RESEARCH ARTICLE

Mechanisms of soil phosphorus components uptake in corn-alfalfa intercropping systems

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In arid and semi-arid regions, insufficient available phosphorus in soil has become the primary bottleneck limiting high crop yields, which has a negative impact on crop growth. Therefore, fully tapping into the biological potential of soil "fixed phosphorus pool" has become a core issue of common concern in current agricultural ecology and soil science. Intercropping is an ancient and efficient ecological planting method that can reshape the process of rhizosphere phosphorus conversion and improve phosphorus utilization efficiency through the synergistic interaction among species roots, microorganisms, and soil. To analyze the mechanism of corn-alfalfa intercropping method in the uptake of phosphorus components in soil and improve phosphorus utilization efficiency, this study set up three experimental groups including corn monoculture, alfalfa monoculture, and corn-alfalfa intercropping. The contents of organic and inorganic phosphorus elements in soil and the changes in soil physicochemical properties were analyzed in the three groups to learn the mechanism of corn-alfalfa intercropping method. The results showed that the pH value of the soil under intercropping was lower than that of corn monoculture and alfalfa monoculture ($P < 0.01$), while the content of water-soluble phosphorus, aluminum bound phosphorus, and closed storage phosphorus, inorganic phosphorus, in the soil exceeded that in the other two groups ($P < 0.01$). The content of calcium bound phosphorus was lower than that of the other two groups ($P < 0.01$). Moreover, the content of active and highly stable organic phosphorus in the soil was lower than that of the other two groups, while the content of moderately active and moderately stable organic phosphorus demonstrated no obvious difference compared to the other two groups. In addition, the phosphorus uptake of corn-alfalfa intercropping area was significantly higher than that in monoculture areas. These results confirmed that corn-alfalfa intercropping could reduce soil salinity, accelerate the transformation process of organic phosphorus, and absorb organic and inorganic phosphorus elements in the soil by plants.

Keywords: corn; alfalfa; intercropping; monoculture; soil phosphorus content; phosphorus uptake capacity.

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Introduction

Phosphorus is one of the important elements in agricultural crops and exerts a crucial function in their growth and development process [1]. When crops grow, phosphorus can participate in plant photosynthesis, material transport, and form the phospholipid bilayer of plant cell membranes, maintaining the integrity of cell structure [2]. Phosphorus is an element of key substances such as nucleic acids, adenosine triphosphate, and phospholipids in plants, which can participate in energy transfer, photosynthesis, and cell division processes, and have important effects on plant growth [3, 4]. In soil, phosphorus mainly exists in inorganic phosphates including dihydrogen phosphate and phosphate ions [5]. Plant roots can absorb inorganic phosphates and other phosphorus elements present in the soil and convert them into usable forms of phosphorus [6]. The soil also contains some organic phosphorus, most of which exists in the form of high polymers with low effectiveness, generally accounting for 10% to 50% of the total phosphorus content in the soil [7]. Most inorganic phosphates in the soil are directly absorbed by the roots and participate in their energy metabolism, while most of the organic phosphorus exists in high molecular weight forms such as phytochemicals and nucleic acids and needs to be hydrolyzed and converted into inorganic phosphorus by phosphatase secreted by microorganisms before it can be absorbed by plants. Inorganic phosphorus and organic phosphorus can undergo bidirectional transformation to maintain phosphorus balance in the soil. After absorbing inorganic phosphorus, plants can metabolize it into organic phosphorus such as phytic acid and organic acids, which are returned to the soil to form organic phosphorus. The mineralization reaction driven by microorganisms in the soil can decompose organic phosphorus into inorganic phosphorus, thereby achieving bidirectional conversion between organic phosphorus and inorganic phosphorus in the soil and maintaining the balance. However, the conversion between organic phosphorus and inorganic phosphorus is closely related to soil pH, organic matter content, and microbial activity in the soil. The higher the phosphorus content in the soil, the better. When the phosphorus content in the soil is too high, it will inhibit the uptake of trace elements such as iron and zinc by plants, leading to the deficiency of trace elements in plants. In addition, excessive phosphorus can lead to underutilization of some phosphorus, which can enter the water body through runoff, resulting in eutrophication of the water body. Further, excessive phosphorus in the soil can cause metal ions such as calcium and aluminum to combine with phosphate ions, forming insoluble compounds that cause soil compaction and reduce soil permeability. Exploring the phosphorus content in soil can ensure the normal growth of plants. However, over 95% of phosphorus in the soil exists in insoluble form, leading to low phosphorus uptake efficiency in crops [8].

