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Enhancing Cropping System Productivity and Soil Properties Through Cotton/Peanut Intercropping With Optimized Row Configurations

Menghua Zhai^{1,2,3} | Xuewen Wei⁴  | Pengcheng Li^{2,3} | Jian Wang^{2,3} | Qinqing Xu⁴ | Guilan Sun^{2,3} | Zhanlei Pan^{2,3}  | Dulin Qin⁴ | Jie Zhang⁴ | Junhong Li^{2,3} | Yaopeng Zhang^{2,3} | Lizhi Wang^{2,3} | Kunfeng Wang^{2,3} | Xueyan Duan⁵ | Wenqi Zhao^{2,3} | Xin Li^{2,3} | Zhenggui Zhang^{1,2,3}  | Zhanbiao Wang^{1,2,3}

¹Zhengzhou Research Base, State Key Laboratory of Cotton Bio-Breeding and Integrated Utilization, School of Agricultural Sciences, Zhengzhou University, Zhengzhou, Henan, China | ²Xinjiang Key Laboratory for Crop Gene Editing and Germplasm Innovation, Institute of Western Agricultural of CAAS, Changji, Xinjiang, China | ³State Key Laboratory of Cotton Bio-Breeding and Integrated Utilization, Institute of Cotton Research of the Chinese Academy of Agricultural Sciences, Anyang, Henan, China | ⁴Shandong Agricultural Technology Extension Center, Jinan, China | ⁵Jinan Qinghe Experimental School, Jinan, China

Correspondence: Zhenggui Zhang (jxzhangzhenggui@163.com) | Zhanbiao Wang (wang_zhanbiao@126.com)

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ABSTRACT

Diversified cropping systems (e.g., intercropping) can enhance soil health and crop productivity via the integrate utilization of resources, and thus have been recognized as a core strategy for advancing sustainable agriculture and safeguarding long-term security. However, varying row configurations in intercropping systems can directly alter soil properties and crop productivity, and existing research findings remain inconsistent due to differences in experimental sites and agronomic management practices. To address this, a split-plot field experiment was conducted at two sites (Pingdu and Changyi in Shandong, China) to evaluate row configuration effects on soil properties and crop productivity. Treatments included cotton (*Gossypium hirsutum* L.) monocropping (MC), peanut (*Arachis hypogaea* L.) monocropping (MP), and three intercropping configurations, namely C2P4 (2 rows of cotton intercropped with 4 rows of peanuts), C4P4 (4 rows of cotton intercropped with 4 rows of peanuts), and C4P6 (4 rows of cotton intercropped with 6 rows of peanuts). The results revealed that, on average, compared with monocropping, cotton-peanut intercropping systems demonstrated comprehensive improvements, reducing soil bulk density by 4.2%–15.5%, increasing soil organic matter (5.2%–15.5%), available nitrogen (4.4%–14.1%), and phosphorus (4.7%–12.0%), while enhancing microbial abundance (bacteria: 14.5%–17.4%; fungi: 27.0%–35.7%; actinomycetes: 24.7%–27.3%). Pearson's correlation analysis showed that humus fractions, microbial abundance, and soil nutrient availability are all key determinants of crop yield. These benefits increased progressively with the peanut-to-cotton row ratio. Specifically, the C4P6 configuration (4 rows of cotton intercropped with 6 rows of peanuts) delivered peak performance: cotton and peanut yields reached 4741.65 kg·ha⁻¹ and 5484.75 kg·ha⁻¹, respectively, while the soil quality index (SQI) hit a maximum of 1335—an increase of 82.4% compared with monocropping systems. In conclusion, cotton-peanut intercropping enhances crop productivity through optimized root-soil interactions that improve soil structure, nutrient availability, and microbial functionality, with the C4P6 configuration exhibiting superior performance by synchronizing interspecific facilitation. This study provides a practical measure for sustainable agricultural intensification in the Yellow River Basin of China and semiarid regions with analogous soil constraints.

Menghua Zhai and Xuewen Wei contributed equally to the present work.

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1 | Introduction

Modern intensive agriculture often relies on monoculture and yield-oriented practices, which can be economically attractive in terms of high yields. However, a great deal of historical experience has shown that the extensive use of chemical fertilizers, pesticides, and over-tillage of soils in order to increase yields inevitably leads to ecological damages, such as ecological imbalances and degradation of natural resources (Ferreira et al. 2022; Li et al. 2020). Crop diversification, as a new crop production paradigm, can reduce damage to the ecosystem by enhancing biodiversity and achieve multiple-dimensional goals such as reducing pests and diseases, improving soil quality, enhancing resource utilization efficiency, and increasing crop yields (Bai et al. 2024; Qiao et al. 2024; Miao et al. 2023; Renard and Tilman 2019; Wagg et al. 2014).

Intercropping is a time-honored traditional farming method, also known as mixed cropping or multi-cropping, which is a typical way of diversifying crops (Li et al. 2023; Martin-Guay et al. 2018). On a smaller land area, intercropping can yield the same amount of produce as monocropping (Li et al. 2020). Moreover, it can enhance biodiversity, improve the microenvironment of farmland, and promote soil quality. Therefore, the intercropping system is one of the important ways to ensure the sustainable development of agriculture and safeguard food security (Maitra et al. 2021). In intercropping systems, the increases in soil C (Ferreira et al. 2022) and N (Zhang et al. 2024) levels as well as soil aggregates contribute to the enhancement of soil fertility, which subsequently leads to an increase in soil biodiversity. Physical root contact leads to an augmentation in the proportion of macroaggregates and microaggregates within intercropping systems (Duan et al. 2026; Peng et al. 2023; Zan et al. 2023), and microbial abundance prefer to inhabit these protected places in aggregates (Chen et al. 2025; Liao et al. 2024). It is self-evident that the elevated microbial diversity and metabolite chemical diversity within the soils of intercropping systems are capable of further influencing the uptake of nutrients by crops (Zhang et al. 2023). In terms of crop production, intercropping has a great potential to make better use of resources such as light, water, and nutrients, thereby increasing crop yields (Qiu et al. 2023; Yin et al. 2020; Zhou et al. 2021). Li et al. (2021) made the discovery in a multiyear experimental study that the grain yields within intercropping systems exhibited a 22% increment in comparison to those of monocropping, accompanied by an enhanced stability over successive years.

China, as the world's largest cotton producer, concentrates its cultivation in three primary regions: the Yellow River Basin, the Yangtze River Basin, and the Northwest Inland (Liang et al. 2025). However, the Yellow River Basin—a traditional cotton-growing heartland—has experienced a severe contraction. Since the early 21st century, its cotton planting area has sharply declined from over 2 million hectares to less than 1 million hectares, with total production falling from over 2 million tons to approximately 1 million tons (Wang et al. 2021). This pronounced downturn stems mainly from two interrelated factors: first, the low level of mechanization and high labor

demands in local cotton farming have undercut its economic returns (Qiao 2023); second, a national policy emphasis on food security has incentivized farmers to shift toward grain crops. Together, these drivers have led to a substantial reduction in cotton cultivation across the Basin. In addition, due to the rapid land transfer in China, land ownership often changes within 2–3 crop growth cycles. This rapid turnover has resulted in problems such as declining farmland productivity and soil degradation, posing challenges to the sustainable development of agriculture. While long-term field trials hold scientific merit, they often misalign with China's rapid land-transfer reality. More pragmatic solutions must therefore deliver short-term, observable benefits. Based on the above background, incorporating cotton into the intercropping system in the Yellow River Basin is a feasible solution. Such systems can not only effectively conserve land resources and improve land use efficiency, but also enhance soil quality by boosting regional biodiversity. Notably, cotton intercropping can play a key role in stabilizing the cotton planting area in this region. Therefore, cotton intercropping systems achieve a tripartite win-win outcome that balances food security, ecological improvement, and sustainable cotton production.

In the investigation of diverse cotton-based intercropping systems (a cropping system where cotton is interplanted with one or more other crops), it was found that cotton-based intercropping exhibited superiority over cotton monocropping, among which the cotton-peanut intercropping system demonstrated the most pronounced enhancement (Qiu et al. 2023). On the one hand, because of the time difference in plant growth and the complementary characteristics in height, it can use space well, make better use of light and heat resources, and help both crops grow better (Bedoussac and Justes 2010; Engbersen et al. 2022). Also, it is better for field management. This can make agricultural production more efficient and lower labor costs (Muke et al. 2025). On the other hand, as a leguminous plant, peanuts have rhizobia in their roots that can fix nitrogen in the air and increase the nitrogen content in the soil (Sannagoudar et al. 2024), thereby reducing cotton's dependence on nitrogen fertilizers, achieving an organic combination of using the land and improving the land, and providing strong support for the sustainable development of agriculture (Chi and Dong 2024).

Taking into account all the factors mentioned above, the cotton-peanut intercropping regime is put forward as a prospective approach to resolving the existing conundrum of the diminishing cotton-planting area in the Yellow River Basin. It is essential to conduct a comprehensive and in-depth study on soil quality and cotton productivity based on different cotton-peanut intercropping patterns. The particular goals were to (i) specify the impact of different cropping patterns on the above-ground productivity (yield and biomass) of cotton and peanuts; (ii) explore the influence of different cropping patterns on soil quality from multiple physical, chemical, and biological dimensions; and (iii) provide a comprehensive evaluation of the impact of cropping patterns on crop yields and soil quality. Based on the above research objectives, the following hypotheses were formulated: Intercropping patterns can improve soil quality by changing the physical, chemical, and biological properties of the soil, thus having a positive impact on productivity.

