddy fields fluctuated between 70% and 90%. The organic matter content of leaves in Paddy Fields 12, 18, 32, and 34 was relatively high, whereas that in the other paddy fields was relatively low. The soluble sugar content in the leaves of different paddy fields showed significant differences. The soluble sugar content in Paddy Field No. 24 was the highest, approaching 1.5%, and those in Paddy Fields No. 18 and 26 were also relatively high, whereas those in Paddy Fields No. 20, 21, and 23 were relatively low. In contrast, soluble protein content was relatively stable, mostly between 1.1% and 1.6%. In addition, in most paddy fields, the soluble protein content of leaves is higher than the soluble sugar content.

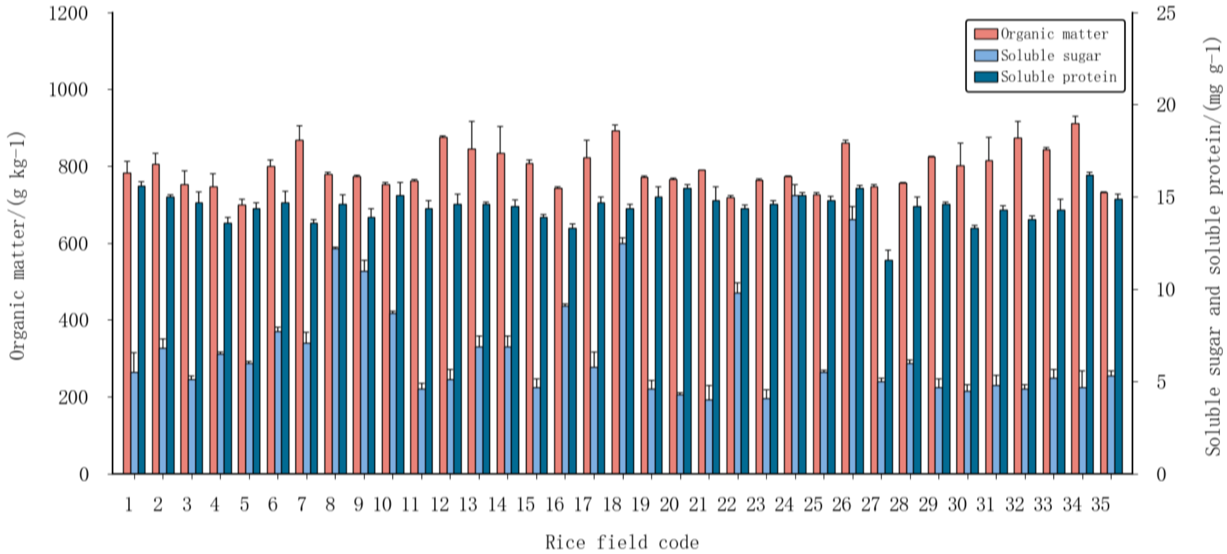

Figure 3. Organic matter, soluble sugar and soluble protein contents of rice leaves in different rice fields.

Principal component analysis of rice growth status

The results of principal component analysis (Table 1) show that the eigenvalues of the first three principal components are greater than 1. After variance decomposition, the cumulative contribution rate reached 75.974%, indicating that the model effectively extracted the main variation characteristics of the six original variables. Therefore, the first three principal component indicators were selected as the basis for a comprehensive evaluation of rice growth status. The initial factor-loading matrix is presented in Table 2.

Table 1
Characteristic values of principal components

Principal component	Eigenvalue	Contribution rate/%	Cumulative contribution rate/%
1	2.197	36.611	36.611
2	1.224	20.396	57.007
3	1.138	18.966	75.974

Table 2
Principal component initial factor loading matrix

Principal component	1	2	3
Plant height	0.704	-0.376	0.082
Leaf length	0.893	0.213	-0.129
Stem thickness	0.696	-0.504	0.059
Leaf organic matter	0.395	0.161	0.69
Leaf soluble sugar	-0.052	0.936	0.074
Leaf soluble protein	-0.283	-0.066	0.828

To mitigate the disproportionate influence of high-variance features (e.g., stem thickness) that may distort principal components, all variables were standardized to zero mean and unit variance before PCA, and the obtained weights were 0.482, 0.268, and 0.250, respectively. Thus, the principal component expression is Y = 0.482Y1 + 0.268Y2 + 0.250Y3. The principal component scores of the rice growth status indicators calculated using this expression are listed in Table 3. Paddy field 14 had the highest comprehensive score, followed by Paddy Fields 18 and 26. Paddy Field 22 had the lowest comprehensive score, indicating that the comprehensive growth status of the rice in this paddy field was relatively poor.

