

Original Research

Phosphorus Condition and Its Affecting Factors in Maize Fields of the Agro-Pastoral Ecotone in Northern Shaanxi

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Abstract

Phosphorus (P) and its availability frequently limit crop productivity in arid and semi-arid regions. However, the status of P accumulation and availability in the crucial agro-pastoral ecotone of northern Shaanxi remains poorly understood. To address this gap, we investigated soil P levels in typical maize croplands within this region to elucidate its current condition and identify key affecting factors. The results showed that while the soil total P was moderate (mean: 0.48 g kg⁻¹), the available P (Olsen P) was low (mean: 5.43 mg kg⁻¹), substantially below the threshold required for high-yield maize. A strong positive correlation was observed between soil organic matter (SOM) and P fractions, particularly with Olsen P. Furthermore, redundancy analysis confirmed that SOM was the most critical explanatory variable, accounting for 76.62% of the total variance in soil P. The currently low level of regional SOM, which is closely linked to soil pH, clay, and metal mineral content, indicates a significant potential for its improvement. In conclusion, the maize fields in this region possess a sufficient total P pool but are constrained by low P availability. Therefore, enhancing SOM, for instance, through manure application, is a crucial strategy to improve P availability for sustainable maize production.

Keywords: agro-pastoral ecotone, maize, phosphorus, fertigation, soil organic matter

Introduction

The agro-pastoral ecotone in northern Shaanxi is a critical ecological transition zone, functioning as both the natural interface between agricultural and pastoral landscapes and a vital ecological barrier. This barrier

is crucial for mitigating southward sand encroachment, preserving the ecological integrity of the Loess Plateau, and providing food and livestock products for the population [1, 2]. However, this region simultaneously exhibits pronounced ecological fragility, rendering it a representative area with heightened environmental sensitivity [3]. Maize is one of China's most important grain crops [4]. In this region, it functions as both the principal food crop and primary feed source, thereby playing a critical role in regional food security

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and the sustainable development of the local livestock industry [5]. Nonetheless, constrained by semi-arid climatic conditions, local maize cultivation predominantly relies on natural precipitation, thereby confronting severe challenges stemming from water resource supply-demand imbalances [6, 7]. Additionally, the generally low soil fertility in the area represents a critical limiting factor for improving maize productivity.

Phosphorus (P) is a macronutrient for crop growth and development. However, soil exhibits strong P fixation capacity, resulting in the rapid turnover of labile P within seconds to minutes [8]. Consequently, ensuring a supply of available P for growing crops often necessitates continuous P fertilizer supplementation in agricultural production [9, 10]. Nevertheless, the P fertilizers currently used in agricultural production are primarily derived from non-renewable phosphate rock resources, the increasingly severe depletion of which poses a significant challenge to the sustainable development of global agriculture [11, 12]. Therefore, a thorough understanding of soil P level status and its influencing factors is crucial for increasing maize yield and ensuring sustainable P management in the agro-pastoral ecotone.

Soil properties exert a decisive influence on P accumulation and transformation. This is typically manifested as pH-dependent P fixation, which is significantly enhanced under both acidic and alkaline conditions [13, 14]. SOM usually exhibits positive effects on P adsorption capacity and its long-term availability [15-17]. Regarding water availability, the biological turnover rate of the soil P pool is generally slow in arid regions [8]. Both global-scale data and a ^{32}P -labeling study in representative Chinese soils (Haplic Alisols, Phaeozems, and Aquents) reveal that strong soil P-fixation immobilizes over 60% of applied inorganic P fertilizer, with a minimal fraction remaining as labile P [18, 19]. Anthropogenic factors also significantly impact soil P condition. Gridded dataset indicates that P fertilizer application rates are concentrated and high per season in traditional agricultural areas, whereas application rates are comparatively lower in agro-pastoral ecotones [20]. Regarding fertilization strategies, the traditional broadcast application practice is progressively being replaced, especially in arid and semi-arid regions, where fertigation technology, by optimizing synergistic water and nutrient utilization, has significantly enhanced P availability and use efficiency [21, 22]. The northern agro-pastoral ecotone of Shaanxi is dominated by Calcareous Cambisols, Chernozems, and Calcisols, which develop under semi-arid conditions and are typically characterized by a high pH and low SOM content. Theoretically, these environmental characteristics collectively promote strong P fixation, reduce P mobility, and present significant challenges for P uptake, particularly under water stress, thereby often limiting the efficacy of conventional P fertilizer management. Furthermore, comprehensive surveys and

assessments of P condition in farmlands within this ecotone are rarely reported. Consequently, the farmland P condition in this region remains largely unknown, warranting further in-depth investigation.