2 | Materials and Methods

2.1 | Site Description

The experiment was conducted simultaneously in 2021 in Pingdu (119.7°E, 36.7°N) and Changyi, Shandong Province (119.4°E, 37.0°N). The area experiences a warm temperate monsoon climate with ample solar and thermal resources. The average annual temperatures in Pingdu and Changyi were 13.80°C and 14.36°C, and the rainfall was 80.62 and 81.74 mm, respectively. The soil fertility at a depth of 0–20 cm before cotton planting at each experimental site is shown in Table 1. Weather data were obtained from an automatic meteorological station at the experimental site during the whole growing season (Figure 1). The selected experimental fields had uniform soil fertility levels, flat terrain, convenient irrigation and drainage, medium to high soil fertility, and no adverse environmental impacts around.

2.2 | Experimental Design and Field Management

A cotton-peanut intercropping planting system was adopted. Luhua8 was chosen as the peanut cultivar, and Lu6269 was chosen as the cotton cultivar in this experiment. Three different row configurations were set: 2 rows of cotton intercropped with 4 rows of peanuts (C2P4), 4 rows of cotton intercropped with 4 rows of peanuts (C4P4), and 4 rows of cotton intercropped with 6 rows of peanuts (C4P6). Cotton monocropping (MC) and peanuts monocropping (MP) were used as the control treatments. MC: Cotton was planted on flat land at a density of 6.75×10^4 plants·ha⁻¹. The row spacing was 76 cm, and the plant spacing

was 20 cm. MP: Peanuts were planted on ridges. The width of each ridge was 80 cm, with two rows on each ridge. The row spacing within the ridges was 30 cm, and the planting density was 3×10^5 plants·ha⁻¹. Two seeds were sown in each hole. In the intercropping system, cotton and peanut were spaced 50 cm apart, and the row spacing, plant spacing, and planting density of the different crops in both monocropping and intercropping were consistent. The experiment was replicated thrice, 24 plots in total. Upon the emergence of the second true leaf of cotton plants, thinning was performed to meet the set density. Field management, such as fertilization, irrigation, and pest control, adhered to local high-yield standards for treatment consistency. Only topping was applied, with no other pruning involved.

2.3 | Plant Sampling and Measurement

During the bud, flowering, blooming, and boll opening stages of the cotton growing season, plant samples were collected from all plots in Pingdu and Changyi. Specifically, three visually uniform plants were randomly selected from each plot and separated into leaves, stems, and reproductive organs. Cut into pieces, placed into separate paper bags, and heated in an electric oven at 105°C for 30 min for enzyme inactivation. Subsequently, the temperature was adjusted to a constant 80°C until the drying time when the weight did not change any more; then the cotton plants were weighed, and the dry weight of each part was recorded, and the percentage of each part was calculated.

Ten consecutive cotton plants were selected for marking at each plot location, and the number of bolls was surveyed on July 15,

TABLE 1 | Initial soil fertility in Pingdu and Changyi in 2021.

Country	pH	Organic matter	Alkali-hydrolyzed nitrogen	Available phosphorus	Available potassium
		(%)	(mg·kg ⁻¹)	(mg·kg ⁻¹)	(mg·kg ⁻¹)
Pingdu	7.13	0.945	50.56	22.78	90.23
Changyi	7.56	0.753	47.56	18.34	75.65

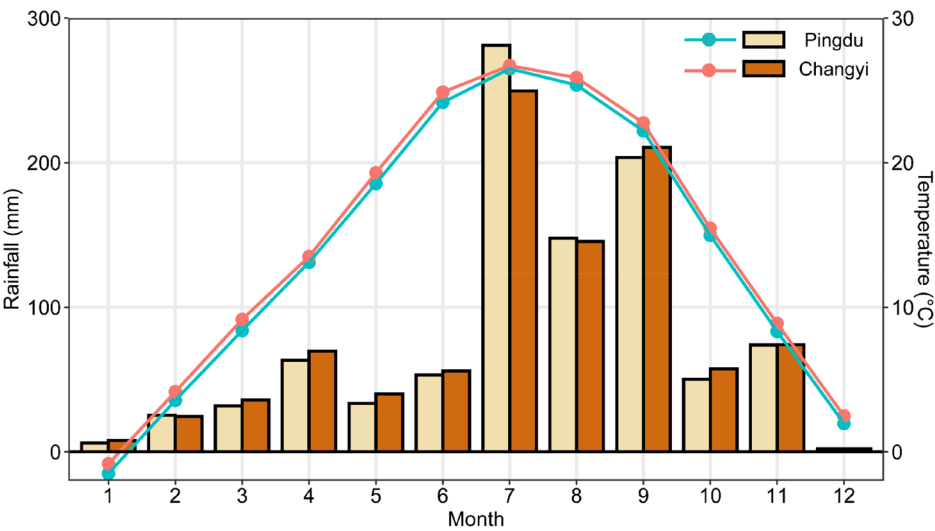


FIGURE 1 | Weather conditions at the Pingdu and Changyi test sites in 2021.

August 15, and September 5, respectively. The number of pre-summer bolls, summer bolls, and autumn bolls were calculated. In Pingdu and Changyi, cotton and peanuts are harvested by hand in each plot. Peanut pods were harvested by digging or shoveling up underground peanut clods after yellowing and then dried in the open. Peanut pods were dried and weighed to determine the weight of pods harvested from each plot. Cotton was harvested at 7-day intervals from the start of boll fluffing, and the multiple harvests from each plot were combined to obtain the harvested cotton yield for each plot.

2.4 | Soil Sampling and Determination

Soil samples were collected after cotton and peanut harvests in Pindu and Changyi counties in 2019. Soil samples from each plot were collected at depths of 0–20 cm and 20–40 cm and were composite samples of three samples collected from three points (avoiding plot boundaries) under each crop in each plot. Then, the soil samples were passed through a 2-mm mesh screen to separate weed straw and pebbles, and each soil sample was divided into two parts. The first part was stored at -80°C in an ultralow-temperature freezer for biochemical analysis, and the other part was kept in the laboratory and air-dried to constant weight for the determination of basic chemical properties. Soil aggregates were determined with the wet sieving method (Márquez et al. 2004). Determination of bulk density (BD) was by the ring knife method.

Direct measurement of the pH value of the soil solution using a pH meter. The soil organic matter (SOM) content was measured by the Potassium Dichromate Oxidation method; the soil available nitrogen (SAN) content was converted to NH_4^+ under alkaline conditions, collected in H_3BO_3 solution, and then determined by titration with standard $0.01\text{ mol}\cdot\text{L}^{-1}$ H_2SO_4 ; the soil available phosphorus (SAP) content was determined spectrophotometrically using the Molybdenum Blue Colorimetric method; and the soil available potassium (SAK) content was measured using the Flame Photometry method (Bao 2000).

Fulvic acid (FA) and humic acid (HA) were extracted from soil by a combination of alkaline extraction and acid precipitation (Hayes et al. 2017; Kopecky et al. 2016). The quantity of soil microorganisms was determined by the plate colony counting method on culture media (Huber et al. 2024). Specifically, beef extract-peptone medium was used for bacteria, Martin's medium was chosen for fungi, and Gao's No. 1 medium was selected for actinomycetes. Soil urease (URE) activity was measured by the sodium phenoxide colorimetric method, alkaline phosphatase (ALP) activity by the phenyl disodium phosphate colorimetric method, and catalase (CAT) activity by the potassium permanganate titration method (Margenot et al. 2018).

2.5 | Soil Quality Comprehensive Evaluation

The minimum data set (MDS) was used for the quantitative evaluation of soil quality, as the raw data of multiple soil quality

indicators (physical, chemical, and biological) often vary in dimensions and orders of magnitude.

$$z_{ij} = \frac{x_{ij} - x_j}{s_j} \quad (1)$$

In this context, Z_{ij} represents the standardized value of the j -th variable of the i -th sample, the x_{ij} is the variable's actual value for a specific treatment, x_j is the variable's mean, and S_j is its standard deviation.

Two standardized principal components were extracted, explaining sufficient information from the raw data. For each soil treatment sample, scores on these components were calculated using standardized data and the extracted eigenvectors.

$$y_{ik} = \sum_{j=1}^p z_{ij} v_{jk} \quad (2)$$

In this context, y_{ik} denotes the score of the i -th sample on the k th principal component, z_{ij} is the value of the j -th variable of the i -th sample after normalization, and v_{jk} is the j -th element of the eigenvector corresponding to the k th principal component. p stands for the total number of the original variables.

Finally, information from multiple principal components was integrated, with weights determined by their variance contribution ratios. These weighted components were summed to calculate a composite score, serving as the soil quality index to reflect the comprehensive soil quality of each sample.

$$w_k = \frac{\lambda_k}{\sum_{k=1}^2 \lambda_k} \quad (3)$$

w_k represents the variance contribution ratio of the k -th principal component, λ_k represents the eigenvalue of the k th principal component.

$$SQI_i = \sum_{k=1}^2 w_k y_{ik} \quad (4)$$

SQI_i denotes the soil quality index of the i -th sample (Reeves 1997), w_k represents the variance contribution ratio of the k th principal component, λ_k represents the eigenvalue of the k th principal component.

2.6 | Statistical Analyses

The data was initially processed using Microsoft Excel 2019 and subsequently underwent statistical analysis employing IBM SPSS 26 software. The differences in the means of various indicators were analyzed using the least significant difference (LSD) method. p values ≤ 0.05 and ≤ 0.01 were, respectively, regarded as indicating significant and highly significant differences, while $p > 0.05$ was deemed nonsignificant. All the figures in this study were generated using Microsoft PowerPoint 2019, R 4.1.0, and Origin 2022. Additionally, the relationships among the cotton yield, peanut yield, SQI, and soil properties were explored using the Mantel test and the “linkET” package in R software.