Figure 4 illustrates the distribution of individual paddy field samples within the spatial framework defined by the first three principal components (PCA1, PCA2, PCA3). Each point in the graph corresponds to an individual paddy field sample positioned according to its score along the three principal component axes. The color bar adjacent to the graph denotes the value range associated with the point colors, which represent variations in the principal component scores across the samples. Paddy Field No. 14, which exhibited a high comprehensive score, occupied a distinct location within the three-dimensional space, whereas Paddy Field No. 22, which was characterized by a low comprehensive score, was situated in a different representative position. The spatial arrangement of the points further reveals similarities and disparities in rice growth characteristics among the fields; a clustered distribution implies comparable growth conditions, whereas a dispersed distribution suggests greater heterogeneity in growth traits.

Table 3
Rice growth condition principal component factor score

Rice field code	Principal component score			Overall score	Sort
	Y1	Y2	Y3		
14	2.21	-0.26	0.98	1.24	1
18	1.56	0.62	1.15	1.20	2
26	1.51	0.46	1.29	1.17	3
12	1.96	-0.41	1.14	1.12	4
31	1.85	-0.30	0.84	1.02	5
30	1.92	-0.36	0.61	0.98	6
32	1.62	-0.41	1.01	0.92	7
9	1.35	0.39	0.67	0.92	8
33	1.52	-0.27	0.97	0.90	9
13	1.33	0.01	1.02	0.90	10
15	1.63	-0.37	0.77	0.88	11
34	1.11	-0.19	1.55	0.87	12
1	1.47	-0.40	1.03	0.86	13
24	0.79	0.92	0.89	0.85	14
29	1.43	-0.34	0.96	0.84	15
16	1.43	0.10	0.46	0.83	16
25	1.58	-0.41	0.68	0.82	17
7	1.12	0.15	0.92	0.81	18
35	1.34	-0.26	0.69	0.75	19
17	1.02	-0.05	0.95	0.71	20
28	1.24	-0.29	0.75	0.71	21
20	1.20	-0.44	0.95	0.70	22
4	1.30	-0.27	0.57	0.70	23
2	0.86	-0.06	1.00	0.65	24
5	1.22	-0.30	0.54	0.64	25
27	1.34	-0.15	0.15	0.64	26
23	1.01	-0.13	0.71	0.63	27
19	1.05	-0.41	0.89	0.62	28
6	0.74	0.07	0.91	0.60	29
8	0.40	0.66	0.83	0.58	30
11	1.01	-0.36	0.75	0.58	31
10	0.62	0.20	0.84	0.56	32
21	0.51	-0.12	0.87	0.43	33
3	0.41	-0.23	0.78	0.33	34
22	0.13	0.34	0.61	0.30	35