Crop intercropping is an ecological planting model that optimizes the spatial distribution of crop roots, regulates root microbial communities and soil physicochemical properties, improves phosphorus utilization efficiency, and increases plant uptake of phosphorus elements [9]. Corn is a high stem crop, while alfalfa is a low stem crop. Corn-alfalfa intercropping can fully utilize sunlight through the vertical structural differences between the two, forming a three-dimensional planting mode and improving light energy utilization efficiency [10]. The alfalfa root system is well-developed, which can loosen the soil, while the corn has a deeper root system, which can break the bottom soil compaction [11]. The combination of the two can improve soil particle structure and reduce soil erosion. Common intercropping modes include 4:4 mode, 2:4 mode, and 4:6 mode. The 4:4 mode refers to intercropping 4 rows of corn and 4 rows of alfalfa with a width of 3 m. The corn ridge spacing is about 60 – 70 cm, and the plant spacing is 25 – 30 cm. The alfalfa row spacing is about 30 – 35 cm, and the distance between the two plants is about 30 – 35 cm. The corn planting density is 4,000 - 4,500 plants per mu, and the alfalfa sowing rate is within the range of 1 - 1.5 kg/mu. The 2:4 mode involves intercropping 2 rows of corn and 4 rows of alfalfa with a corn row spacing 40 cm and a width of about 1.85 m. The corn row spacing is 40 cm and the plant spacing is 20 – 25 cm. The row spacing of alfalfa is about 15 – 20 cm, and the spacing between corn and alfalfa is about 25 cm. In this mode, the corn planting density is 4,500 - 5,000 plants per mu, and the sowing rate of alfalfa is within 0.8 to 1.3 kg/mu. The 4:6 mode involves intercropping 4 rows of corn and 6 rows of alfalfa with a width ranging from 2.5 cm to 2.7 m, a corn row spacing 30 cm, and a plant spacing approximately 25 cm. The row spacing of alfalfa is about 30 cm. In this mode, there are approximately 4,200 corn seedlings per mu, and the sowing rate of alfalfa is within 1.2 - 1.8 kg/mu. The row spacing between corn and alfalfa is approximately 30 cm. Traditional agriculture uses excessive chemical fertilizers during crop growth and development to address the low efficiency of soil phosphorus utilization. This method not only exacerbates the depletion of phosphorus resources, but also easily leads to environmental pollution problems such as eutrophication of water bodies, which is not in line with the current concept of sustainable development [12, 13]. Therefore, many scholars have proposed various methods to accelerate the uptake rate of phosphorus elements in soil by crops. Basak *et al*. used an impedance spectroscopy sensor to measure the phosphorus content in crop leaves to promote plant phosphorus uptake rate and determine the amount of phosphorus fertilizer applied, thereby improving crop phosphorus uptake rate [14]. In addition, Wu *et al*. correlated the uptake rate of phosphorus in lettuce hydroponics with transpiration to promote the uptake of phosphorus in lettuce hydroponics and adjust the uptake rate of phosphorus in lettuce [15]. However, the above methods still require significant resource investment and high costs. Therefore, there is an urgent need to design a crop planting method that can improve crop phosphorus uptake efficiency, reduce resource input, and lower costs.

This study focused on typical soda-saline soils in western Jilin Province, China and conducted comparative experiments on corn-alfalfa intercropping to investigate the content of organic and inorganic phosphorus elements in the soil, as well as changes in soil physicochemical properties, under three planting patterns of corn monoculture, alfalfa monoculture, and corn-alfalfa intercropping to elucidate the mechanism of soil phosphorus absorption under intercropping conditions and to improve soil phosphorus absorption efficiency through corn-alfalfa intercropping, thereby reducing phosphorus fertilizer use and increasing phosphorus resource utilization. This study measured the specific content of inorganic and organic phosphorus in the soil under monoculture and intercropping patterns and combined with soil pH, water content, and microbial communities to reveal the mechanism by which intercropping systems improved phosphorus absorption efficiency. By measuring the content of different forms of phosphorus, soil physicochemical properties, and plant phosphorus uptake, this study revealed the intrinsic mechanism by which corn-alfalfa intercropping improved soil phosphorus availability, providing a theoretical basis for the efficient utilization of phosphorus resources in cold and arid regions.

