

Research paper

Effects of four soil types on growth responses and nutrient stoichiometry in *Phellodendron chinense* seedlings

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Ren, H., He, M., Qian, W., Li, J., Guo, Z., Zhuang, G., Gao, S. 2023. Effects of four soil types on growth responses and nutrient stoichiometry in *Phellodendron chinense* seedlings. – Forestry Studies | Metsanduslikud Uurimused 79, 105–119, ISSN 1406-9954. Journal homepage: <http://mi.emu.ee/forestry.studies>

Abstract. *Phellodendron chinense* is an extraordinary medicinal plant, and its stem bark is a famous traditional Chinese medicine in China, containing a number of phytochemicals with biological and pharmacological functions. Studies have shown that the medicinal ingredients in *P. chinense* from various regions are different, as soil types might be important factors affecting the growth and quality of *P. chinense*. In this study, the effects of acidic purple soil, alkaline purple soil, yellow soil and red soil on the growth, nutrient element accumulation and partitioning in *P. chinense* seedlings were studied. Our results showed that the biomass of leaves and stems in acidic purple soil was significantly higher than in other soils, and the root biomass was significantly lower than that in yellow soil. C, N, P and Ca contents cultured in acidic purple soil were the highest compared to other soils, and K and Mg content were the highest in yellow soil and red soil, respectively. The distribution of carbon between different organs can reflect environmental stress. N has become a limiting factor for the growth and development of *P. chinense* seedlings. C:N and C:P ratios in the leaves were significantly lower than those in the stem and roots. Among four soil types, the highest N:P ratio was 1.65 in *P. chinense* seedlings. These results suggest that four soil types may significantly affect the accumulation and distribution of biomass and nutrient elements in *P. chinense* seedlings. The characteristic patterns in different organs have different responses. Acidic purple soil is more suitable for the growth of *P. chinense*. These findings will help to understand the distribution characteristics and requirements of nutrient elements in *P. chinense* seedlings, and further provide a theoretical basis and reference for site selection and cultivation strategy.

Key words: soil type, traditional medicinal plant, plant development, nutrient distribution and accumulation.

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Introduction

Soil is the foundation and medium for plant growth, providing water and nutrients for plants to survive, and plays an extremely important role in plant growth and development (Li *et al.*, 2021; Wang *et al.*, 2023a). Different soil types have different physical and chemical properties due to their different texture, structure, and nutrient content (Yu *et al.*, 2019). The type of soil environment determines the accumulation and distribution of plant biomass (Yang *et al.*, 2020). Different nutrient supply in soil affects the uptake and transportation of nutrients in plants, resulting in different morphological, growth, and metabolic characteristics of plants (Zhi *et al.*, 2022). During growth and development, plants in different soils have significant differences between nutrient requirements. In plants, the relationship between size, biomass and function often depends on the distribution of metabolically active and/or structural tissues as well as their stoichiometric components (Minden & Kleyer, 2014). Carbon (C), nitrogen (N), phosphorus (P), potassium (K), calcium (Ca) and magnesium (Mg), etc., are important macroelements and microelements for the growth, development and metabolism of plants. The C:N:P ratio in various organs of plants varies depending on their different functions, and organs with an active metabolism require more N and P than structural organs (Minden & Kleyer, 2014). Plants undergo different physiological and biochemical reactions under different environmental conditions, regulating the metabolism and circulation of C, N, and P, with a different content and distribution, ultimately exhibiting specific element eco-stoichiometric characteristics (Güsewell, 2004; Sardans & Peñuelas, 2012; Minden & Kleyer, 2014). Thus, a complete description of the allocation of nutrients in different plant tissues is critical for explaining plant functional diversity. In addition, plants also regulate their ability to uptake and redistribute nutrient elements' com-

position and chemometrics in response to these external environments, and further maintain normal growth and development (Sardans & Peñuelas, 2012).