This study was conducted in Dingbian County, a representative region within the agro-pastoral ecotone in northern Shaanxi. Maize (corn) serves not only as a crucial food crop but also as an excellent silage feed, with its cultivated area exceeding 100,000 ha⁻¹ in the region [23], making a significant contribution to regional agricultural development. However, the soils in this region experienced severe degradation in the past due to energy development and exacerbated drought [24]. In recent years, the regional soil environment has significantly improved, driven by increasing national emphasis on land protection and the implementation of land remediation measures [25]. Despite these improvements, given the generally strong P-fixing capacity of soils in this region, the current soil P condition urgently requires a comprehensive regional assessment. Therefore, maize fields in this region were selected as the study object. Using systematic point sampling and analysis, we comprehensively investigated: (1) the levels and availability of soil P in maize farmland, and (2) its relationships with soil properties, fertilization management practices, and other influencing factors. The findings are expected to provide a scientific basis for optimizing P fertilizer management strategies and enhancing soil P supply capacity in the agro-pastoral ecotone.

Materials and Methods

Overview of Study Region

Our in situ regional survey and soil sampling were conducted in Dingbian County (36°49'-37°53'N, 107°15'-108°22'E), located in the northwest of Shaanxi Province, China (Fig. 1). The region is characterized by a temperate semi-arid continental monsoon climate, with an annual average temperature of 9.3°C and an annual average precipitation of 346.9 mm. The total cultivated land area is approximately 260,000 ha⁻¹. According to the World Reference Base for Soil Resources (WRB), the predominant soil types include Calcareous Cambisols, Chernozems, and Calcisols.

Soil Sampling and Analyses

In October 2025, a total of 100 sampling points were established in maize fields within Dingbian County (Fig. 1). At each sampling point, altitude, fertilization regimes, and straw return practices were thoroughly investigated and recorded through a structured questionnaire survey with the local farmers at each site. From the vicinity of each sampling point, five soil subsamples (0-20 cm) were collected and thoroughly mixed to form a composite sample. These samples were

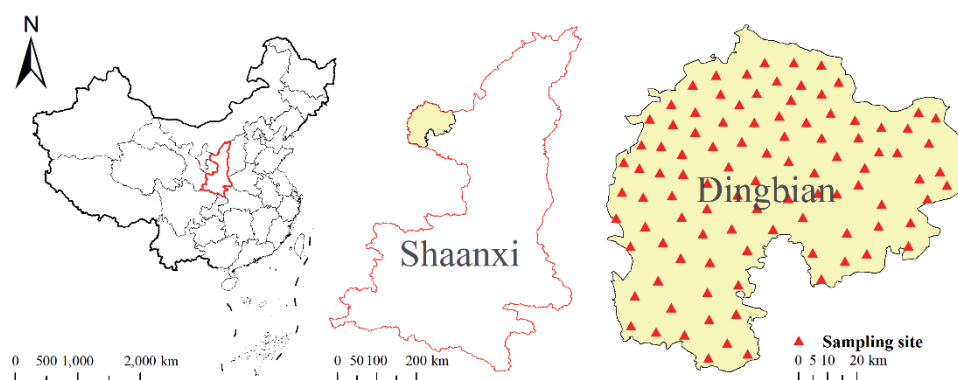


Fig. 1. Location of Dingbian County and soil sampling sites.

then transported to the laboratory, where plant debris, stones, and other impurities were carefully removed. Following air-drying, the samples were sieved through 2 mm and 0.5 mm screens, respectively.