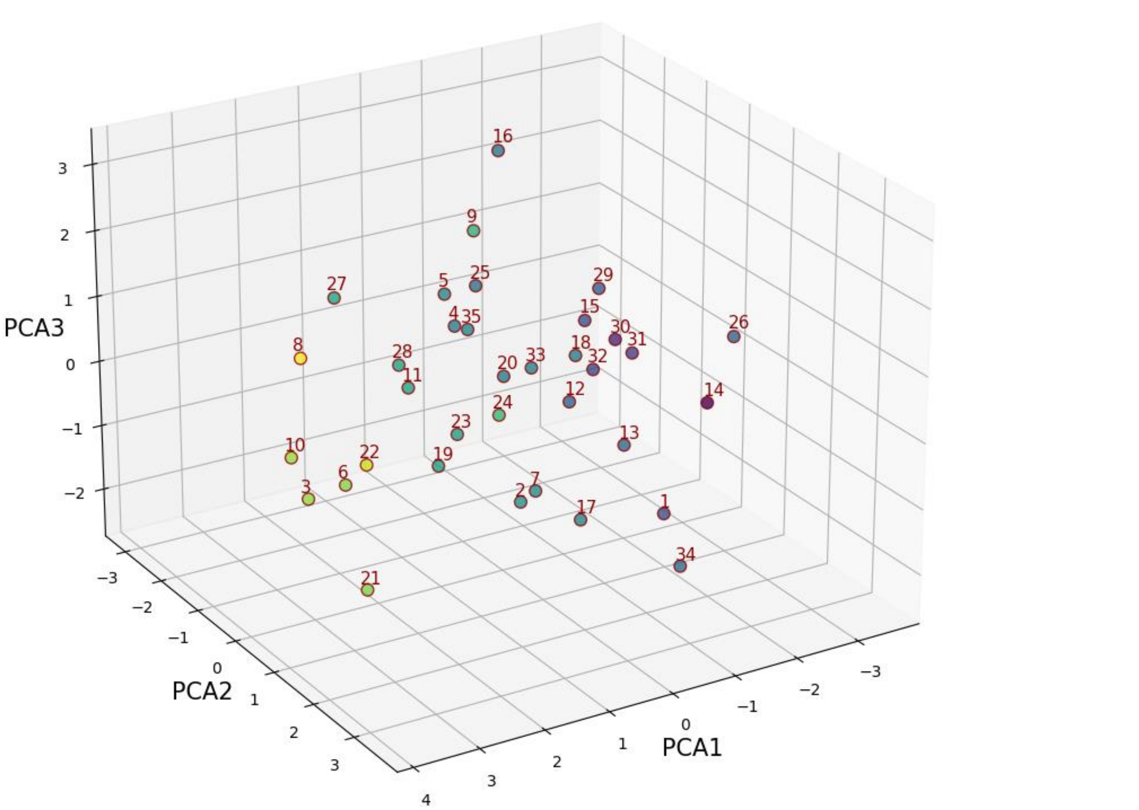

Figure 4. 3D PCA map of the first three main features.

Physicochemical properties and nutrient element contents of soils in different paddy fields

As shown in Figure 5, the water content of the different paddy fields varied significantly. The water content in the 0 - 20 cm soil layer in most fields was relatively high. The water content in the 0–20 cm soil layer of paddy field 1 exceeded 60%. The soil pH value of paddy fields mostly ranges from 7.0 to 8.5, indicating a neutral to weakly alkaline state, which is suitable for rice growth. Overall, the soil pH in paddy field 8 was relatively high. The EC and organic matter content of most paddy fields decreased with increasing soil depth. The organic matter content in the 0 - 20 cm soil layer was relatively high, which can provide rich nutrients and is beneficial for the growth of rice roots.