Materials and methods

Research location and materials

This research was conducted in the National Field Scientific Observation and Research Station of Da'an Farmland Ecosystem in Jilin Province, China with geographical coordinates of 123°50′27″E to 123°51′31″E and 45°35′58″N to 45°36′28″N. The region belongs to the temperate continental monsoon climate and has ample sunshine throughout the year. The annual average temperature in the region is between 4℃ and 6℃. The winter in the region is cold and long with the average temperature in January as -15℃ to -20℃, while the summer is warm and short with the average temperature in July ranging from 22℃ to 25℃. The precipitation in this region is mainly concentrated in summer, which accounts for over 60% of the total annual precipitation, while the precipitations in other seasons are relatively low with an annual precipitation of 400 – 500 mm in this region. There are many types of soil in Da'an City with a complex distribution, mainly consisting of soda saline alkali land. The pH value is high, usually above 8.5, and the alkalinity is strong, which is not conducive to crop growth. Xianyu 335 corn (Yulin Feiyu Seed Industry Co., Ltd., Yulin, Shaanxi, China) that is tolerant to salt alkali with high and stable yields and Algonquin alfalfa (Gansu Chuanglvcao Technology Co., Ltd., Lanzhou, Gansu, China) that has strong adaptability and high protein content were selected as experimental varieties.

Experimental grouping and sampling

This research included corn planting alone (A), alfalfa planting alone (B), and 4:6 corn-alfalfa intercropping (C) three groups. The experiment plot A was 4 × 6 m^2 with a row spacing of 60 cm. A total of six rows were planted. The experimental plot B was also 4 × 6 m^2 with 12 rows of alfalfa planted at intervals of 30 cm. The experimental plot C consisted of 4 rows of corn and 6 rows of alfalfa with a width of 2.5 - 2.7 m, a corn row spacing of 30 cm, and a plant spacing of about 25 cm. The row spacing of alfalfa was about 30 cm. The interval among experimental plots A, B, and C was 0.5 m. Multiple experimental plots were prepared to ensure the accuracy of the experimental results. Before starting planting, the land in the experimental plot was treated to ensure that the ground was flat and there were no obvious undulations. A rotary tiller was used to plow the experimental plot to a depth of 20 – 25 cm to loosen the soil and enhance its permeability and water retention. The amount of fertilizer applied to the soil in each experimental plot was the same to accurately measure the uptake effect of corn and alfalfa intercropping on phosphorus components in the soil. Before sowing, base fertilizer was applied in combination with soil preparation by using 750 kg of superphosphate, 150 kg of urea, and 150 kg of potassium chloride per hectare. The fertilizer was spread evenly on the soil surface and then thoroughly mixed with the soil through plowing. For corn topdressing, urea was applied at 225 kg/ha during the tasseling stage. Additionally, 75 kg/ha of urea was applied after each alfalfa harvest in the experimental plots. During the growth period of corn and alfalfa, sufficient water supply was ensured, and crops were irrigated in a timely manner during drought with each irrigation amount making the soil moist to approximately 20 – 30 cm. Weeding and insecticidal measures during crop growth were designed according to local agricultural practices. Soil samples were taken from the experimental plot during the flowering period of corn with 5 - 10 sampling points being selected in each experimental plot. Soil samples were collected from the 0 – 10 cm and 10 – 20 cm soil layers. The soil samples obtained from each sampling point were mixed evenly. The quartering method was used to take 1 kg of soil sample. The edge positions of corn and alfalfa were avoided during sampling. The soil samples were taken at the middle point of each row of crops planted in experimental plots A and B, and in the middle of each row of corn and alfalfa in experimental plot C. Samples were also taken between rows of corn and alfalfa in experimental plot C. Three different soil samples obtained in the middle of each row of corn and alfalfa, as well as between rows of corn and alfalfa in experimental plot C were mixed together as one sample. During the maturity period of corn and the cutting period of alfalfa, 15 corn plants and 70 – 80 cm long alfalfa were selected as experimental samples in each experimental plot to determine the phosphorus content of crops.