Soil properties that potentially influence soil P were determined according to standard methods [26]. Specifically, soil organic matter (SOM) was determined by the external heating- $K_2Cr_2O_7$ oxidation-titration method. Total phosphorus (Total P) was determined by the NaOH melting-molybdenum blue colorimetric method. Olsen P was determined by the 0.5 M $NaHCO_3$ extraction-molybdenum blue colorimetric method. The P activation coefficient (PAC) is the ratio of Olsen P to total P. Soil pH was determined using the potentiometric method at a 1:2.5 soil-to-water (w/v) ratio. Exchangeable calcium (Ca_{Ex}), magnesium (Mg_{Ex}), and available manganese (Mn) were determined by ammonium acetate extraction followed by ICP-OES (Varian 715-ES). Clay content was determined by the hydrometer method.

Statistical Analyses

Descriptive statistical analyses of total P, Olsen P, and PAC were performed using SPSS Ver 23 (IBM Corp., Armonk, NY, USA). Regression analysis between SOM and P (total P, Olsen P, and PAC), as well as correlation heatmap analysis of the relationships between P and environmental variables and the inter-correlations among environmental factors, were conducted in Origin Ver 2025 (OriginLab Corporation, Northampton, MA, USA). In the R software (Ver 4.5.2) environment (R Core Team, 2025), redundancy analysis (RDA) was implemented via the vegan package to explore the associations between P and environmental variables under different fertilization regimes. The rdacca.hp package [27] was used to quantify the individual contributions of environmental variables to P variation, and the randomForest package was employed to evaluate the importance of environmental variables in driving SOM variation.

Results

Fertilization Management

The statistical results show that within the study area, 69% of maize fields used broadcast fertilization, 17% adopted fertigation, and 14% employed other fertilization methods, primarily including hole application and furrow application (Fig. 2a)). At the surveyed sites, the straw return coverage reached 100%. High-stubble retention was the most prevalent method, implemented across 58% of the area. This was followed by straw shredding and incorporation (36%), while mulching constituted the remaining 6% (Fig. 2b)).

Soil P Condition

The soil P condition in maize fields within the agro-pastoral ecotone in northern Shaanxi is summarized in Table 1. The total P content ranged from 0.21 to 0.81 $g\ kg^{-1}$, with a mean of 0.48 $g\ kg^{-1}$. The median value of total P in the surveyed soil samples was 0.50 $g\ kg^{-1}$, exhibiting a relatively low coefficient of variation (CV) of 0.27. The Olsen P content ranged from 1.51 to 12.00 $mg\ kg^{-1}$, averaging 5.43 $mg\ kg^{-1}$. The PAC ranged from 0.49 to 3.77%, with a mean of 1.20%, and showed a higher CV of 0.44.

When grouped by fertilization method, the results showed no significant differences in soil P condition among the treatments (Fig. 3(a-c)). However, it was observed that the mean total P content under fertigation was lower than that under broadcast (Fig. 3a)), while the mean Olsen P content was comparable between the two methods (Fig. 3b)). Consequently, the PAC was slightly higher for fertigation than for broadcast (Fig. 3c)).

Linkage of Soil P and Soil Properties

Significant positive correlations were found between SOM content and total P, Olsen P, and PAC through linear regression analysis (Fig. 4(a-c)). According to the regression slopes, each 1 $g\ kg^{-1}$ increment in SOM

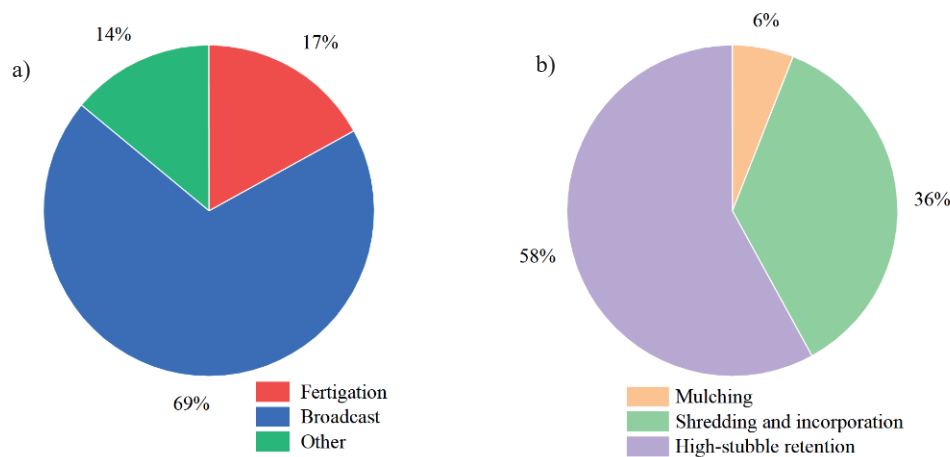


Fig. 2. a) Proportion of different fertilization regimes and b) straw return practices in maize fields of the agro-pastoral ecotone in northern Shaanxi (n = 100).