3.1 | Different Cropping System Productivity

3.1.1 | Yield of Cotton and Peanut Under Different Cropping Patterns

In Pingdu, cotton yields under intercropping system demonstrated a 1.43%–4.58% increase compared with MC, with the C4P6 treatment achieving the highest yield of 4741.65 kg·ha⁻¹ (Table 2). Similarly, peanut yields in Pingdu increased by 1.76%–3.71% under intercropping, peaking at 5484.75 kg·ha⁻¹ in the C4P6 treatment. In contrast, Changyi exhibited lower yields for both crops: cotton and peanut yields across all planting patterns were 5.52%–5.75% and 7.70%–8.11% lower, respectively, than those in Pingdu. Despite this regional disparity, yield trends between the two regions remained consistent, with intercropping systems outperforming monocropping. Notably, the C4P6 showed superior performance in both crops, with cotton and peanut yields reaching 4518.6 kg·ha⁻¹ and 4881.3 kg·ha⁻¹, respectively. These values represented 5.50% and

3.03% increases compared with MP, significantly more than other cropping patterns within the same region.

3.1.2 | Temporal Distribution of Cotton Bolls Under Different Cropping Patterns

Compared with MC, the cotton-peanut intercropping system significantly increased the proportions of pre-summer and summer bolls in both regions (Table 3). In Pingdu, the proportions of pre-summer and summer bolls increased by 24.38%–38.48% and 5.84%–19.95%, respectively. In contrast, Changyi exhibited smaller increases for pre-summer bolls (1.76%–15.66%) but larger gains for summer bolls (9.17%–24.29%). However, the proportion of autumn bolls in Changyi decreased significantly by 21.11%–39.97% under intercropping. Temporal analysis further revealed that in Pingdu, the number of cotton bolls across all treatments consistently followed the order of pre-summer bolls > summer bolls > autumn bolls, with the C4P6 treatment yielding the highest pre-summer boll count (6.7 bolls per plant). In

TABLE 2 | Cotton and peanut yield in Pingdu and Changyi under different cropping patterns.

Country	Treatment	Seed cotton yield (kg·ha ⁻¹)	Peanut pod yield (kg·ha ⁻¹)
Pingdu	MC	4533.75 ± 277.62 ^a	0
	MP	0	5288.7 ± 242.48 ^a
	C2P4	4672.2 ± 231.92 ^a	5437.65 ± 270.12 ^a
	C4P4	4598.7 ± 225.94 ^a	5381.55 ± 269.07 ^a
	C4P6	4741.65 ± 232.08 ^a	5484.75 ± 270.32 ^a
Changyi	MC	4283.4 ± 214.17 ^d	0
	MP	0	4881.3 ± 242.17 ^d
	C2P4	4403.7 ± 223.24 ^b	4928.4 ± 245.42 ^c
	C4P4	4341.75 ± 220.08 ^c	4944.75 ± 245.32 ^b
	C4P6	4518.6 ± 252.55 ^a	5031.15 ± 252.55 ^a

Note: MC and MP denote cotton monocropping and peanut monocropping. C2P4, C4P4, and C4P6 represent 2 rows of cotton intercropped with 4 rows of peanuts, 4 rows of cotton intercropped with 4 rows of peanuts, and 4 rows of cotton intercropped with 6 rows of peanuts, respectively. In the same column, different letters indicate significant differences at the 5% level.

TABLE 3 | Bolling time of cotton under different cropping patterns.

Treatment		Pre-summer bolls		Summer bolls		Autumn bolls	
		Number	Ratio%	Number	Ratio%	Number	Ratio%
Pingdu	MC	2.7	27.83	2.7	27.84	4.3	44.33
	C2P4	5.9	52.21	5.4	47.79	0	0
	C4P4	6.3	66.31	3.2	33.68	0	0
	C4P6	6.7	55.83	5.3	44.17	0	0
Changyi	MC	4.1	34.75	2.4	20.34	5.3	44.92
	C2P4	4.6	36.51	5	39.69	3	23.81
	C4P4	5.8	47.54	3.6	29.51	2.8	22.95
	C4P6	6.1	50.41	5.4	44.63	0.6	4.95

Note: MC and MP denote cotton monocropping and peanut monocropping. C2P4, C4P4, and C4P6 represent 2 rows of cotton intercropped with 4 rows of peanuts, 4 rows of cotton intercropped with 4 rows of peanuts, and 4 rows of cotton intercropped with 6 rows of peanuts, respectively.

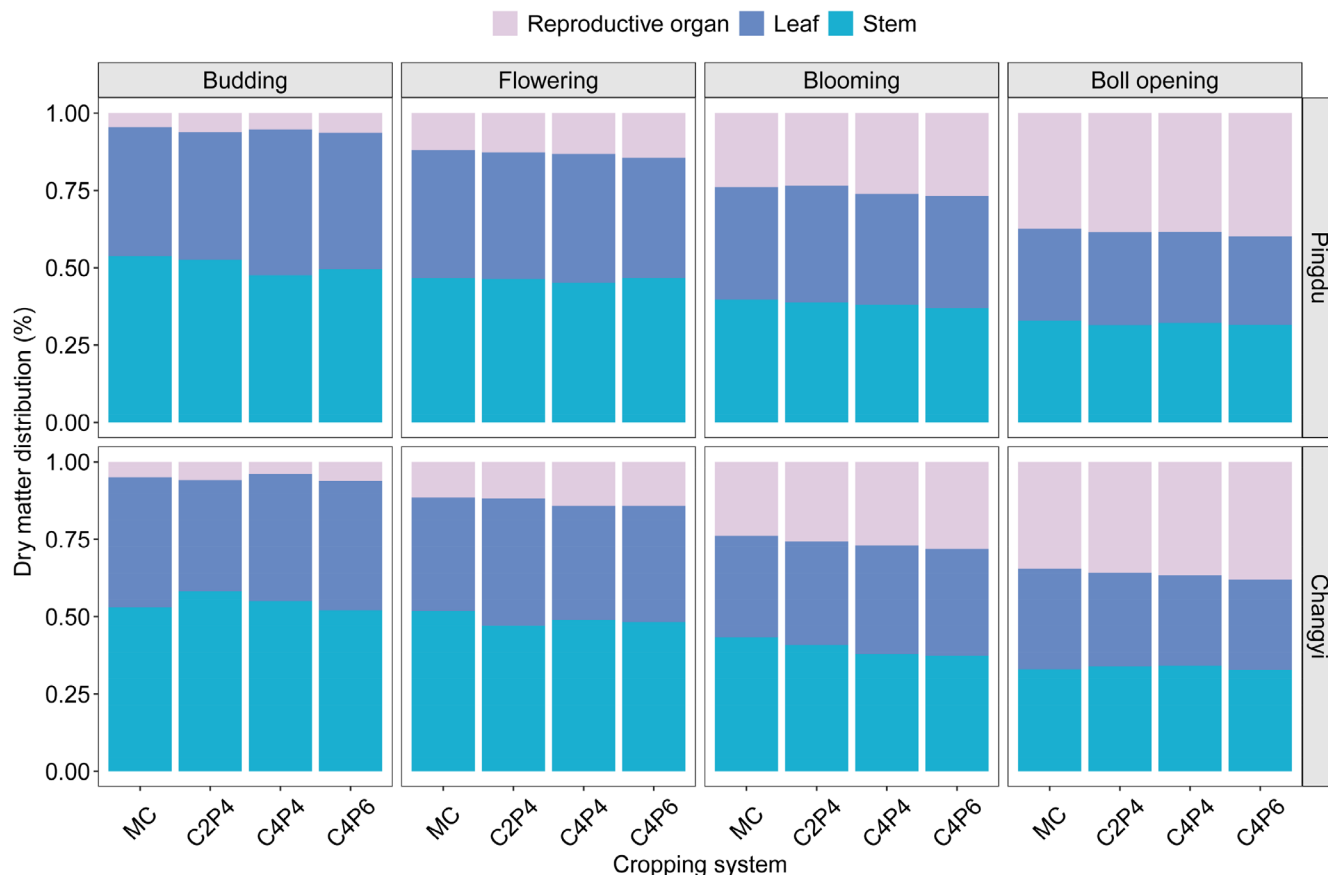


FIGURE 2 | Effects of different cropping patterns on biomass allocation in cotton plants. MC, C2P4, C4P4, and C4P6 denote cotton monocropping, 2 rows of cotton intercropped with 4 rows of peanuts, 4 rows of cotton intercropped with 4 rows of peanuts, and 4 rows of cotton intercropped with 6 rows of peanuts, respectively.

Changyi, MC produced the highest proportion of autumn bolls, whereas the intercropping system showed seasonal advantages—C2P4 dominated in summer boll proportion, while C4P4 and C4P6 excelled in pre-summer boll production.

3.1.3 | Biomass Accumulation and Distribution of Different Cotton Cropping Patterns

During the bud and flowering stages, cotton biomass was predominantly composed of stems and leaves (accounting for over 75% of total biomass) (Figure 2). As the growth period progressed, the proportion of reproductive organs gradually increased, while the proportions of stems and leaves decreased. By the boll-opening stage, reproductive organs exceeded 30% of total biomass across all treatments. Notably, the intercropping system exhibited a significantly higher proportion of reproductive organs compared with Mono. For instance, under the C4P6 treatment, the proportion of reproductive organs increased by 7.01% in Pingdu and 10.23% in Changyi relative to Mono. Among all intercropping patterns, C4P6 achieved the highest proportion of reproductive organs, reaching 39.94% in Pingdu and 38.05% in Changyi.