Determination of indicators

The content of inorganic phosphorus in soil was determined by using chemical leaching method combined with molybdenum antimony colorimetric method [16]. After air drying the collected soil samples and filtering through a 2 mm sieve, extract solutions were added to the soil samples in a 20:1 ratio and shaken at 25℃ for 30 minutes before filtering. The filtrates were used to determine phosphorus content using the molybdenum antimony colorimetric method. Water-soluble phosphorus in soil was extracted using a 1 mol/L NH_4Cl solution, while aluminum bound phosphorus (Al-P) was extracted using a 0.5 mol/L NH_4F solution. In addition, iron bound phosphorus was extracted using a 0.1 mol/L NaOH solution, and closed state phosphorus (O-P) was extracted using a combination of 0.3 mol/L sodium citrate solution and sodium hydrosulfite. Calcium bound phosphorus (Ca-P) was extracted using a 0.5 mol/L H_2SO_4 solution. The color developing solution was prepared by dissolving 10 g of $(NH_4)_6Mo_7O_{24}\cdot 4H_2O$ in 300 mL of 60℃ water. After cooling down, 126 mL of concentrated H_2SO_4 and 100 mL of 5 g/L antimony potassium tartrate (Aladdin Reagent, Shanghai, China) solution were added to dilute to 1 L as stock solution. The molybdenum antimony anti-color reagent was prepared by dissolving 1.5 g of L-ascorbic acid to every 100 mL of stock solution right before usage. For color development and comparison, an appropriate amount of filtrate was added to a 50 mL volumetric flask followed by adding 2 drops of dinitrophenol indicator and adjusting to a slight yellow color with dilute NH_4OH or H_2SO_4. 5.0 mL of molybdenum antimony anti-color reagent was added to make up for the volume. After standing at 20 - 30℃ for 30 minutes, the absorbance at 700 or 880 nm was measured using a New Century T6 Spectrophotometer (Beijing Puxi General Instrument Co., Ltd., Beijing, China) and quantified. The content of each inorganic phosphorus in the soil was calculated as follows.

$$P = (C \times V \times ts) / m \quad (1)$$

where *P* was the calculated inorganic phosphorus content. *C* was the filtrate phosphorus concentration measured by colorimetric method. *V* was the volume of the extraction solution. *m* was the soil sample mass. *ts* was the division multiple. The extraction method for labile organic phosphorus (LOP) involved mixing soil with a sodium bicarbonate extraction solution at a ratio of 1:20, adjusting the pH to 8.5, shaking for 30 minutes using a HY-4 reciprocating oscillating machine (Jiangsu Jintan Guorui Instrument Co., Ltd., Changzhou, Jiangsu, China), filtering, and then converting the organic phosphorus to inorganic phosphorus through ammonium sulfate oxidation. The LOP content was determined by measuring the total phosphorus content and subtracting the inorganic phosphorus content. Moderately labile organic phosphorus (MLOP) was extracted by leaching the residue after LOP extraction with 1 mol/L H_2SO_4 solution. The medium-stability organic phosphorus (MSOP) was extracted by using a 0.5 mol/L NaOH solution to leach the residue extracted from MLOP. The high-stability organic phosphorus (HSOP) was obtained by extracting the residue of MSOP with 12 mol/L H_2SO_4-HCl, boiling in water for 1 hour, filtering, and determining the phosphorus content. The soil pH was measured by using a pH meter. 10 g of soil sample was mixed with 25 mL of purified water. After stirring evenly and standing for 30 minutes, the pH value was measured. The soil moisture content was calculated by first measuring the wet weight of the sampled soil, then drying the soil sample in a 105℃ oven for 6 - 8 hours until the soil weight remains constant before measuring the dry weight of the soil. The soil moisture content was then calculated based on the wet and dry weight of the soil. The phosphorus uptake of the plants was determined by using air dried corn and alfalfa samples from experimental plots A, B, and C, crushing and sieving the samples, and then adding concentrated sulfuric acid and perchloric acid and heating the solution continuously until it turned transparent. After cooling down, the solution was transferred to a volumetric flask, shaken well, and let it settle for clarification. The upper clear liquid was taken and added dinitrophenol indicator to adjust the pH to a slight yellow color before adding molybdenum antimony anti-color agent. The phosphorus content was calculated by comparing colors at a wavelength of 700 nm on a New Century T6 Spectrophotometer using a standard curve.

Data processing and statistical analysis

Microsoft Excel 2010 (Microsoft, Redmond, Washington, USA) and SPSS 22.0 (IBM, Armonk, New York, USA) were used to organize and analyze experimental data. The significant differences in soil phosphorus composition and crop phosphorus uptake under different planting methods were compared through one-way analysis of variance (ANOVA). The *P* value less than 0.05 was defined as statistically significant difference, while the *P* value less than 0.01 was defined as very significant difference.