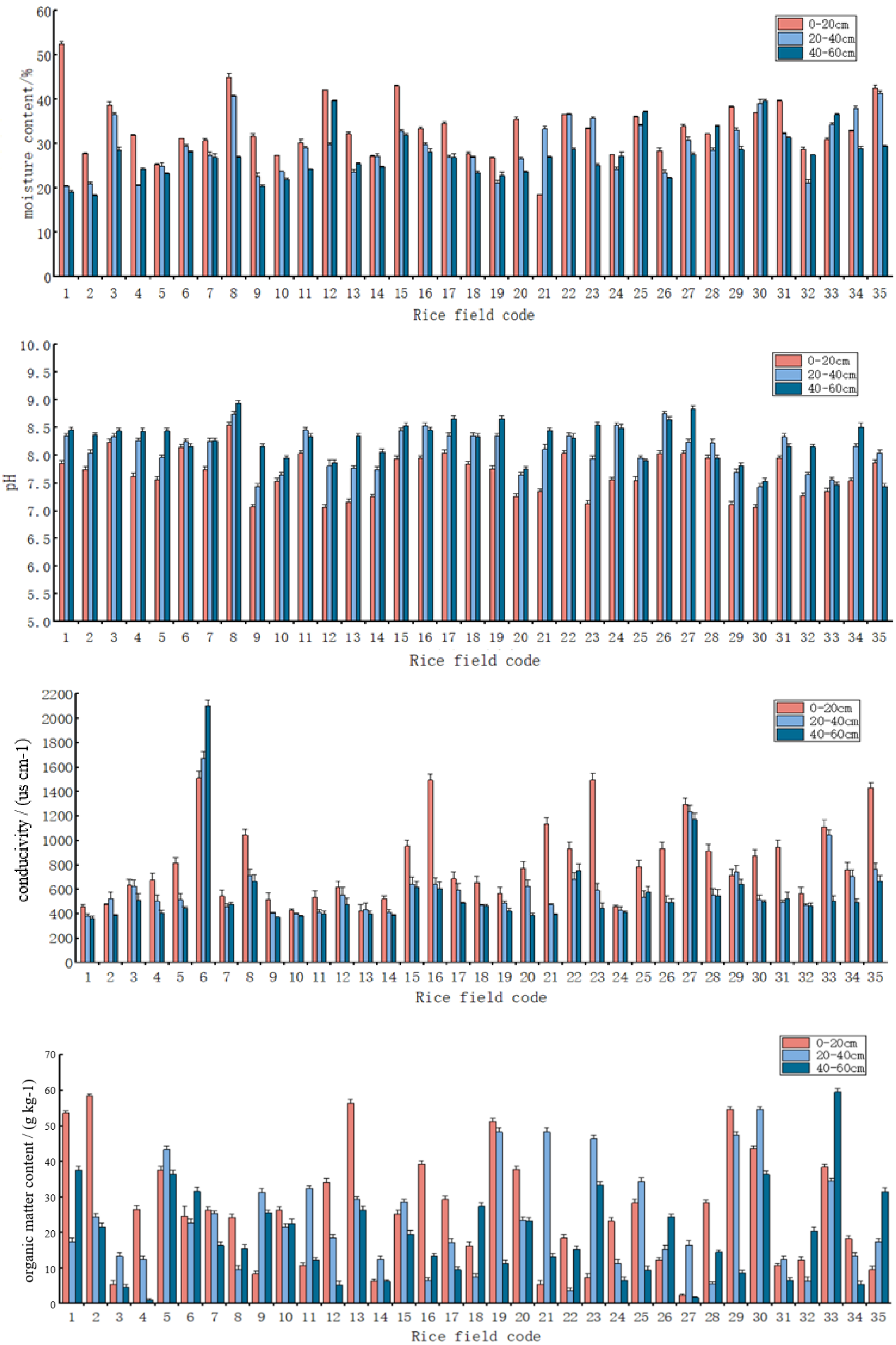

Figure 5. Physicochemical properties of soil in three soil horizons of different rice fields.

The contents of various nutrients vary among the paddy fields. As shown in Figure 6, the nitrogen content in the 0 - 20 cm soil layer fluctuated greatly. Paddy Fields No. 4, No. 30, and No. 33 had relatively high soil nitrogen content, whereas Paddy Fields No. 19 and No. 26 had relatively low overall nitrogen content. Compared to the other two soil layers, the phosphorus content in the 0 - 20 cm soil layer was relatively high. In some fields, the phosphorus content in the 20–40 cm soil layer was prominent, such as in Paddy Fields No. 3 and 22. The distribution of K at different depths showed no clear pattern. Content differences in different fields are affected by multiple factors and have different effects on the stress resistance and grain filling of rice at different growth stages. The potassium content in the 40 - 60 cm soil layer of Paddy Fields 15 and 17 was relatively high, whereas that in Paddy Fields 12 and 34 was relatively low. From the perspective of soil depth, the 0–20 cm soil layer was rich in nutrients and had large differences. The nutrient content in the 20–40 cm soil layer decreased and changed steadily, and the nitrogen and phosphorus contents in the 40–60 cm soil layer were generally the lowest, while the potassium content in some fields was prominent.