3.2 | Soil Physical Properties

Soil aggregates were predominantly distributed in the <0.5mm fraction, constituting over 50% of total aggregates,

while the >1 mm and 0.5–1 mm fraction collectively accounted for less than 50% (Figure 3). The distribution exhibited significant spatial heterogeneity: macroaggregates (>1 mm) were more abundant in the 0–20 cm layer than in the 20–40 cm layer. Specifically, as soil depth increased from 0–20 cm to 20–40 cm, the >1 mm fraction decreased by 7.64% in Pingdu and 7.91% in Changyi, whereas the <0.5 mm fraction increased by 3.21% and 4.30%, respectively. From Mono to C4P6 intercropping, soil aggregate structure shifted toward fewer coarse aggregates and more fine aggregates. For instance, in Pingdu's 0–20 cm layer, the >1 mm fraction declined from 18.46% (Mono) to 13.05% (C4P6), while the <0.5 mm fraction rose from 64.53% to 73.85%. Notably, Pingdu consistently exhibited higher proportions of <0.5 mm fine aggregates than Changyi, with differences of 10.35% (0–20 cm) and 9.33% (20–40 cm) between the regions. In addition, as the cropping pattern progressed from Mono to C4P6, the soil bulk density of each treatment gradually decreased, with C4P6 having the lowest value among all treatments (Figure 3).

3.3 | Soil Chemical Properties

Intercropping system significantly enhanced SOM content in both study areas (Figure 4). In Pingdu, SOM increased by 4.31%–10.76% in the 0–20 cm layer and 7.45%–20.99% in the 20–40 cm layer under intercropping system. Similarly, in Changyi, the C4P6 treatment elevated SOM to 0.913%

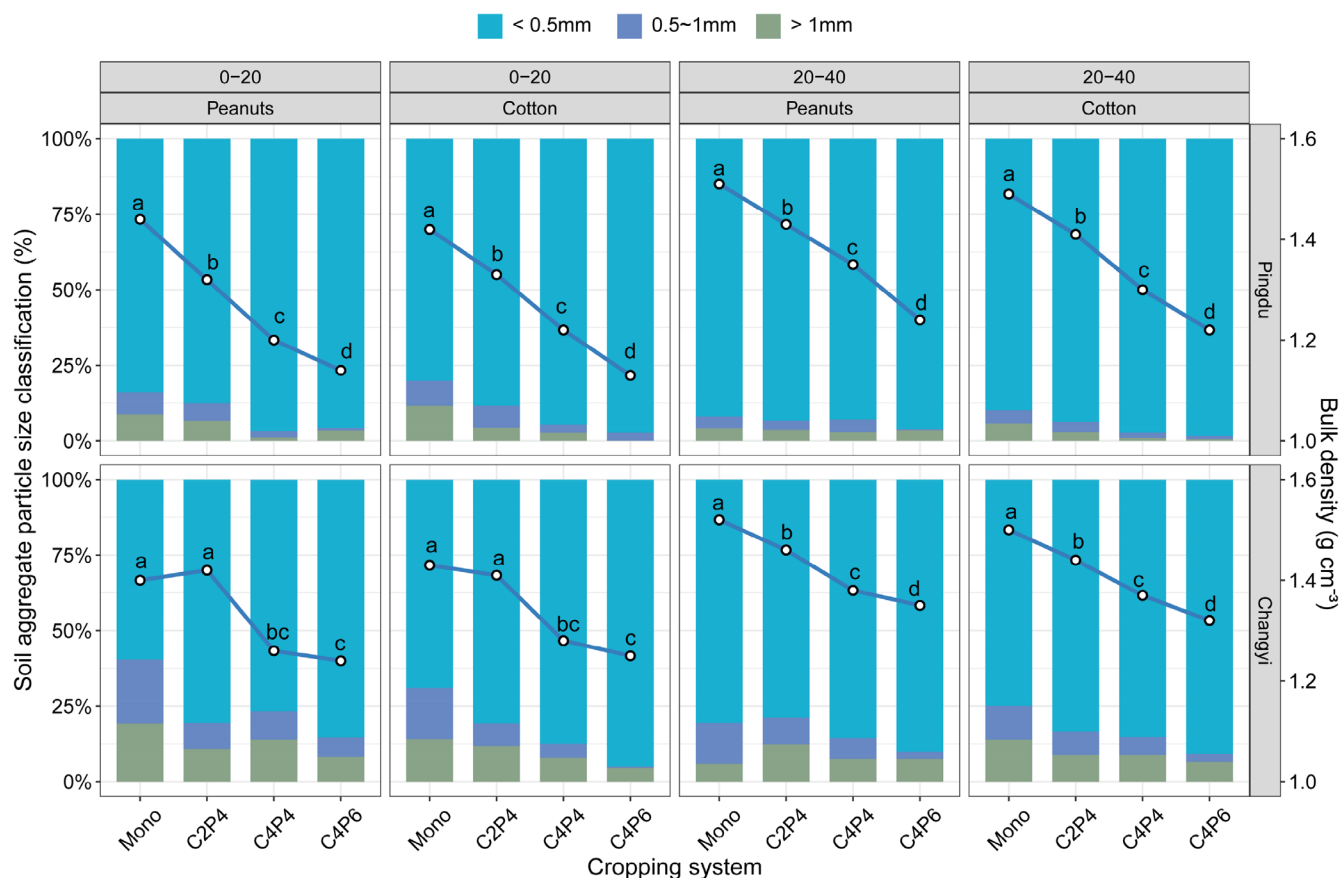


FIGURE 3 | Effects of different cropping patterns on soil aggregates and bulk density at different soil depths. Mono, C2P4, C4P4, and C4P6 denote monocropping, 2 rows of cotton intercropped with 4 rows of peanuts, 4 rows of cotton intercropped with 4 rows of peanuts, and 4 rows of cotton intercropped with 6 rows of peanuts, respectively; 0–20 and 20–40 refer to soil depths of 0–20 cm and 20–40 cm, respectively; particle size fractions <0.5, 0.5–1, and >1 represent soil aggregates with diameters of <0.5 mm, 0.5–1 mm, and >1 mm, respectively. Different letters indicate significant differences at the 5% level.

(peanut rows) and 0.903% (cotton rows). Soil pH in Changyi was 5.89%–8.65% lower than in Pingdu ($p < 0.05$) but showed minimal variation across cropping patterns and soil layers. Compared with Mono, intercropping system significantly increased SAN content. In Pingdu, SAN in the 0–20 cm layer under C4P6 increased by 12.39% (peanut rows) and 15.80% (cotton rows) compared with Mono. A similar trend was observed in the 20–40 cm layer, with SAN in cotton rows reaching its maximum ($46.85 \text{ mg} \cdot \text{kg}^{-1}$) under the C4P6 treatment, representing a 15.76% increase compared with Mono. Intercropping system also significantly enhanced SAP content. In Pingdu, SAP levels increased by 5.40%–13.39% (cotton rows) and 4.21%–11.40% (peanut rows) compared with Mono, with C4P6 achieving the highest values of $20.15 \text{ mg} \cdot \text{kg}^{-1}$ (cotton rows) and $20.13 \text{ mg} \cdot \text{kg}^{-1}$ (peanut rows). However, SAP levels in the 20–40 cm layer decreased by 76.27% (Pingdu) and 77.64% (Changyi) compared with the 0–20 cm layer. Similarly, intercropping significantly improved SAK content. Under the C4P6, SAK in the 0–20 cm layer increased by an average of 7.34% (Pingdu) and 6.35% (Changyi) compared with Mono. In contrast, SAK levels in the 20–40 cm layer showed modest increases of 2.20% (Pingdu) and 2.58% (Changyi) relative to the surface soil. Notably, substantial inter-layer differences in SAK were observed, with the 20–40 cm layer displaying

reductions of 48.06% (Pingdu) and 48.10% (Changyi) compared with the 0–20 cm layer.

3.4 | Soil Biological Properties

3.4.1 | Soil Humus

As illustrated in Figure 5, humic substance distribution varied with soil depth and cropping systems. In Pingdu, humic acid and fulvic acid content decreased by 19.54% and 50.47%, respectively, from the 0–20 cm to 20–40 cm layer, while humic content increased significantly by 48.54%. In contrast, Changyi exhibited a distinct pattern: humic acid and fulvic acid decreased by 10.71% and 5.73%, respectively, with increasing depth, and humic content declined by 12.71%. Compared with Mono, the intercropping system progressively enhanced humic substance content, with the C4P6 treatment achieving the highest values. For example, in the 0–20 cm soil layer of Pingdu under C4P6, humic acid, fulvic acid, and humic content in peanut rows reached $0.88 \text{ g} \cdot \text{kg}^{-1}$, $1.6 \text{ g} \cdot \text{kg}^{-1}$, and $0.81 \text{ g} \cdot \text{kg}^{-1}$, respectively, representing increases of 14.29%, 15.94%, and 14.08% compared with Mono. A similar trend was observed in Changyi, in cotton rows under C4P6 (0–20 cm layer), fulvic acid, humic acid, and