Plant stoichiometry has focused on the relationships between different nutrients and how this balance is affected by the abiotic and biotic environment. During the growth and development of plants, C provides a structural basis and constitutes a relatively stable 50% of plant dry matter (Ågren, 2008). N and P are the driving elements of plant stoichiometric relationships, and other elements are scaled relative to them (Ågren & Weih, 2020). C:N and C:P represent the utilization efficiency of nitrogen and phosphorus in plants, the response to C fixation and nitrogen assimilation, and the balance between C fixation and phosphorus assimilation, respectively. The changes in C:N and C:P ratios with growth reflect the dynamic response of plants to changes in N and P utilization efficiency at different growth stages, and correspond to plant ontogeny patterns (Li *et al.*, 2017). The N:P ratio represents the photosynthetic carbon fixation capacity of plants under N or P accumulation conditions. It is as an indicator for studying nutrient constraints in adverse environments. A ratio of <10 indicates N limitation, and a ratio of >20 indicates P limitation (Güsewell, 2004; Li *et al.*, 2017). So far, the focus of plant stoichiometry has mainly been on the three elements – C, N, and P – but many additional elements like K, Ca, Mg, etc., are essential for proper plant growth. The stoichiometric flexibility of plants reflects their physiological ability to accumulate and store elements that exceed their immediate needs, adjust distribution to synthesize more C or eutrophic compounds, and change growth patterns to defend, store, and structure tissues (Sistla & Schimel, 2012). The stoichiometric ratio can affect the nutrient conservation strategies of plants, thereby extending the retention time of nutrients in the plant body, and helping to reduce the dependence of

plants on soil nutrients (Huang *et al.*, 2018).

The active components of medicinal plants are mostly secondary metabolites, and their accumulation in plants is largely directly or indirectly affected by the growth environment, such as climate, soil, and other factors (Ågren & Weih, 2012). Due to differences in physical and chemical properties, different soil types have a significant impact on the nutritional status and pharmacodynamic components of medicinal plants at different growth stages. There are certain differences in the content of chemical components in some medicinal plants from different production areas, such as *Actaea cimicifuga* L., *Gynura japonica* (Thunb.) Juel, *Commelina communis* L. and *Phellodendron amurense* Rupr. Differences in soil factors can lead to significant changes in the content of various chemical components of *Phellodendron chinense* C. K. Schneid. (*P. chinense*) (Xu *et al.*, 2014). Studies have shown that appropriately increasing nitrogen and phosphorus contents in the environment and adjusting their reasonable proportion can promote the growth and development of medicinal plants, and increase biomass and the content of effective components, thus further improving medicinal values (Naeem *et al.*, 2009). Therefore, the influence of different soil types on the growth and nutritional status in medicinal plants is of great significance for understanding the changes of effective component contents.

P. chinense is widely used as traditional medicinal material in China. Its roots, stems and leaves contain many active ingredients, such as alkaloids, flavonoids, and sterols. These compounds have anti-pyretic, detoxifying, analgesic, anti-inflammatory, anti-tumor, and hypoglycemic effects, and are widely used in the treatment of diseases, such as dysentery, tetanus, and joint disorders (Yan *et al.*, 2016; Yang *et al.*, 2019). As an antiviral medicinal raw material, *P. chinense* is commonly used as a traditional Chinese medicinal material and an important pharmaceutical industry raw

material and export commodity, with a high demand for it in the market. In south-west China, this plant is widely planted in a variety of soil types, such as yellow soil, purple soil, red soil, alluvial soil, etc. The differences in the content of eight components of *P. chinense* from six different production areas are mainly reflected in the differences in protein, sugars, lipids, alkaloids, phellosterols, phellolactone, phellodendrone, and phellonic acid (Yuan *et al.*, 2011). Although *P. chinense* can adapt to different soil types, its different geographical sources lead to significant differences in its alkaloid content, which varies greatly (Yang *et al.*, 2019; Wang *et al.*, 2023b). This may largely depend on the general heterogeneity of soil types, which may affect plant growth, nutrient uptake, and utilization efficiency, and further affect the synthesis and accumulation of secondary metabolites in this plant. The objective of this study was to evaluate the effects of yellow soil, red soil, alkaline purple soil, and acidic purple soil on the biomass and nutrient uptake of *P. chinense* seedlings in a pot experiment.

Materials and Methods

Plant materials and soil

P. chinense seeds were purchased in Baoping County, Ya'an City, China, and stored in labeled seed mesh bags for use. Red soil, yellow soil, acidic purple soil and alkaline purple soil are the main distributed soil types in Sichuan, China, and were used for culture seedling. Acidic purple soil was collected at Boss Mountain, District Yu-cheng, Yaan, China (N29°58' E102°58', altitude 578 m). Alkaline purple soil was collected at Town Ji-feng, County Zhong-jiang, Deyang, China (N31°03' E104°68', altitude 900 m). Yellow soil was collected at Village Bai-sheng, Town Bao-lin, Qionglai, China (N 30°21' E103°30', altitude 552 m). Red soil was collected at Village Sanxing, Town Feng-le, County Shi-mian,

Yaan, China (N29°32' E102°54', altitude 878 m). The soil was air-dried, ground, debris removed, screened and mixed, and then the basic physical and chemical properties were analyzed and shown in Table 1.