Table 1 Descriptive statistics of soil P in maize fields of the agro-pastoral ecotone in northern Shaanxi (n = 100).

Parameter	Min	Max	Mean	Median	CV
Total P	0.21 g kg ⁻¹	0.81 g kg ⁻¹	0.48 g kg ⁻¹	0.50 g kg ⁻¹	0.27
Olsen P	1.51 mg kg ⁻¹	12.00 mg kg ⁻¹	5.43 mg kg ⁻¹	5.08 mg kg ⁻¹	0.36
PAC	0.49%	3.77%	1.20%	1.16%	0.44

Note: PAC, P activation coefficient; CV, coefficient of variation.

corresponded to an increase of 0.018 g kg⁻¹ in TP (Fig. 4a)), 0.52 mg kg⁻¹ in Olsen P (Fig. 4b)), and 0.071% in PAC (Fig. 4c)). Notably, Olsen P exhibited the strongest positive linear correlation with SOM ($R^2 = 0.50$), underscoring the critical role of SOM as a predictor of phosphorus availability (Fig. 4b)).

Correlation analysis revealed that both total P and Olsen P were significantly negatively correlated with pH, but significantly positively correlated with Mn

(Fig. 5a)). Additionally, TP showed a positive correlation with altitude (Fig. 5a)). The RDA indicated that the first two axes (RDA1 and RDA2) collectively explained 72.55% of the total variation in P condition (total P, Olsen P, and PAC) (Fig. 5b)). Furthermore, hierarchical partitioning showed that SOM, pH, Mn, and altitude individually explained 76.62%, 11.13%, 10.89%, and 1.36% of the variation, respectively (Fig. 5c)).

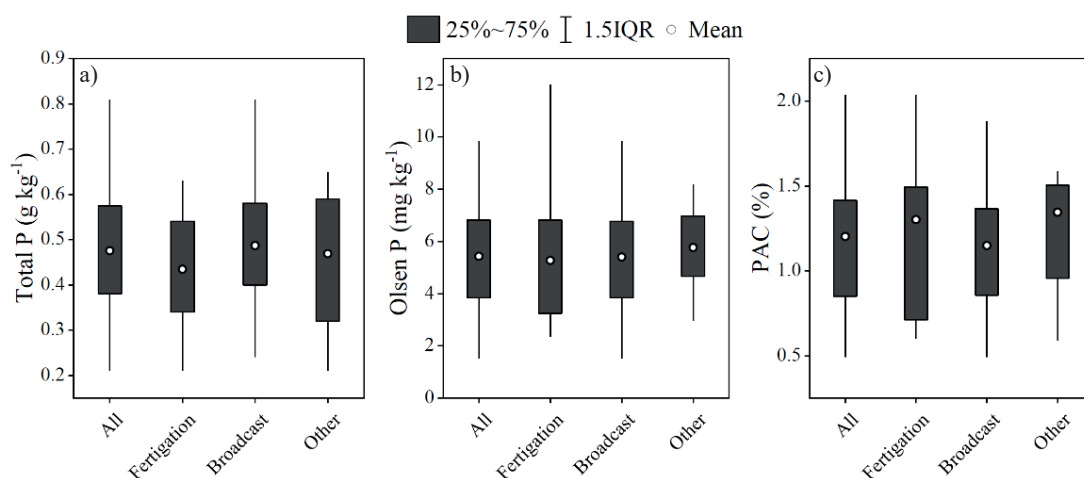


Fig. 3. Contents of a) total P and b) Olsen P, and c) P activation coefficient (PAC) under fertilization practices including overall (fertilization + broadcast + other approaches, n = 100), fertilization (n = 17), broadcast (n = 69), and other approaches (n = 14) in maize fields of the agro-pastoral ecotone in Northern Shaanxi.