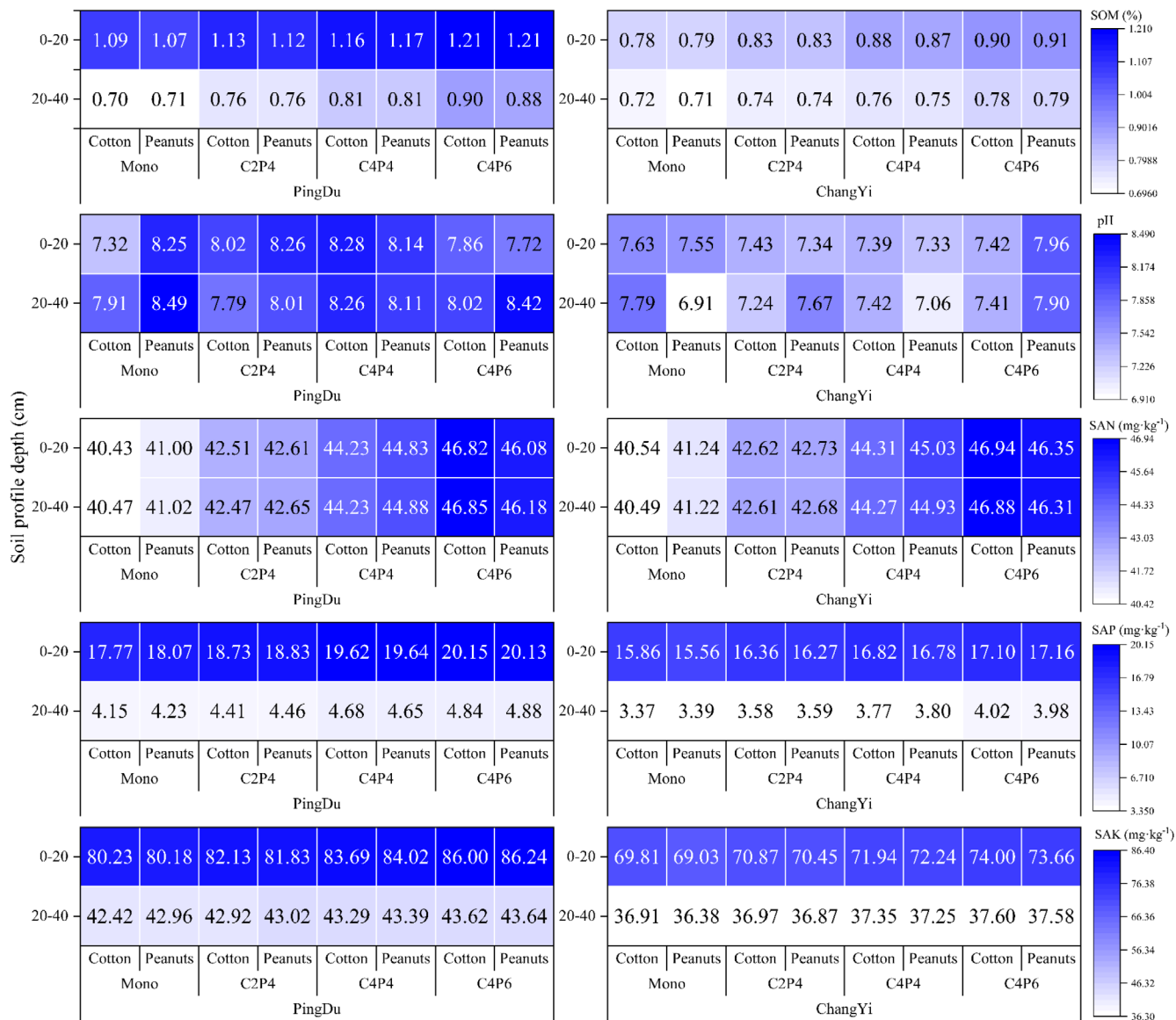


FIGURE 4 | Effects of different cropping patterns on soil chemical properties at different soil depths. Mono, C2P4, C4P4, and C4P6 denote mono-cropping, 2 rows of cotton intercropped with 4 rows of peanuts, 4 rows of cotton intercropped with 4 rows of peanuts, and 4 rows of cotton intercropped with 6 rows of peanuts, respectively; 0–20 and 20–40 refer to soil depths of 0–20 cm and 20–40 cm, respectively; SOM, SAN, SAP, and SAK represent soil organic matter, available nitrogen, available phosphorus, and available potassium, respectively. The color gradient in the heatmap corresponds to the values of soil chemical properties: Darker colors indicate higher property contents, and the numeric labels denote the specific values of each property.

humic content increased by 13.89%, 9.84%, and 16.13%, respectively, relative to MC.

3.4.2 | Soil Microorganisms and Enzyme Activities

Soil microbial abundance exhibited a consistent hierarchical structure across treatments: bacteria > actinomycetes > fungi (Figure 6). In Pingdu, soil microbial populations were higher in peanut rows than in cotton rows, with an increase of 0.28%, 3.37%, and 3.52% for bacteria, fungi, and actinomycetes, respectively. Intercropping systems generally increased the abundance of microbial abundance compared with monocropping, especially

under the C4P6 treatment. For instance, the abundance of bacteria, fungi, and actinomycetes peaked in the soil of cotton rows in Pingdu under C4P6 treatment, which increased by 28.4%, 53.8%, and 44.4%, respectively, compared with MC. In Changyi, soil bacterial abundance in peanut rows was 3.74% lower than in cotton rows, whereas fungi and actinomycetes increased by 4.05% and 0.83%, respectively. Notably, intercropping significantly boosted microbial populations of soil in peanut rows compared with MP, with increases of 12.63%–42.10% (bacteria), 7.82%–61.45% (fungi), and 17.05%–45.32% (actinomycetes). Similarly, soils of cotton rows showed enhancements of 26.34%–50.00% (bacteria), 21.10%–53.77% (fungi), and 21.51%–53.77% (actinomycetes), all maximized under the C4P6 treatment.

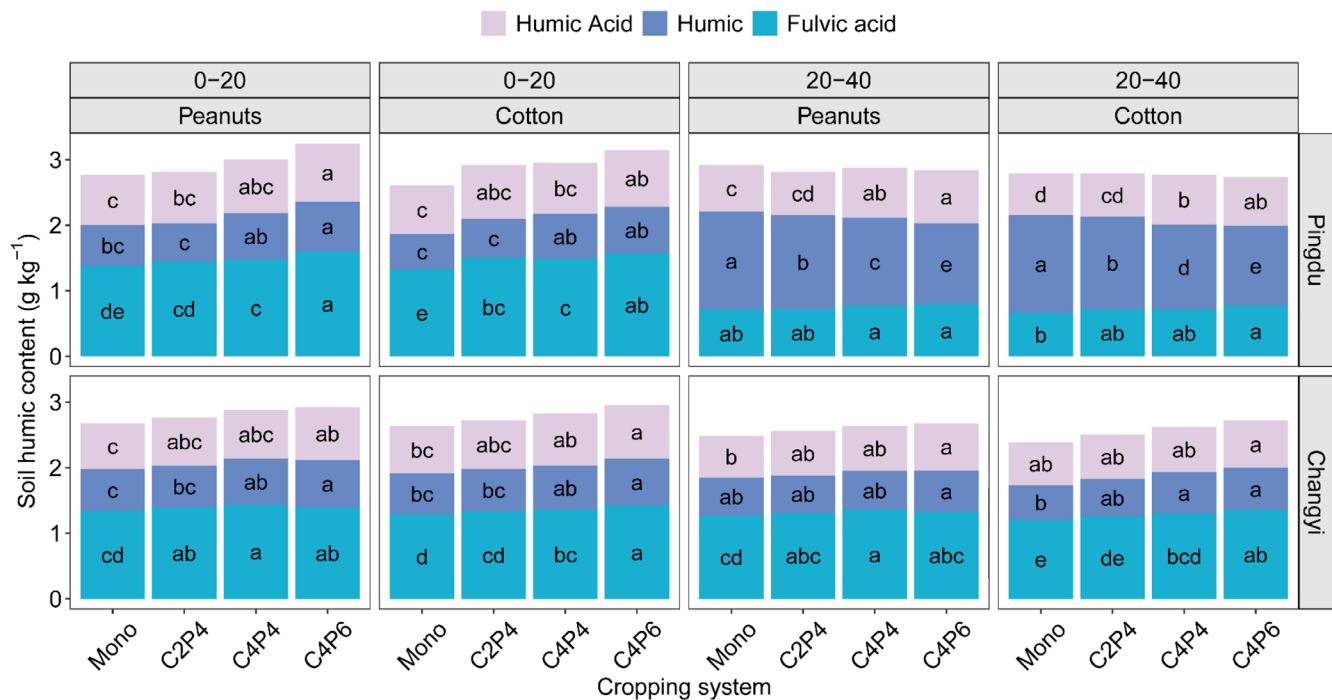


FIGURE 5 | Effects of different cropping patterns on soil humic substances at different soil depths. Mono, C2P4, C4P4, and C4P6 denote monocropping, 2 rows of cotton intercropped with 4 rows of peanuts, 4 rows of cotton intercropped with 4 rows of peanuts, and 4 rows of cotton intercropped with 6 rows of peanuts, respectively; 0–20 and 20–40 refer to soil depths of 0–20 cm and 20–40 cm, respectively; different letters indicate significant differences at the 5% level.

Intercropping consistently elevated URE, ALP, and CAT activities above monocropping levels across soil layers (Figure 7). In Changyi, as the intercropping ratio shifted from C2P4 to C4P6, URE, ALP, and CAT activities progressively increased, peaking under the C4P6 treatment. Although Pingdu also showed intercropping-induced enzyme activity enhancements, no consistent trends emerged among different planting configurations.

3.5 | Relationships Between Soil Properties and Cotton Yield

The results demonstrate significant positive correlations between cotton yield and the proportion of soil aggregates <0.5 mm, HM (humic), FA (fulvic acid), and Bact. (bacteria), with FA exhibiting the strongest association ($R=0.84$, $p<0.01$) followed by Bact. ($R=0.75$, $p<0.01$) (Figure 8). Similarly, soil pH, AP, AK, HM, FA, and Bact. showed significant positive correlations with peanut yield, where FA demonstrated the most pronounced correlation ($R=0.92$, $p<0.01$). In addition, SQI was significantly and positively correlated with BD ($R=0.43$, $p<0.01$), AN ($R=0.35$, $p<0.05$), Fung ($R=0.33$, $p<0.05$), Actino ($R=0.36$, $p<0.05$), and ALP ($R=0.37$, $p<0.05$) were significantly positively correlated. Collectively, these findings indicate that within the cotton/peanut intercropping system, humus fractions (particularly FA and HM), microbial abundance, and soil nutrient availability collectively constitute key determinants of crop productivity. Significant synergistic interactions exist among these soil properties.