Seed germination and seedling culture

P. chinense plants were raised in a greenhouse located in the No. 5 teaching building of Sichuan Agricultural University, Wenjiang district, Chengdu, China. The *P. chinense* seeds were selected, soaked in 1% potassium permanganate and then sown in 40 °C hot water for 24 h to sterilize and accelerate germination. These seeds were planted in 10 kg soil pots (28 cm × 21 cm). The experiment adopted a split-plot randomized design of the experiment (Figure 1). After seed germination, only 1 seedling per pot was maintained. A total of 36 pots for four soil type treatment were established based on a random block design (4 treatments × 9 replicates). Throughout the cultivation process, the soil was maintained at a moderate level of moisture, and a consistent regimen of weeding, insect control, and disease prevention measures were implemented.



Figure 1. Growth of *P. chinense* seedlings in four soil types.

Sample collection and nutrient element analysis

After 3 months of culture, six seedlings with consistent height were randomly selected and divided into roots, stems and

leaves. After cleaning with deionized water, the samples were put into an oven at 105 °C for 30 min, and then adjusted to 65 °C for drying to constant weight. Then the dry matter of each organ was weighed. The dried roots, stems and leaves were crushed and screened by a multifunctional sample grinder (FW80). These samples were analyzed to determine the C, N, P, K, Ca, and Mg contents. The C contents were determined by potassium dichromate oxidation and an external heating method. The measured liquid of N, P, K, Ca, Mg was prepared by a thick H₂SO₄-HClO₄. N content was determined using the semimicro-Kjeldahl method and P content was determined by the Mo-Sb colorimetric method (Hu *et al.*, 2019). K, Ca and Mg contents were determined by atomic absorption spectrophotometry.

Statistical analysis

Statistics analysis was calculated using Excel for the mean and standard deviation of biomass, element content and their total content and stoichiometric ratios. The analysis of correlation between biomass, element content and stoichiometric ratio and binary analysis of variance of C, N, P, K and their C, N, P ratio of the soil type and organs as well as their interaction were performed by SPSS 20.0. Further tests for differential significance of soil data from different organs and soils between treatments were performed by one-way ANOVA of variance and the Tukey method ($\alpha=0.05$) (Zhi *et al.*, 2022). Table and plots were finally made using Excel and Origin.

Results

Effects of four soil types on biomass

Soil types, plant organs, and their interactions had significant effects on biomass distribution (Table 2, $P<0.001$). The biomass cultured in acidic purple soil was the highest (12.86 ± 1.75 g), and its values were higher than those in yellow soil (12.80

Table 1. Basic physical and chemical properties of four soil types (means $\pm$ SE, $n = 3$).

Soil type	pH	Organic matter (g·kg ⁻¹)	Bulk density (g·cm ⁻³)	Total nitrogen (g·kg ⁻¹)	Total phosphorus (g·kg ⁻¹)	Total potassium (g·kg ⁻¹)
YS	4.79 ^B $\pm$ 0.12	33.50 ^A $\pm$ 0.64	1.32 ^A $\pm$ 0.07	1.89 ^A $\pm$ 0.11	0.08 ^C $\pm$ 0.00	2.21 ^B $\pm$ 0.09
ACS	5.12 ^A $\pm$ 0.14	35.51 ^A $\pm$ 0.74	1.29 ^A $\pm$ 0.04	1.67 ^A $\pm$ 0.09	0.83 ^A $\pm$ 0.03	2.49 ^B $\pm$ 0.06
RS	5.14 ^A $\pm$ 0.16	16.64 ^C $\pm$ 0.66	1.30 ^A $\pm$ 0.06	1.14 ^B $\pm$ 0.07	0.07 ^C $\pm$ 0.00	3.15 ^A $\pm$ 0.08
ALS	8.67 ^A $\pm$ 0.23	20.99 ^B $\pm$ 0.91	1.25 ^B $\pm$ 0.08	1.65 ^A $\pm$ 0.15	0.30 ^B $\pm$ 0.01	3.56 ^A $\pm$ 0.10

Values followed by the same letter in the same column are not significantly different according to Tukey's test ($\alpha = 0.05$).

Table 2. Two-dimensional variance analysis of effects of soil types, organs and their interactions on biomass, nutrient element, C:N, C:P, and N:P ratios.

Factor	Biomass	C	N	P	K	Ca	Mg	C:N	C:P	N:P
Soil types	***	***	***	***	***	***	***	***	***	***
Organ	***	ns	***	***	***	***	***	***	***	***
Soil types* Organ	***	**	***	***	***	***	***	***	***	***

Note: ns, *, ** and *** represented $P > 0.05$, $0.01 < P \leq 0.05$, $0.001 < P \leq 0.01$, $P \leq 0.001$, respectively.