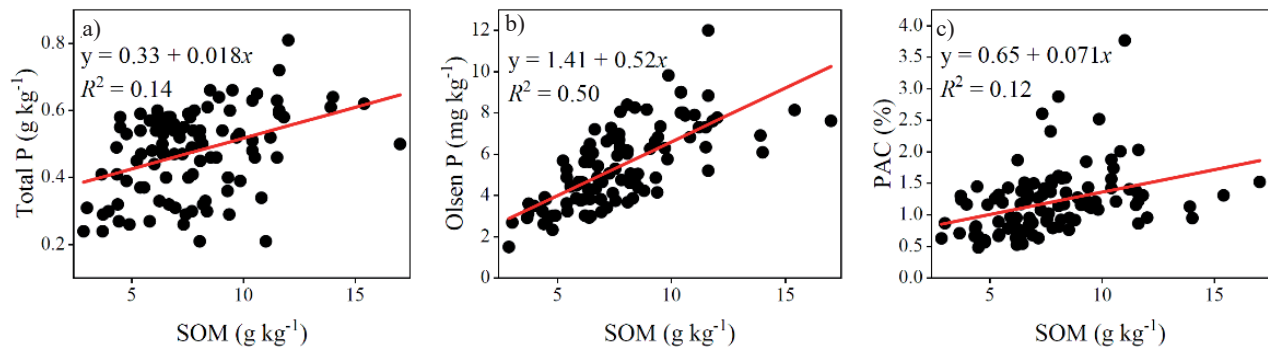


Fig. 4. Relationship between a) total P, b) Olsen P, c) P activation coefficient (PAC), and soil organic matter (SOM) in maize fields of the agro-pastoral ecotone in northern Shaanxi ($n = 100$).