3.6 | Cropping Patterns Comprehensive Evaluation

Comprehensive analysis demonstrated that the C4P6 row configuration achieved optimal synergies among crop productivity and soil sustainability (Figure 9), with peak regional average values in cotton yield (4630.13 kg·ha⁻¹), peanut yield (5257.95 kg·ha⁻¹), and soil quality index (SQI=1335.19). In contrast, monocropping system consistently underperformed, exhibiting the lowest values across all metrics: cotton yield (4408.58 kg·ha⁻¹), peanut yield (5085.00 kg·ha⁻¹), and SQI (−1545.22). Notably, the C2P4 pattern provided a trade-off between high crop yields (averaging 4537.95 kg·ha⁻¹ for cotton and 5183.01 kg·ha⁻¹ for peanut across both regions) and poor soil quality (SQI=−410.29). While the C4P4 pattern moderately improved soil quality (SQI=401.67), its limited yield gains—cotton: 4630.13 kg·ha⁻¹; peanut: 5257.85 kg·ha⁻¹ (site averaged)—failed to match the holistic benefits of C4P6 in terms of productivity and soil sustainability.

4 | Discussion

4.1 | Effect of Different Cropping Patterns on Cotton and Peanuts Yield

Intercropping systems enhance crop production potential by optimizing resource use efficiency through spatiotemporal complementarity in light interception, water utilization, and nutrient acquisition (Chang et al. 2025; Khan et al. 2025). In this study, the cotton-peanut intercropping system demonstrated synergistic yield enhancement, aligning with

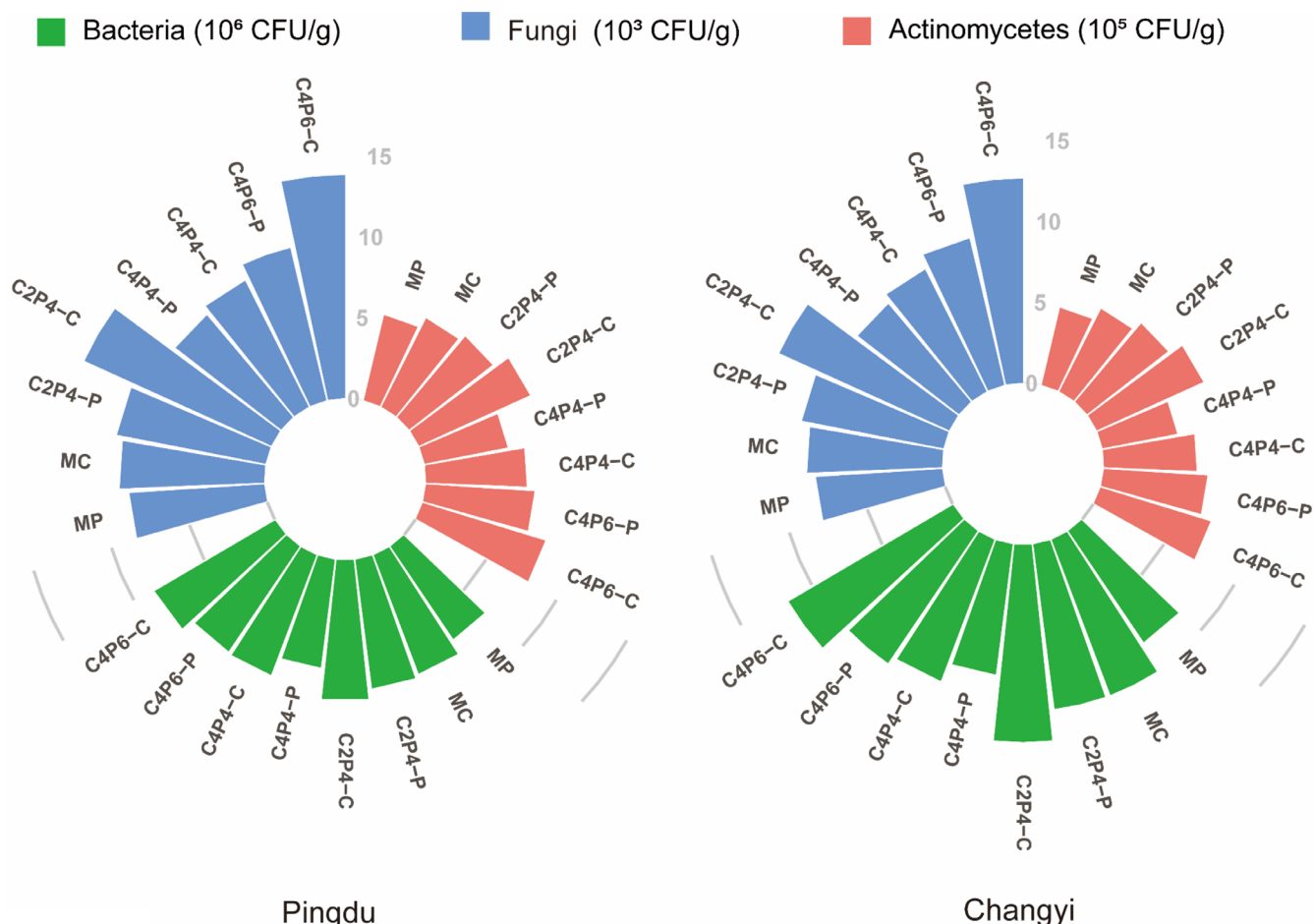


FIGURE 6 | Effects of different cropping patterns on the abundance of bacteria, fungi, and actinomycetes in soils. MC, MP, C2P4, C4P4, and C4P6 denote cotton monocropping, peanut monocropping, 2 rows of cotton intercropped with 4 rows of peanuts, 4 rows of cotton intercropped with 4 rows of peanuts, and 4 rows of cotton intercropped with 6 rows of peanuts, respectively. The letters P and C stand for peanut and cotton, respectively.

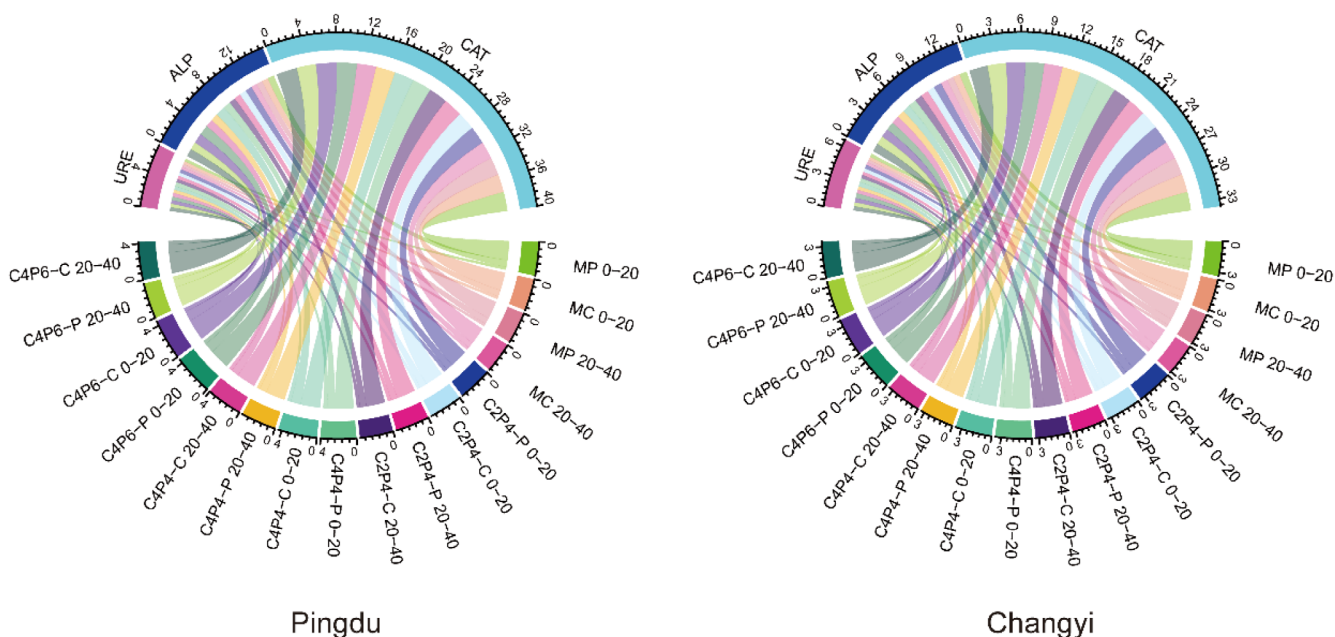


FIGURE 7 | Effect of different cropping patterns on urease (URE), Alkaline Phosphatase (ALP), and Catalase (CAT) in different soils. MC and MP denote cotton monocropping and peanut monocropping. C2P4, C4P4, and C4P6 represent 2 rows of cotton intercropped with 4 rows of peanuts, 4 rows of cotton intercropped with 4 rows of peanuts, and 4 rows of cotton intercropped with 6 rows of peanuts, respectively. The letters P and C stand for peanut and cotton, respectively. 0–20 and 20–40 represent the soil depths of 0–20 cm and soil depths of 20–40 cm, respectively.