Results and discussion

Changes in soil physical and chemical properties

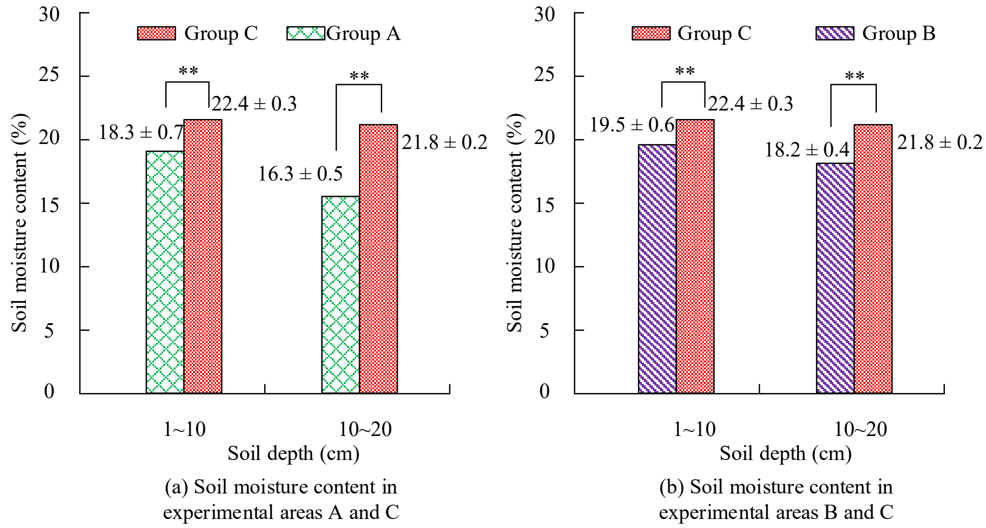

Figure 1. Soil moisture content in the experimental area. **: $P < 0.01$.

The pH changes of the experimental plots A, B, and C demonstrated that the pH value of the 0 – 10 cm soil in experimental plot C was the lowest at 8.07, which was 0.45 lower than that in plot A ($P < 0.01$) and 0.38 lower than that in plot B ($P < 0.05$). The pH value of the 0 – 10 cm soil layer in the surface soil was lower than that of the 10 - 20 cm soil layer, indicating that surface soil acidification was more pronounced. The difference between the sudden pH values in experimental plots A and B was not significant, indicating that planting corn or alfalfa alone did not have a significant effect on improving the pH of saline alkali land (Table 1). This result was roughly consistent with the results of Muhammad *et al*. who found that intercropping non-leguminous plants could reduce soil salinity [17].

Table 1. Changes in soil pH value.

Plot	Soil depth	pH	*P* value
A	0 – 10 cm	8.52 ± 0.08	**
	10 – 20 cm	8.61 ± 0.05	**
B	0 – 10 cm	8.45 ± 0.10	*
	10 – 20 cm	8.52 ± 0.06	*
C	0 – 10 cm	8.07 ± 0.03	-
	10 – 20 cm	8.11 ± 0.02	-

Note: *: $P < 0.05$. **: $P < 0.01$.

Corn-alfalfa intercropping could reduce soil salinity because it absorbed water through the deep roots of corn, and the salt in the soil migrated with the water. Alfalfa maintained soil moisture through shallow root systems, reducing the salt accumulation in surface soil and adjusting the soil pH value. The soil moisture content in experimental plots A and C showed that the soil moisture content in the 0 – 10 cm soil layer of the plot C was the highest, reaching 22.4%, while the plot A was 18.3% ($P < 0.01$). Moreover, there was a significant difference in the soil moisture content in the 10 – 20 cm layer between plots A and C with the moisture contents of plot A reaching 21.8% and plot C reaching 16.3% ($P < 0.01$) (Figure 1a). The soil moisture content of plots B was 19.5% in the 0 – 10 cm soil layer, which was significantly lower than that in the plot C ($P < 0.01$), while the moisture content in the 10 – 20 cm soil layer of plot B was lower than that of plot C ($P < 0.01$) (Figure 1b). The results indicated that plot C could reduce the pH value of saline alkali land and improve soil moisture content. This result coincided with the findings of Fernandez *et al*. with the potential mechanisms that corn plants were tall and had wider leaves, which could provide shade in the upper layer and reduce direct sunlight exposure, while alfalfa plants were low in height and had dense branches, making them easy to form dense coverage in the lower layer, filling the gaps formed by corn plants and providing shading conditions for the surface, significantly reducing the water evaporation in the soil [18].