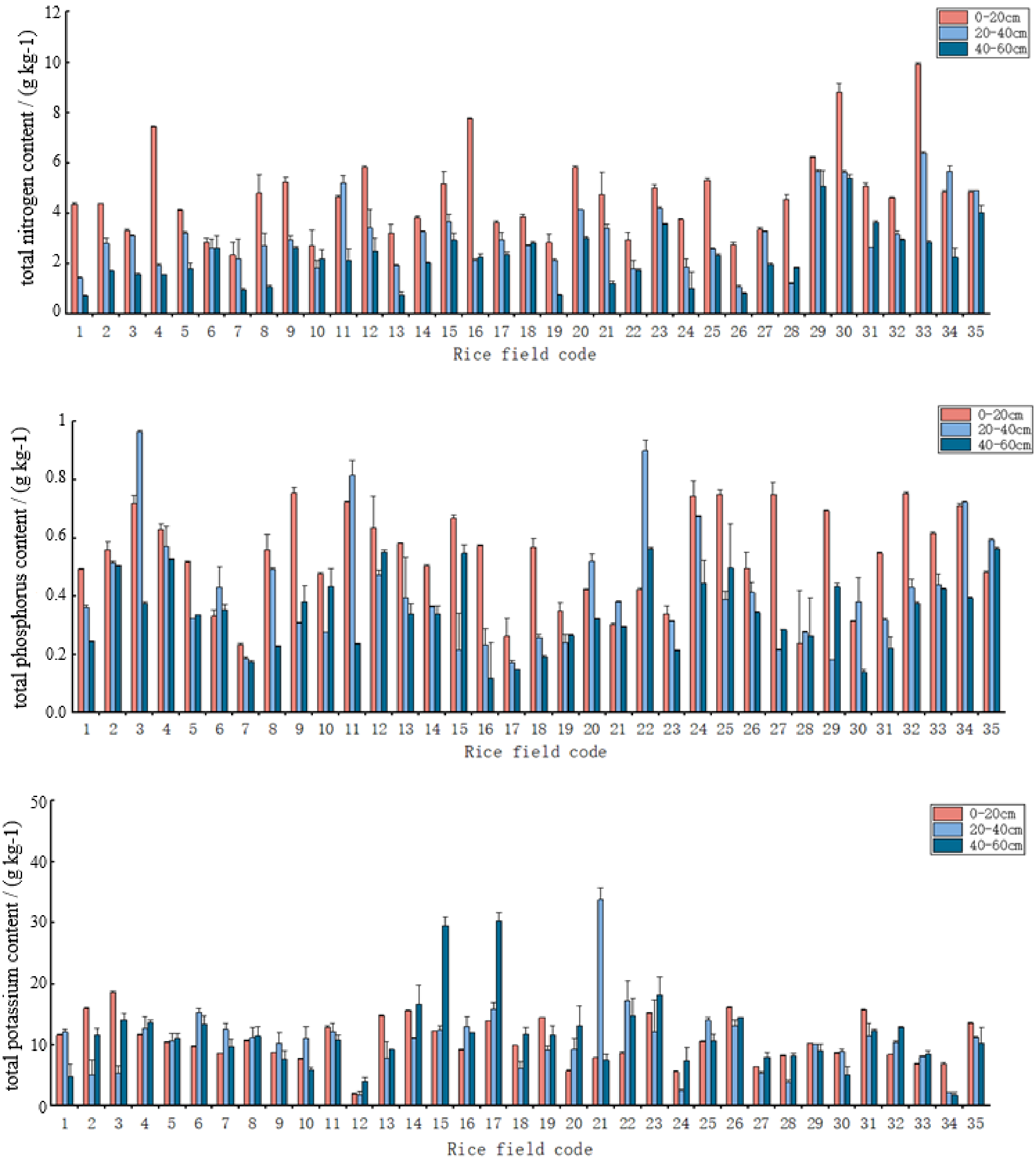

Figure 6. Soil nutrient contents of three soil horizons in different rice fields.