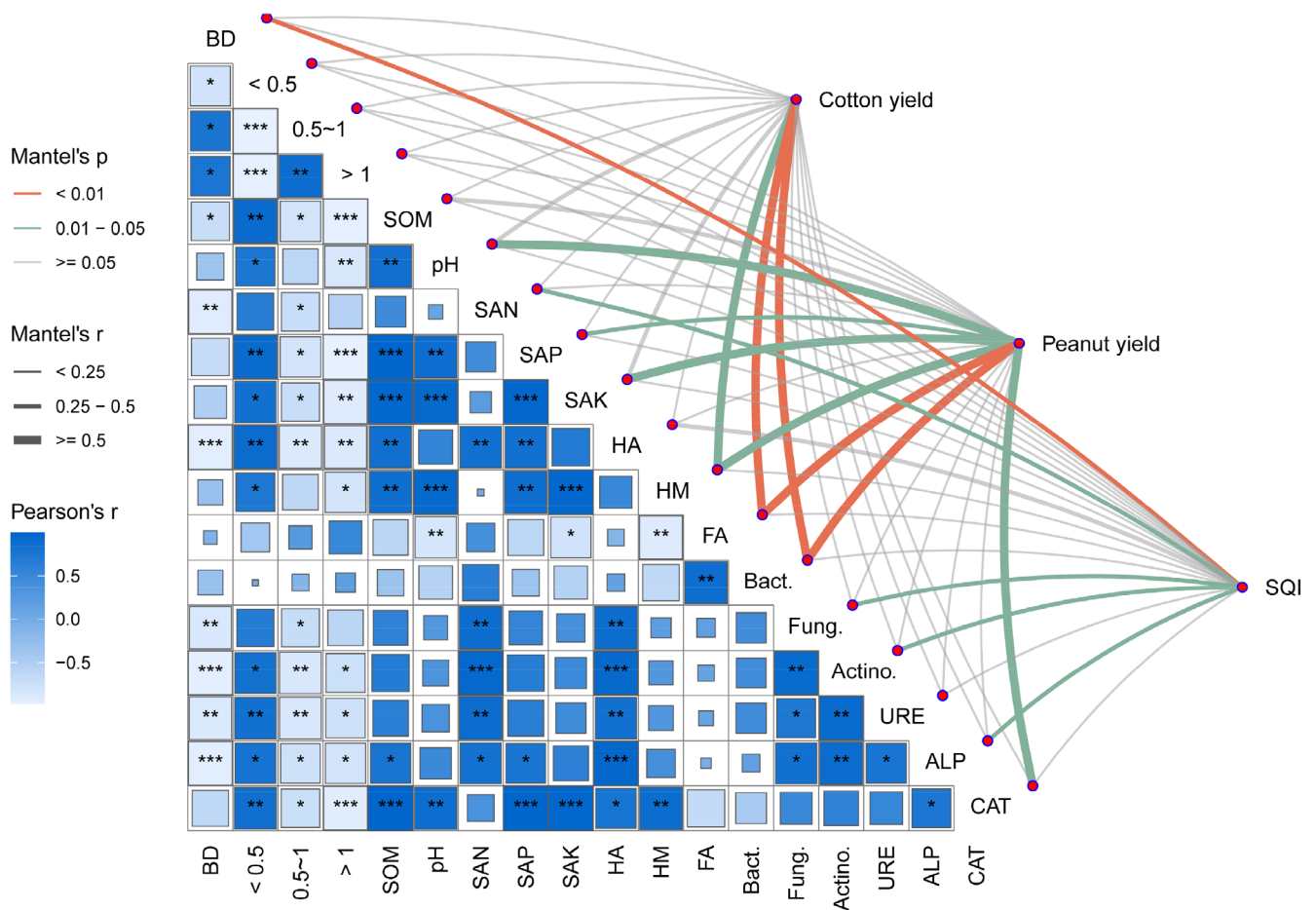


FIGURE 8 | Relationships among soil properties, cotton yield, peanut yield and SQI. BD represents the bulk density. <0.5, 0.5–1 and >1 represent soil aggregates <0.5 mm, 0.5–1 mm and >1 mm in diameter, respectively. SOM, SAN, SAP, and SAK represent soil organic matter, available nitrogen, available phosphorus, and available potassium, respectively. HA, HM, and FA represent humic acid, humic and fulvic acid, respectively. Bact., Fung., and Actino. represent bacteria, fungi, and actinomycetes, respectively. URE, ALP, and CAT represent urease, alkaline phosphatase, and catalase, respectively. SQI represents soil quality index. *, **, *** represent significant correlations at the levels of $p \leq 0.05$, $p < 0.01$, and $p < 0.001$, respectively.

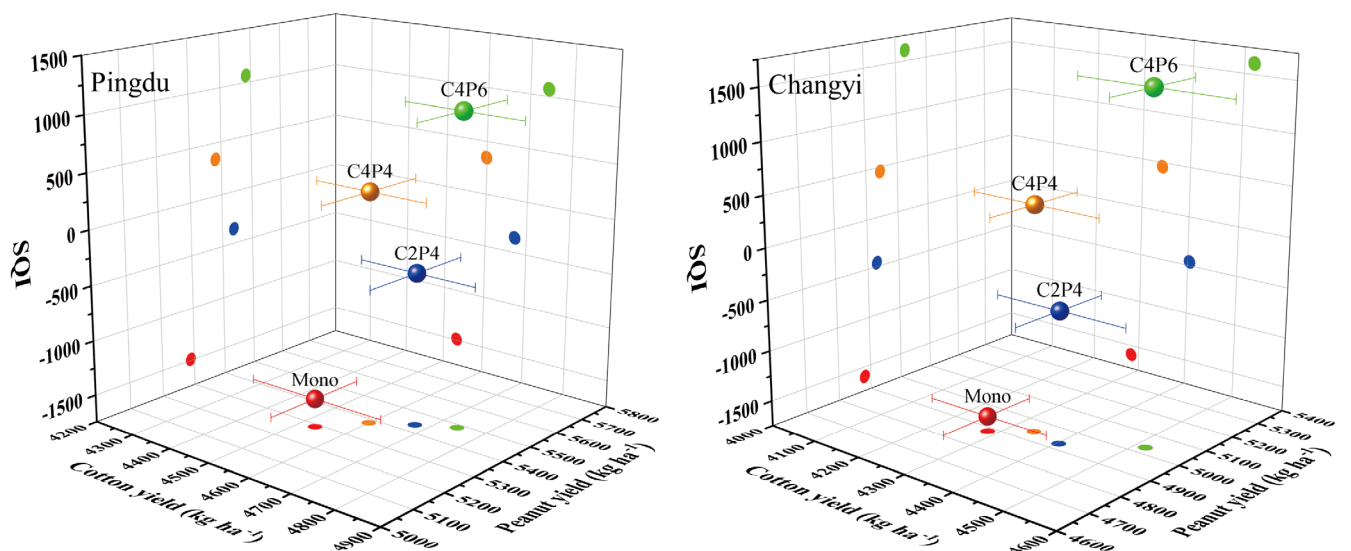


FIGURE 9 | Comprehensive evaluation of crop yields and soil quality. SQI represents the soil quality index. Mono, C2P4, C4P4, and C4P6 denote monocropping, 2 rows of cotton intercropped with 4 rows of peanuts, 4 rows of cotton intercropped with 4 rows of peanuts, and 4 rows of cotton intercropped with 6 rows of peanuts, respectively.

previous findings (Xie et al. 2022). The distribution of bolls across pre-summer, summer, and autumn periods serves as a critical measure of cotton development and productivity (Li et al. 2001; Wang et al. 2012). Analysis of boll temporal distribution and biomass allocation revealed that intercropping significantly increased the proportional contribution of pre-summer and summer bolls to total cotton yield, which are key determinants of productivity. In Pingdu, cotton yield was exclusively composed of pre-summer and summer bolls, while Changyi exhibited a higher proportion of autumn bolls. This divergence likely results from regional differences in climatic conditions or soil fertility gradients, which delayed boll development and reduced summer boll maturity, ultimately leading to lower yields in Changyi compared with Pingdu (Feng et al. 2024). In addition, from the row configurations C2P4 to C4P6, the proportion of autumn bolls decreased, and the allocation to cotton reproductive organs gradually increased, reaching its maximum under the C4P6 treatment. This may be attributed to enhanced soil nitrogen availability from peanut nitrogen fixation (Sannagoudar et al. 2024), which prioritized resource partitioning toward reproductive growth.

4.2 | Effect of Different Cropping Patterns on Soil Physical Properties

Soil physical properties, including texture, structure, bulk density, moisture content, permeability, temperature, and color, play a fundamental role in agricultural ecosystems. Alterations in these properties can significantly impact ecosystem services provided by soils, such as soil fertility maintenance, crop growth regulation, water resource management, and land use optimization (Zhao et al. 2025). These physical characteristics critically influence soil functional capacities and ultimately determine agricultural productivity and environmental sustainability (Jiang et al. 2023).

Bulk density is an important parameter for understanding the physical properties of soil (Al-Shammmary et al. 2018) and serves as an indicator of surface soil compaction stress (Frene et al. 2024). Intercropping system can effectively reduce soil bulk density through mechanisms such as enhancing soil organic carbon content, improving soil structural organization, and increasing soil porosity. This study showed that the adoption of intercropping system significantly increased the soil bulk density, a phenomenon that is consistent with Yang's findings (Yang et al. 2023). In addition, the lowest soil bulk density was observed in the row configurations with C4P6, which may be related to the higher number of rows planted with peanut in this pattern. Polysaccharides and organic acids secreted by the peanut roots enhance soil particle adhesion, promote microaggregate formation, and increase soil porosity, thereby reducing soil bulk density (Bodner et al. 2014).