Changes in soil inorganic phosphorus

The water-soluble phosphorus included Al-P, O-P, and Ca-P. Under the intercropping mode of corn and alfalfa in experimental plot C, the water-soluble phosphorus in the 0 – 10 cm soil layer was the highest, reaching 1.6 ± 0.3 mg/kg, significantly higher than the 1.1 ± 0.3 mg/kg in experimental plot A and the 1.1 ± 0.2 mg/kg in experimental plot B ($P < 0.01$). The contents of Al-P and O-P in plot C exceeded that of plots B and A ($P < 0.01$). However, the content of Ca-P in plot C was 42.3 ± 0.4 mg/kg, significantly lower than that in plots A and B ($P < 0.01$) (Table 2). The results suggested that the corn-alfalfa intercropping could significantly increase the water-soluble phosphorus of Al-P and O-P but reduce Ca-P in 0 – 10 cm soil layer.

Table 2. Changes in inorganic phosphorus (mg/kg) in 0 – 10 cm soil layer.

Plot	A	B	C
Water-soluble phosphorus	1.1±0.3**	1.1±0.2**	1.6±0.3
Al-P	8.1±03**	8.3±0.2**	9.2±0.1
O-P	11.9±0.2**	12.1±0.1**	13.2±0.5
Ca-P	48.3±0.2**	48.4±0.1**	42.3±0.4

Note: **: $P < 0.01$.

The changes of inorganic phosphorus in the 10 – 20 cm soil layer among three experimental plots showed that the water-soluble phosphorus content in plot C was the highest with a content of 1.2 ± 0.1 mg/kg, significantly higher than that of 0.8 ± 0.1 mg/kg in plot A ($P < 0.01$) and 0.9 ± 0.1 mg/kg in plot B ($P < 0.01$). The Al-P and O-P contents in plot C exceeded those in plots A and B ($P < 0.01$). However, the content of Ca-P in plot C was significantly lower than that in plots A and B ($P < 0.01$) (Table 3). The results confirmed that the inorganic phosphorus content at the 0 – 10 cm soil layer was significantly higher than that in the 10 – 20 cm soil layer. Corn-alfalfa intercropping in experimental plot C could increase the water-soluble phosphorus, Al-P, and O-P in the 0 – 10 cm and 10 – 20 cm soil layers but reduce the Ca-P inorganic phosphorus. This result was consistent with the peanut intercropping model designed by Lal *et al*. [19], which might be that the organic acids secreted by alfalfa roots reacted chemically with insoluble phosphorus in the soil, converting it into water-soluble phosphorus. The converted phosphorus existed in the forms of Al-P and O-P, which increased the content of this part of phosphorus. During intercropping, the soil pH decreased, the solubility of calcium ions increased, the precipitation of calcium phosphate weakened, resulting in a decrease in the Ca-P.

Table 3. Changes in inorganic phosphorus (mg/kg) in 10 – 20 cm soil layer.

Plot	A	B	C
Water-soluble phosphorus	0.8±0.1**	0.9±0.1**	1.2±0.1
Al-P	7.0±03**	87.3±0.4**	8.1±0.1
O-P	10.5±0.1**	11.0±0.2**	12.2±0.2
Ca-P	46.1±0.3**	47.3±0.4**	41.1±0.1

Note: **: $P < 0.01$.

Changes in soil organic phosphorus

In terms of the changes of organic phosphorus in the soil, the variations of LOP, MLOP, MSOP, and HSOP in different soil layers were examined. The results showed that the content of MLOP in plot C was the highest followed by HSOP and MSOP with the LOP as the lowest content. The distribution of organic phosphorus contents in other experimental plots was roughly the same as that of experimental plot C. The content of soil LOP and HSOP in 0 – 10 cm soil layer of plot C were 8.7 ± 0.2 g/kg and 34.3 ± 0.2 mg/kg, respectively, which were significantly lower than those in plots A and B ($P < 0.01$). There was no significant difference in the content of MSOP and MLOP among these three experimental plots (Table 4). The results concluded that the corn-alfalfa intercropping had obvious impacts on the content of LOP, HSOP and lower impact on MSOP, MLOP in 0 – 10 cm soil layer.

Table 4. Differences in organic phosphorus content (mg/kg) in 0 – 10 cm soil layer.