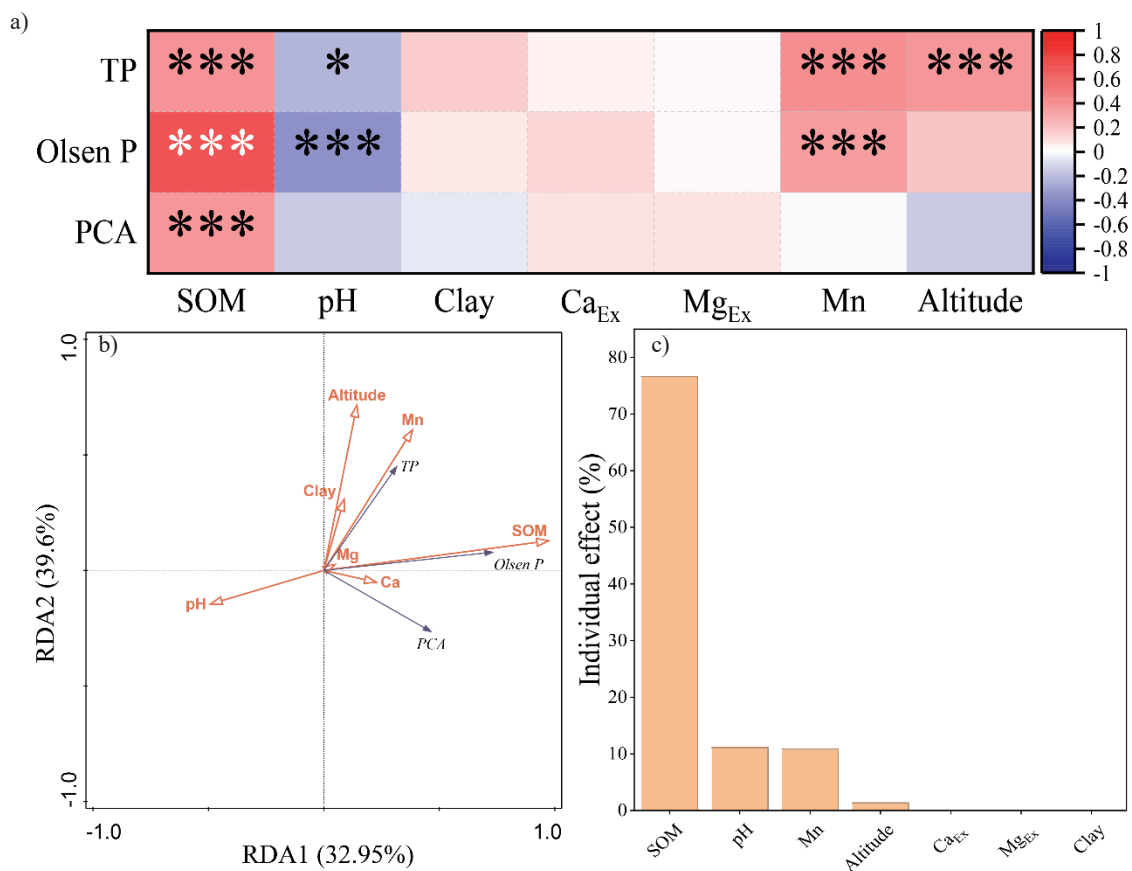


Fig. 5. Relationship between soil P condition and environmental variables using a) correlation analysis, b) redundancy analysis (RDA), and c) the hierarchical partitioning of RDA ($n = 100$). PAC, P activation coefficient; SOM, soil organic matter; Ca_{ex} and Mg_{ex}, exchangeable Ca and Mg ions; Mn, available Mn. *, ** and ***, $p < 0.05$, $p < 0.01$ and $p < 0.001$.

Affecting Factors of SOM

Soil organic matter (SOM) exhibited significant positive correlations with Clay, Ca_{ex}, and Mn, and a significant negative correlation with pH (Fig. 6a)). A Random Forest model further identified pH, Clay, and Mn as key predictors of SOM, with their relative contributions to SOM variation being 14.2%, 9.44%, and 8.04%, respectively (Fig. 6b)).

Discussion

P Limitation in Maize Fields of the Agro-Pastoral Ecotone

Soil total P serves as a critical indicator for evaluating the reserve pool of plant-available P and its long-term supply potential [28, 29]. In contrast, Olsen P (available P) represents the immediate plant-

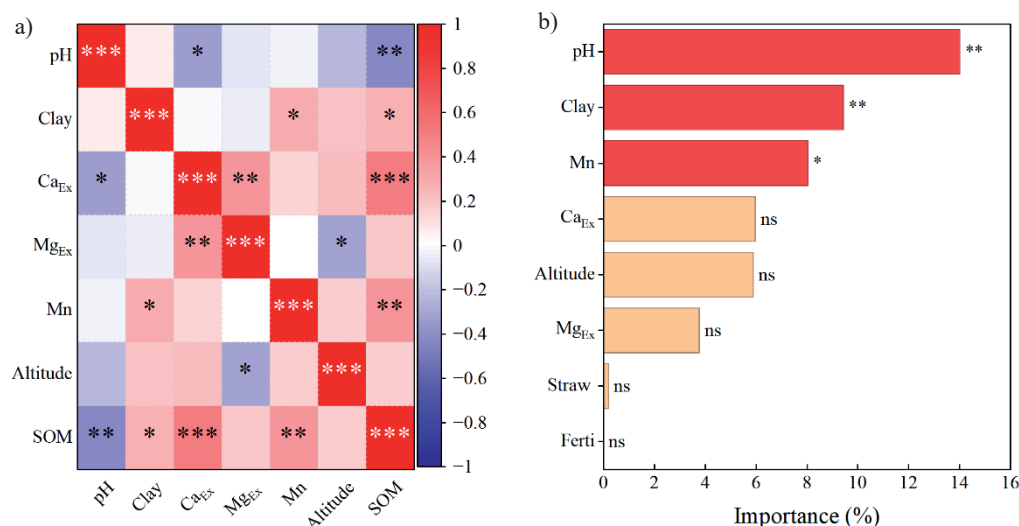


Fig. 6. a) Pairwise correlation between environmental variables and b) the relative importance of properties selected by the Random Forest model to explain the variation of SOM ($n = 100$). SOM, soil organic matter; Ca_{Ex} and Mg_{Ex}, exchangeable Ca and Mg ions; Mn, available Mn. Straw, Straw return practices; Ferti, Fertilization regimes. *, ** and ***, $p < 0.05$, $p < 0.01$ and $p < 0.001$.