Soil aggregates are the basic units of soil structure and play a vital role in maintaining soil quality, improving soil fertility, and promoting plant growth. The intercropping system can improve soil structural stability by increasing the proportion of large aggregates (> 0.25 mm). In this study, soil aggregates were classified into three size categories: > 1 mm, 0.5 – 1 mm, and < 0.5 mm. The findings revealed that the intercropping

system significantly increased the proportion of < 0.5 mm aggregates compared with monocropping. Notably, as the row configurations transitioned from C2P4 to C4P6, a progressive reduction in the > 1 mm fraction was observed, accompanied by a corresponding increase in the < 0.5 mm fraction. This phenomenon may be attributed to the higher tillage frequency in the C4P4 pattern, which induces mechanical disturbance and nutrient imbalance, thereby accelerating the breakdown of macroaggregates. Additionally, the proportion of < 0.5 mm aggregates in the 0 – 20 cm surface soil layer exhibited a decline, consistent with the postulation by Zhang et al. (2022) that surface soils generally favor macroaggregate formation due to enhanced root activity, organic matter input, and microbial processes.

4.3 | Effect of Different Cropping Patterns on Soil Chemical Properties

Soil chemical properties include soil pH, organic matter content, nitrogen, phosphorus, and potassium (Duckworth et al. 2022). These properties play a key role in maintaining ecological balance and ensuring the sustainable development of agriculture by affecting plant growth, soil physical structure, and biological activity (Zhao et al. 2025), and are considered core regulators of cultivated land productivity. The results clearly showed that soil chemical properties were significantly influenced by the cropping pattern and soil depth. In detail, the intercropping system significantly increased the levels of SOM, SAN, SAP, and SAK, which is consistent with the findings of Li et al. (2021), he demonstrated that intercropping can improve soil fertility by increasing soil organic matter, total nitrogen, and macroaggregate content compared with monocropping. A progressive increase in soil nutrient content was observed as the row configurations transitioned from C2P4 to C4P6, with the highest levels achieved under the C4P6. Peanuts have a unique ability to fix nitrogen, which can significantly increase soil nitrogen content (Chi and Dong 2024). A higher number of peanut rows in the C4P6 pattern may further enhance the nitrogen fixation effect while reducing nutrient competition between cotton and peanuts.

In addition, vertical stratification analysis revealed significant variations in soil fertility parameters with depth. SOM, SAP, and SAK exhibited a progressive decline with increasing soil depth. These findings align with the observations by Wang, Han, et al. (2024), who reported a 10% higher OM content in the 0 – 20 cm layer compared with the 40 – 60 cm layer. Notably, soil pH and SAN demonstrated depth-independent behavior, potentially attributable to the interactive effects of agronomic management practices and soil microbial community dynamics.

4.4 | Effects of Different Cropping Patterns on Soil Biological Properties

Soil biological properties serve as critical indicators for assessing soil quality and ecosystem functionality, encompassing soil humic substances, microbial community abundance, and enzymatic activities. These properties play pivotal roles in soil ecosystems by driving organic matter decomposition, nutrient

cycling, and energy flow, thereby maintaining soil ecosystem stability and productivity (Esmailizad et al. 2024). Numerous studies have demonstrated that intercropping systems can significantly enhance soil biological properties through optimized resource utilization and ecological niche complementarity (Homulle et al. 2022; Lan et al. 2023; Liang et al. 2024).

Soil organic matter (SOM) can be categorized into humic and non-humic substances. Humic substances, primarily composed of humic acid, fulvic acid, and humin, typically constitute 60%–80% of SOM and play a significant role in promoting crop growth and development (Kopecky et al. 2016; Tiwari et al. 2023). Intercropping systems enhance the decomposition rate of soil organic carbon (SOC) by stimulating microbial metabolic activity (Duchene et al. 2017). Bernard et al. (2007) demonstrated that legume-based intercropping enhances soil carbon inputs, promoting the transformation of fresh organic matter into stable humic substances through microbial activity. In this study, the intercropping system elevated soil humic substance content, corroborating previous findings. Notably, in the topsoil layer of Pingdu and throughout Changyi, humic substance content progressively increased with the number of peanut rows. This phenomenon may be attributed to the increase in rows of leguminous crops, which enhances litter decomposition and transformation, thereby providing essential substrates for humic substance formation (Chamkhi et al. 2022).

Furthermore, this study elucidated the spatial heterogeneity of soil humic substance content. Stratified sampling analysis revealed that as soil depth increased from 0–20 cm to 20–40 cm, humic acid content decreased by 19.54% in Pingdu and 10.71% in Changyi, while fulvic acid content declined by 50.47% in Pingdu and 5.73% in Changyi. These vertical distribution patterns are likely driven by the shallow root architecture of peanuts, which predominantly influences the upper soil layers (Wang, Wang, et al. 2024).

Intercropping fosters beneficial interactions by enhancing the relationships between plants and microorganisms. In a legume-based intercropping system, positive soil-crop-microbe interactions are facilitated through root complementarity between different crops (Duchene et al. 2017). This study demonstrated that the intercropping system significantly increased the abundance of soil microorganisms, including bacteria, fungi, and actinomycetes. This phenomenon may be attributed to the co-growth of diverse plant root systems in the intercropping system, which modifies the rhizosphere environment and intensifies plant-microbe interactions, thereby creating more favorable conditions for microbial proliferation (Bargaz et al. 2015). Furthermore, this study found that the abundance of bacteria, fungi, and actinomycetes in cotton rhizosphere soil was higher than in peanut rhizosphere soil. This may be attributed to the more developed root system of cotton, which provides more habitats for microorganisms, promoting their colonization and growth (Bais et al. 2006; Ulbrich et al. 2022). In different intercropping configurations, soil microbial abundance was higher in patterns with a greater proportion of peanut rows, such as C2P4 and C4P6. This suggests a positive correlation between the proportion of peanuts and soil microbial abundance in the cotton-peanut intercropping system.

This study employed a three-dimensional coordinate-based data visualization approach to comprehensively evaluate the relationship between crop productivity and soil quality under different cropping patterns. Results showed that the C4P6 intercropping pattern achieved optimal synergies between crop productivity and soil health, exhibiting peak regional averages in cotton yield ($4630.13 \text{ kg} \cdot \text{ha}^{-1}$), peanut yield ($5257.95 \text{ kg} \cdot \text{ha}^{-1}$), and soil quality index ($\text{SQI} = 1335.19$). Indicating significant advantages in enhancing yield and improving soil quality. This superior performance likely originated from the strategic peanut row placement (particularly in C4P6), enhanced biological nitrogen fixation, which improved soil nitrogen availability (Sannagoudar et al. 2024), as well as the optimized spatial configuration that minimized interspecific competition for light and nutrients between cotton and peanut, thereby synchronously boosting productivity and soil functionality (Chi et al. 2023). In contrast, monocropping systems showed the lowest yields and SQI values, underscoring their limitations in sustaining soil quality and productivity. These findings emphasize the necessity of adopting diversified cropping practices (e.g., intercropping) or refined management strategies to optimize agricultural production. Overall, intercropping systems demonstrate significant advantages in balancing soil quality and productivity, with the C4P6 pattern emerging as the optimal paradigm, offering a scientific foundation for sustainable cotton production in the Yellow River Basin. Although the conclusions of this study are based on field experiments in the Yellow River Basin, the revealed “soil-plant synergistic mechanism” has broader reference significance. These findings can provide a valuable perspective for other agricultural ecosystems facing similar challenges, such as areas with intense resource competition and early soil degradation. By integrating local conditions such as dominant crop types and resource availability with the configuration principles and evaluation methods proposed in this study, stakeholders can develop tailored cropping patterns that support local agricultural sustainability.

5 | Conclusion

Short-term field studies in two locations have shown that the cotton-peanut intercropping system synergistically increases crop yields while optimizing soil health through multidimensional improvements. Physically, intercropping reduced soil bulk density by 4.18%–15.54% and improved soil aggregate distribution. Chemically, intercropping significantly increased the content of essential nutrients, with soil organic matter (SOM) increasing by 4.44%–14.09%, available nitrogen (SAN) by 4.44%–14.09%, available phosphorus (SAP) by 4.66%–11.97%, and available potassium (SAK) by 1.56%–5.33%. Biologically, the intercropping system increased soil microbial populations and enzymatic activities while also enhancing the accumulation of humic substances in the soil. These comprehensive improvements significantly promoted cotton and peanut yields, with the C4P6 pattern exhibiting optimal performance, achieving the highest values in both soil quality indicators (1335) and crop productivity (cotton: $4742 \text{ kg} \cdot \text{ha}^{-1}$; peanut: $5485 \text{ kg} \cdot \text{ha}^{-1}$). Overall, the short-term finding indicates that the cotton-peanut intercropping system can improve agricultural productivity by improving soil quality, thereby providing an effective

management strategy and theoretical basis for sustainable agricultural development.

Author Contributions

Menghua Zhai: conceptualization, data analysis, data curation, visualization, and writing – original draft. **Xuwen Wei:** hardware, conceptualization, validation, data curation, software, and visualization. **Pengcheng Li** and **Jian Wang:** methodology, validation, and supervision. **Qinqing Xu, Guilan Sun, Zhanlei Pan,** and **Dulin Qin:** investigation and supervision. **Jie Zhang, Yaopeng Zhang, Lizhi Wang,** and **Xueyan Duan:** investigation. **Junhong Li** and **Kunfeng Wang:** project administration. **Wenqi Zhao** and **Xin Li:** formal analysis. **Zhenggui Zhang:** conceptualization, methodology, visualization, supervision, writing – review and editing. **Zhanbiao Wang:** resources, supervision, writing – review and editing, and funding acquisition.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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