Plot	A	B	C
LOP	21.3 ± 0.4**	19.5 ± 0.3**	8.7 ± 0.2
MLOP	46.1 ± 0.1	45.8 ± 0.3	45.9 ± 0.2
MSOP	20.1 ± 0.2	19.4 ± 0.2	20.2 ± 0.1
HSOP	40.2 ± 0.4**	43.3 ± 0.4**	34.3 ± 0.2

Note: **: $P < 0.01$.

The organic phosphorus contents in the 10 – 20 cm soil layer in the three experimental plots showed that the total LOP content in plot C was only 7.2 ± 0.1 mg/kg, which was significantly lower than the 10.3 ± 0.1 mg/kg in plot A ($P < 0.01$) and the 9.5 ± 0.3 mg/kg in plot B ($P < 0.01$). There was no significant difference in the content of MLOP and MSOP among experimental plots A, B, and C. The content of HSOP in plot C was lower than that in plots A and B (Table 5). The results indicated that corn-alfalfa intercropping could significantly reduce the content of LOP and HSOP, but the effects on MLOP and MSOP were not significant, which might be due to that intercropping patterns increased the diversity of plant species, promoted the complexity of soil microbial communities, accelerated the mineralization process of LOP, and converted it into inorganic phosphorus, thereby reducing LOP content. The decrease in soil pH could chelate metal ions such as iron and aluminum in the soil, reduce phosphorus fixation, and further promote the decomposition of LOP. MLOP and MSOP were in the intermediate stage of organic phosphorus decomposition. Although corn-alfalfa intercropping enhanced the overall microbial activity in the soil, it would not significantly change the ability to decompose intermediate organic phosphorus.

Table 5. Changes in organic phosphorus (mg/kg) in 10 – 20 cm soil layer.

Plot	A	B	C
LOP	10.3 ± 0.1**	9.5 ± 0.3**	7.2 ± 0.1
MLOP	35.7 ± 0.1	36.1 ± 0.3	36.3 ± 0.1
MSOP	15.7 ± 0.1	15.6 ± 0.3	15.9 ± 0.1
HSOP	28.6±0.1**	18.7±0.3**	26.3±0.1

Note: **: $P < 0.01$.

Analysis of plant phosphorus uptake

The phosphorus uptake of corn and alfalfa plants demonstrated that plot C was higher than plots A and B ($P < 0.01$). The phosphorus contents of corn and alfalfa plants in plot C were 18.9 ± 0.7 mg/kg and 14.8 ± 0.8mg/kg, respectively. The phosphorus content of corn in plot A was only 12.5 ± 0.8 mg/kg, and the phosphorus content of alfalfa in plot B was only 14.8 ± 0.8 mg/kg. The results suggested that corn-alfalfa intercropping could improve the phosphorus uptake efficiency of plants, which was fitted with the results of the soybean-corn intercropping experiment by Anyoni *et al*. [20]. The potential reason for this result was that the soil pH value decreased in the intercropping mode, which adapted to the growth of phosphorus solubilizing bacteria and other microorganisms, thereby accelerating the conversion of organic phosphorus to inorganic phosphorus and enhancing plant uptake of phosphorus.

Conclusion

Phosphorus is one of the important components in plants and exerts a meaningful function in their growth and development. This research explored the changes of phosphorus content in soil under corn monoculture, alfalfa monoculture, and corn-alfalfa intercropping and found that corn-alfalfa intercropping in experimental plot C improved soil pH and reduced soil salinity. The pH value at 0 – 10 cm soil layer was lower than that at 10 – 20 cm under this planting method. In experimental plot C, its moisture content exceeded that in experimental plots B and C ($P < 0.01$). The inorganic phosphorus content of the soil under three different modes showed that the inorganic phosphorus content in 0 – 10 cm soil layer was higher than that in 10 – 20 cm soil layer. In 0 – 10 cm soil layer, the water-soluble phosphorus, Al-P, and O-P in plot C exceeded that in plots A and B, while Ca-P was significantly lower than that in plots A and B ($P < 0.01$). Detected LOP and HSOP contents in 0 – 10 cm soil layer in plot C was lower than that in plots A and B ($P < 0.01$), while there was no significant difference in the contents of MLOP and MSOP organic phosphorus among the three experimental plots. The phosphorus uptake of corn and alfalfa in experimental plots A, B, C showed higher in plot C than plots A and B ($P < 0.01$). The results of this research suggested that corn-alfalfa intercropping reduced soil salinity and accelerated the conversion of organic phosphorus, and consequently enhanced plant uptake of soil phosphorus fractions. However, current research had only analyzed the changes in pH, moisture content, organic and inorganic phosphorus in soil within one year, without conducting long-term effect analysis. Future research should extend the study period to more accurately determine how corn-alfalfa intercropping affects the uptake of different soil phosphorus fractions.