Multiple regression analysis of rice growth indicators and soil quality

It can be seen from the principal component loading matrix in Table 2 that in Principal Component 1, the loading of leaf length was 0.893, which is most closely related to Principal Component 1. In Principal Component 2, the loading of leaf-soluble sugars was 0.936, which was most closely related to that of Principal Component 2. In Principal Component 3, the loading of leaf-soluble proteins was 0.828, which was most closely related to Principal Component 3. Therefore, these three characteristics were selected as the main characteristics reflecting rice growth for multiple regression analysis.

Table 4 presents the relevant statistical results of the regression analysis. As shown in Table 4, the regression equations of the first three principal components fit the relationship between rice growth indicators and soil quality, with relatively high reliability.

Table 4
Regression statistics table

Name	R^2	Errors in standardized estimates	DW value
Leaf length	0.824	2.56860	2.276
Leaf soluble sugar	0.854	0.18172	2.316
Leaf soluble protein	0.534	0.08891	2.659

In Tables 5, 6, and 7, the partial correlation coefficient is used as a statistic to measure the strength and direction of the partial correlation, and the t-test is used to evaluate the reliability of the statistical results. From the regression equation coefficients of various influencing factors in Tables 5, 6, and 7, in the 0 - 20 cm soil layer, leaf length was positively correlated with water content, nitrogen, phosphorus, and potassium; leaf soluble sugar was positively correlated with nitrogen and phosphorus; and leaf soluble protein was positively correlated with water content, organic matter, and potassium. In the 20–40 cm soil layer, leaf length was positively correlated with water content and pH, leaf soluble sugar was positively correlated with water content, pH, and organic matter, and leaf soluble protein was positively correlated with water content, pH, nitrogen, phosphorus, and potassium. In the 40–60 cm soil layer, leaf length was positively correlated with electrical conductivity, organic matter, and potassium; leaf soluble sugar was positively correlated with organic matter, nitrogen, and potassium; and leaf soluble protein was positively correlated with organic matter, nitrogen, and phosphorus.

Table 5
Partial Correlation Coefficients and Significance Tests for Leaf length with stratified soil properties

Name	Leaf length		
	r	t	p
$W_{0\text{-}20}$	0.07	0.69	0.50
$pH_{0\text{-}20}$	-9.30	-2.89	0.01
$EC_{0\text{-}20}$	0.00	-0.11	0.92
$OM_{0\text{-}20}$	-0.90	-1.95	0.07
$TN_{0\text{-}20}$	0.68	1.08	0.30
$TP_{0\text{-}20}$	63.97	1.54	0.15
$TK_{0\text{-}20}$	1.85	1.00	0.33
$W_{20\text{-}40}$	0.17	0.80	0.44
$pH_{20\text{-}40}$	8.12	2.16	0.05
$EC_{20\text{-}40}$	-0.01	-1.04	0.32
$OM^{20\text{-}40}$	-0.27	-0.43	0.68
$TN_{20\text{-}40}$	-0.34	-0.33	0.75
$TP_{20\text{-}40}$	-113.5	-2.93	0.01
$TK_{20\text{-}40}$	-2.31	-1.75	0.10
$W_{40\text{-}60}$	-0.07	-0.37	0.72
$pH_{40\text{-}60}$	-6.62	-2.05	0.06
$EC_{40\text{-}60}$	0.01	1.31	0.21
$OM_{40\text{-}60}$	0.47	0.93	0.37
$TN_{40\text{-}60}$	-0.74	-0.67	0.52
$TP_{40\text{-}60}$	-67.64	-1.24	0.24
$TK_{40\text{-}60}$	0.81	0.63	0.54

r, partial correlation coefficient; t, test value; p, significance level; $W_{0\text{-}20}$, 0-20 cm soil water content; $pH_{0\text{-}20}$, 0-20 cm soil pH; $EC_{0\text{-}20}$, 0-20 cm soil electrical conductivity; $OM_{0\text{-}20}$, 0-20 cm soil organic matter; $TN_{0\text{-}20}$, 0-20 cm soil total nitrogen; $TP_{0\text{-}20}$, 0-20 cm soil total phosphorus; $TK_{0\text{-}20}$, 0–20 cm soil total potassium; 20-40, 40-60 same.