absorbable P fraction for the current growing season, directly reflecting the supplying capacity of soil P. The mean total P content in maize fields of the agro-pastoral ecotone in northern Shaanxi was 0.48 g kg^{-1} (Table 1). For comparison, previous soil sampling analyses have reported that total P content in most farmlands of China's major grain-producing Northeast region typically ranges from 0.4 to 0.6 g kg^{-1} , whereas in the Southern region, total P predominantly falls between 0.2 and 0.4 g kg^{-1} [30]. Based on these comparisons, the soil total P in the current study area is considered to be at a moderate level.

Our analysis revealed a mean Olsen P content of 5.43 mg kg^{-1} within the study area, with even the maximum observed value reaching only 12.00 mg kg^{-1} (Table 1). A significant proportion (75%) of the surveyed sites displayed Olsen P levels below 8 mg kg^{-1} (Fig. 3b). Given that maize is a high-yielding crop, its optimal growth demands a substantial uptake of essential nutrient elements, including P. Compared to these observed levels, previous studies suggest a considerably higher agronomic threshold for Olsen P, ranging from 8.3 to 59.9 mg kg^{-1} across various soil types, for achieving maximum maize yields [31-33]. Moreover, even under conditions of enhanced P mobilization via scientific management and microbial regulation, Olsen P levels of at least 15 mg kg^{-1} are typically recommended [34]. These findings collectively provide strong evidence for pervasive P limitation (Olsen P) for maize across the agro-pastoral ecotone in Northern Shaanxi. This low soil P availability was further substantiated by the remarkably low average P activation coefficient (PAC) of merely 1.2% (Table 1), which represents the ratio of Olsen P to total P.

The observed P limitation could be attributed to several interacting factors: (i) Fragmented topography:

This geographical feature significantly impedes the effective implementation of precision nutrient management and scientific fertilization practices. Research data from field surveys revealed that most sites relied on traditional broadcast at 69%, with the adoption of fertigation remaining critically low at only 17% (Fig. 2). (ii) Aeolian erosion: These processes lead to topsoil stripping and consequent loss of essential nutrients, including P [35, 36]. (iii) Elevated soil pH (ranging from 8.03 to 9.47): The high alkalinity prevalent in these soils promotes the robust fixation of P by Ca ions, thereby substantially curtailing its bioavailability for plant uptake [13].

Affecting Factors of P Condition in Maize Fields of the Agro-Pastoral Ecotone

Grouped analysis results showed that no significant differences in soil P conditions (total P, Olsen P, and PAC) were observed under different fertilization regimes (Fig. 3(a-c)). This is likely because severe pedoclimatic constraints such as arid conditions and high P-fixation capacity mask the impact of fertilization regimes on soil P. Nevertheless, it is widely reported that fertigation (water-fertilizer integration) significantly enhances maize yield in arid/semi-arid agroecosystems [37, 38], indicating an increased P acquisition by crops from the soil. Our findings faintly corroborate this perspective: while the mean total P under fertigation treatment was marginally lower than broadcast application, the mean PAC was slightly higher (Fig. 3(a-c)). This subtle yet important difference suggests that fertigation effectively enhances soil P availability, even without significant increases in the total P pool. This is likely because fertigation facilitates a more concentrated delivery of available P to the vicinity of crop roots, enhances the

activity of phosphatase, promotes the synergistic supply of water and P [39-41].

Our findings demonstrate that SOM exhibited a significant positive correlation with total P, Olsen P, and PAC (Fig. 4(a-c)), highlighting SOM as a primary driver explaining P variations (Fig. 5c)). These observations are consistent with previous reports. For example, a strong spatial distribution similarity between SOM and P was observed in a clayey Oxisol under long-term broadcast P fertilizer application [42]. Similarly, in a long-term fertilized black soil, SOM showed a significant positive correlation with most P fractions [43]. While not further analyzed, the low SOM content in our study area, coupled with its association with clay, Ca_{ex} , and Mn (Fig. 6a) and b)), indirectly suggests that this SOM is likely mineral-associated organic matter. This type of SOM is intimately linked with P dynamics, as SOM containing P is more readily stored in the soil due to the strong mineral affinity of phosphate [44, 45]. Furthermore, SOM can enhance or maintain P availability through mechanisms such as competing for adsorption sites, hindering P migration into micropores, and delaying the conversion of labile P to stable forms [17, 46, 47]. These mechanisms likely explain the observed stronger correlation between SOM and Olsen P (Fig. 4b)).