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References

1. Bhattacharya S, Pandey M. 2024. Pcfrimds: Smart next-generation approach for precision crop and fertilizer recommendations using integrated multimodal data fusion for sustainable agriculture. IEEE T Consum Electr. 70(3):6250-6261.
2. Kumar S, Kumar M. 2025. Developing an XAI-based crop recommendation framework using soil nutrient profiles and historical crop yields. IEEE T Consum Electr. 3(5):1-2.
3. Sethi S, Lakhina U. 2024. Intelligent crop selection and soil nutrient management using machine learning. ICCICA. 1(4):459-464.
4. Xu Y, Smirnov M, Kohler MC, Dong Z, Amineh RK, Li F, *et al*. 2024. A survey of wireless soil sensing technologies. IEEE Access. 12(5):12010-12038.
5. Sharma R, Mishra V, Srivastava S. 2023. Enhancing crop yields through IoT-enabled precision agriculture. ICDT. 11(5):279-283.
6. Kumar R, Gupta S, Srivastava Y, Srivastava H. 2024. AI assisted plant disease detection, crop and fertilizer recommendation system. INCET. 24(6):1-6.
7. Mwawado R, Zennaro M, Nsenga J, Hanyurwimfura D. 2024. Optimizing soil-based crop recommendations with federated learning on raspberry Pi edge computing nodes. IOTSMS. 2(4):82-89.
8. Kulkarni A, Panda SK, Keerthana K. 2025. Soil nutrient prediction and crop recommendation system: Conventional to modern methods of soil NPK sensing. IITCEE. 16(7):1-5.
9. Souza LFN, Ciampitti IA, Fernandez JA. 2024. Maize-Brachiaria grass intercropping: A meta-analysis of major productivity drivers in Brazil. Field Crop Res. 306(4):109205-109214.
10. Khakbazan M, Liu K, Biswas D. 2025. Economic analysis of legume-based intercropping across Canadian Prairies. Can J Plant Sci. 105(1):1-13.
11. Rehman MZ, Islam SM, Ulhaq A, Blake D, Janjua N. 2024. Effective land use classification through hybrid transformer using remote sensing imagery. IEEE J-STARS. 18(5):2252-2268.
12. Saha G, Suvo SH, Tonmoy FT, Asad JB, Imran MT, Azad AA. 2024. Smart soil monitoring system with crop and fertilizer recommendation features. IEEE CSNT. 6(5):1190-1196.
13. Oh C. 2023. Exploring the way to harmonize sustainable development assessment methods. In: Article 6.2 Cooperative Approaches of the Paris Agreement. GLCE. 1(3):121-129.
14. Basak R, Wahid KA. 2023. Assessment of leaf phosphorus for multiple crop species using an electrical impedance spectroscopy sensor. IEEE SAS. 18(5):1-6.
15. Wu YM, Liu SY, Shi BY, Peng JY, Kao ZW, Chung HY, *et al*. 2024. Field study correlating nutrient absorption and transpiration in lettuce hydroponics using an IoT-interfaced solid-state ion sensor array. IEEE Sens Lett. 8(6):1-4.
16. Xu J, Lin J, Chen S. 2025. Application of the phosphomolybdate blue colorimetric method to the detection of alkaline phosphatase activity. J Anal Chem. 80(5):813-821.
17. Muhammad KUR, Saati-Santamaría Z, García-Fraile P. 2025. Intercropping of non-leguminous crops improves soil biochemistry and crop productivity: A meta-analysis. New Phytol. 246(3):961-971.
18. Fernandez MR, Lokuruge P, Abdellatif L. 2025. Cereal crop following organic intercrops and their respective monocultures in the semiarid Canadian Prairie. Agron J. 117(3):12-23.
19. Lal B, Sarkar S, Kumawat PK. 2024. Enhancement in fodder productivity and quality of feather *Pennisetum grass* by intercropping with groundnut. J Plant Nutr. 47(14):22-32.
20. Anyoni OG, Susan T, Joseph E. 2024. Effects of intercropping on maize and soybean yield performance, land equivalent ratio, and maize leaf area in conservation agriculture. J Agr Sci-Sri Lanka. 16(1):12-19.