Table 6
Partial Correlation Coefficients and Significance Tests for Leaf soluble sugar with Stratified soil properties

Name	Leaf soluble sugar		
	r	t	p
W_{0-20}	-0.02	-3.39	0.01
pH_{0-20}	-0.65	-2.86	0.01
EC_{0-20}	-0.00	-3.18	0.01
OM_{0-20}	-0.04	-1.25	0.23
TN_{0-20}	0.09	2.05	0.06
TP_{0-20}	6.19	2.10	0.06
TK_{0-20}	-0.25	-1.89	0.08
W_{20-40}	0.07	4.56	0.00
pH_{20-40}	1.03	3.88	0.00
EC_{20-40}	0.00	0.58	0.57
OM^{20-40}	0.00	0.02	0.99
TN_{20-40}	-0.30	-4.12	0.00
TP_{20-40}	-2.07	-0.76	0.46
TK_{20-40}	-0.17	-1.78	0.10
W_{40-60}	-0.05	-3.67	0.00
pH_{40-60}	-0.41	-1.77	0.10
EC_{40-60}	0.00	0.65	0.53
OM_{40-60}	0.12	3.19	0.01
TN_{40-60}	0.04	0.48	0.64
TP_{40-60}	-3.39	-0.88	0.39
TK_{40-60}	0.14	1.47	0.16

r, partial correlation coefficient; t, test value; p, significance level; W_{0-20}, 0-20 cm soil water content; pH_{0-20}, 0-20 cm soil pH; EC_{0-20}, 0-20 cm soil electrical conductivity; OM_{0-20}, 0-20 cm soil organic matter; TN_{0-20}, 0-20 cm soil total nitrogen; TP_{0-20}, 0-20 cm soil total phosphorus; TK_{0-20}, 0–20 cm soil total potassium; 20-40, 40-60 same.

Table 7
Partial Correlation Coefficients and Significance Tests for Leaf soluble protein with Stratified soil properties

Name	Leaf soluble protein		
	r	t	p
$W_{0\text{-}20}$	0.00	0.16	0.88
$pH_{0\text{-}20}$	-0.15	-1.32	0.21
$EC_{0\text{-}20}$	0.00	-0.45	0.66
$OM_{0\text{-}20}$	0.01	0.91	0.38
$TN_{0\text{-}20}$	-0.02	-0.10	0.34
$TP_{0\text{-}20}$	-0.56	-0.39	0.70
$TK_{0\text{-}20}$	0.030	0.45	0.66
$W_{20\text{-}40}$	0.00	0.45	0.66
$pH_{20\text{-}40}$	0.19	1.50	0.16
$EC_{20\text{-}40}$	0.00	0.46	0.65
$OM^{20\text{-}40}$	-0.01	-0.52	0.62
$TN_{20\text{-}40}$	0.01	0.21	0.84
$TP_{20\text{-}40}$	0.75	0.56	0.58
$TK_{20\text{-}40}$	0.02	0.52	0.61
$W_{40\text{-}60}$	-0.00	-0.57	0.58
$pH_{40\text{-}60}$	-0.08	-0.74	0.47
$EC_{40\text{-}60}$	0.00	-0.54	0.60
$OM_{40\text{-}60}$	0.01	0.730	0.48
$TN_{40\text{-}60}$	0.00	0.02	0.98
$TP_{40\text{-}60}$	0.59	0.31	0.76
$TK_{40\text{-}60}$	-0.01	-0.26	0.80

r, partial correlation coefficient; t, test value; p, significance level; $W_{0\text{-}20}$, 0-20 cm soil water content; $pH_{0\text{-}20}$, 0-20 cm soil pH; $EC_{0\text{-}20}$, 0-20 cm soil electrical conductivity; $OM_{0\text{-}20}$, 0-20 cm soil organic matter; $TN_{0\text{-}20}$, 0-20 cm soil total nitrogen; $TP_{0\text{-}20}$, 0-20 cm soil total phosphorus; $TK_{0\text{-}20}$, 0–20 cm soil total potassium; 20-40, 40-60 same.