Soil pH was found to be significantly negatively correlated with Olsen P content (Fig. 5a)). This phenomenon is primarily attributed to abundant soil Ca, present as both free ions and their associated compounds, which bind with or occlude phosphate under elevated pH conditions, consequently reducing P availability [13, 48]. A positive correlation was observed between altitude and total P content (Fig. 5a)). This phenomenon can be attributed to the general trend of lower temperatures at higher altitudes, which consequently suppresses microbial activity. The resulting decrease in microbial P turnover may then contribute to the accumulation of total P. Interestingly, available Mn correlated positively with both total P and Olsen P (Fig. 5a)). It is important to note that Mn's significant influence on P dynamics is typically observed under acidic conditions [49]. In this study, a significant positive correlation was observed between Mn and SOM (Fig. 6a)), suggesting its potential involvement in SOM storage. This finding is consistent with previous research that highlights Mn's important role in SOM preservation, particularly in northern forest ecosystems [50]. Consequently, Mn likely exerts a positive influence on P accumulation and availability via its association with SOM.

Limitations and Implications

Our study revealed a widespread P (Olsen P) limitation in maize fields across the agro-pastoral ecotone of Northern Shaanxi. Nevertheless, the precise quantitative assessment of its limiting effect on crop yield requires further evaluation, as maize yield data were not tracked in this study. Although research

consistently demonstrates that fertigation can effectively enhance P efficiency, its widespread adoption and comprehensive promotion in this specific region face substantial challenges, primarily stemming from water scarcity and high initial investment costs. Coupled with the generally low existing SOM content and considering the still-present organic matter adsorption potential of soil clay, Ca_{ex} , and Mn, the application of organic fertilizers (manure) to elevate SOM content is thus proposed as a highly recommended strategy for future soil P management in this study area. This approach is expected to effectively augment the total P reservoir and concurrently enhance P availability [46, 47]. Beyond its direct impact on P, increasing SOM also contributes to improving soil water and nutrient retention capacity, fostering the formation of soil aggregates, and ultimately enhancing overall soil health [51, 52]. Concurrently, the associated carbon sequestration effect of SOM can make a positive contribution to mitigating climate change [53]. Therefore, future research should investigate optimal organic fertilizer (manure) application methods, types, and dosages, and systematically evaluate their long-term impacts on both soil P pools and P availability.

Conclusions

Based on comprehensive field investigations and detailed soil chemical analyses, our study revealed that in the agro-pastoral ecotone of Dingbian County, the soil total P is at a moderate level compared to other major grain-producing regions in China. However, the supply of available P (Olsen P) was severely deficient, with a mean value of only 5.43 mg kg^{-1} (ranging from 1.51 to 12.00 mg kg^{-1}), constituting a primary constraint on maize productivity. Although current agronomic practices, such as fertigation, adopted by approximately 17% of farmers, provided a slight improvement in P availability, the overall impact was limited. Our analysis further confirmed that SOM is a key driver influencing both P accumulation and availability, exhibiting a significant positive relationship. Therefore, in light of the regional water scarcity and low intrinsic SOM levels, we propose that improving soil fertility by increasing SOM content should be a core future management strategy. This strategy is expected to have a positive long-term impact on soil health and P supply potential, thereby laying the foundation for ensuring and increasing maize yield.

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AI Usage Disclosure Statement

During the preparation of this manuscript, the authors used Gemini 2.5 Pro (OpenAI, 2025) for language editing and grammar checking. The authors have thoroughly reviewed and verified all content generated by the AI tool and take full responsibility for the accuracy and integrity of the final manuscript. No AI tools were used for data generation, data analysis, or content creation.

Conflict of Interest

The authors declare no conflict of interest.

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