Discussion

As an important food crop worldwide, rice growth is closely related to the physicochemical properties of the soil (Wu et al., 2017). The supply of soil nutrients directly affects rice growth and development. Elements such as nitrogen, phosphorus, and K have significant effects on rice growth (Zhang et al., 2024). Rice plants mainly absorb nutrients from the soil via their roots. Therefore, the soil quality of paddy fields is of great significance for the absorption and utilization of nutrients by rice (Li et al., 2017). In this study, there were obvious differences in the morphological and physiological indicators of rice in the different fields. The plant height and leaf length values of Paddy Field No. 14 were the largest, which may be related to the relatively high soil nitrogen content in the 0–20 cm soil layer, whereas the stem of rice in Paddy Field No. 30 was the thickest, which may be related to the relatively rich soil water content and nitrogen content in the 40–60 cm soil layer. Among the physiological indicators, the soluble sugar content in the leaves of Paddy Field No. 24 was the highest, and the soil phosphorus content in the 20–40 cm soil layer was significantly higher than that in the other fields, indicating that excessive phosphorus may interfere with sugar metabolism. In this study, the first three principal components were extracted through principal component analysis, with a cumulative contribution rate of 75.974%, reflecting the main information on the rice growth indicators. Leaf length contributed the most significantly to Principal Component 1, which is consistent with previous studies on the mechanism of photosynthetic area expansion and material accumulation in rice. Nutrients affect the light-use efficiency of rice crops (Xue et al., 2016). In this study, the strong correlation between leaf length and nitrogen and phosphorus in the 0 - 20 cm soil layer further verified this view. In addition, in Paddy Fields No. 14, 18, and 26, with the highest comprehensive scores, the nitrogen and organic matter contents in the 0–20 cm soil layer were significantly higher than those in other fields, indicating that the enrichment of surface nutrients is key to the formation of the aboveground biomass of rice (King et al., 2020).

Multiple regression analysis identified the key driving factors affecting rice growth indicators. The regression model showed that the regression coefficients of leaf length with nitrogen and phosphorus in the 0–20 cm soil layer were the highest, reinforcing the view that nitrogen and phosphorus are key drivers of leaf growth (Haefele et al., 2008). For stem diameter, the significant effect of soil nitrogen and water content in the 40 - 60 cm soil layer indicated that deep soil layers also play a regulatory role in stem development. In addition, the positive correlation between soil pH in the 20–40 cm soil layer and soluble sugar content suggests that a more alkaline environment may promote sugar accumulation (Ruan et al., 2018); however, further field verification is required.

This study builds on recent research by domestic and international scholars while also incorporating the practical conditions of our sampling and experimentation in the selection of indicators for soil quality evaluation and rice quality analysis. However, the coverage of the indicator system may be constrained, lacking: (1) tracking of dynamic changes during rice growth stages and (2) determination of physiological metabolic intermediate products, such as hormone levels and antioxidants. Regarding soil research, the investigation was restricted to soil types within the study area without extending to other soil conditions, potentially limiting the applicability of the conclusions. Consequently, these shortcomings may have influenced the depth and breadth of the research findings, underscoring the need for further studies across diverse soil types and regions.

Conclusion

In this study, a layered soil model was constructed as a new framework for precision fertilization management, and the results show that vertical directional fertilization can effectively improve quality and stress resistance in the Panjin rice. Through actual testing and verification of 35 fields, it was confirmed that the model had significant effects on growth heterogeneity, with Field 14 being established as the benchmark field for ideal nutrient coordination. We propose a paradigm shift from unified fertilization to soil-depth zoning fertilization: surface nitrogen and phosphorus synergistically enhance photosynthetic capacity; medium pH and water balance promote metabolic balance; and deep slow-release nitrogen fertilizer integrates and strengthens structural support. In addition, cross-layer K redistribution is a key regulatory factor for nutrient synergy. These conclusions redefine the sustainable cultivation model of rice in coastal saline alkali areas and provide a scalable solution for optimizing the soil–plant continuum under vertical nutrient heterogeneity.

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