± 2.39 g), red soil (10.43 ± 1.44 g), and alkaline purple soil (10.13 ± 0.46 g). The order of biomass content in leaves and stems was red soil, alkaline purple soil, yellow soil, and acidic purple soil, with a range of 2.08 ± 0.42 g to 3.31 ± 0.44 g and 6.19 ± 0.76 g to 6.19 ± 1.76 g, respectively. In the root, the order was alkaline purple soil, acidic purple soil, red soil, and yellow soil, ranging from 1.43 ± 0.22 g to 2.93 ± 1.62 g. The biomass of the stem cultured in acidic purple soil was significantly higher than in yellow soil (Figure 2, $P < 0.05$), alkaline purple soil (Figure 2, $P < 0.01$) and red soil (Figure 2, $P < 0.01$). In four soil types, the leaves' biomass was obviously higher than that of stems and roots (Figure 2, $P < 0.01$), while there were no evident differences in stems and roots. In summary, the biomass of the leaves was the highest compared to the roots and stems, and biomass cultured in the acidic purple soil was the highest among the four soil types.

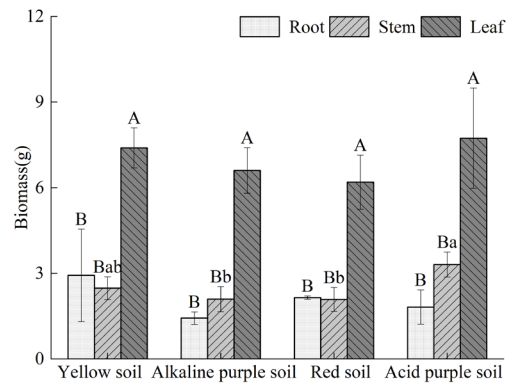


Figure 2. Effects of four soil types on biomass accumulation and distribution in *P. chinense* seedlings. Different uppercase letters indicated significant differences between different soil types in different organs ($P < 0.05$). Different lowercase letters indicate significant differences between different organs in different soil types ($P < 0.05$).

Effects of four soil types on C, N, and P content

Soil type had a significant influence on the accumulation and distribution of C content ($P < 0.001$), while organs had no significant impact ($P > 0.05$). The interactions between the soil type and organs were very significant (Table 2, $P < 0.01$). The total C content cultured in acidic purple soil was 574.35 ± 6.80 g/kg, significantly higher than in yellow soil ($P < 0.05$), red soil ($P < 0.001$), and alkaline purple soil (Figure 3A, $P < 0.001$). In different soil types, the C content in various organs was also significantly different. The C content in the leaves cultured in yellow soil was 603.85 ± 17.38 g/kg, significantly higher than in red soil and alkaline purple soil (Figure 4A, $P < 0.01$), and there were no obvious distinctions between yellow soil and acidic purple soil. The C content in the stems grown in acidic purple soil was 559.83 ± 31.46 g/kg, significantly higher than in alkaline purple soil (Figure 4A, $P < 0.05$), but there was no significant difference compared to other soils. Moreover, the C content of roots cultured in acidic purple soil was the highest, representing 595.95 ± 23.05 g/kg, and is significantly higher than that in red soil (Figure 4A, $P < 0.05$), yellow soil (Figure 4A, $P < 0.01$) and alkaline purple soil (Figure 4A, $P < 0.01$).

Soil types, organs, and their interactions have extremely significant effects on the distribution of N content in *P. chinense* seedlings (Table 2, $P < 0.001$). The total N content grown in acidic purple soil was 1.45 ± 0.05 g/kg, which was not significantly different from those cultured in alkaline purple soil, and obviously higher than that in other soils (Figure 3B, $P < 0.001$). The N content in leaves was 2.38 ± 0.08 g/kg in acidic purple soil, which was not evidently different from those in alkaline purple soil, but both were visibly higher than that in yellow soil and red soil (Figure 4B, $P < 0.001$). The stem N content cultured in yellow soil was 1.19 ± 0.20 g/kg, which was not significantly different from acidic purple soil and alkaline purple soil. How-

ever, the values were clearly higher than those in red soil (Figure 4B, $P < 0.01$). The root N content cultured in yellow soil was 1.08 ± 0.03 g/kg, which was significantly higher than that in acidic purple soil (Figure 4B, $P < 0.05$) compared to red soil and alkaline purple soil (Figure 4B, $P < 0.01$). There were visible differences among the four soil types (Figure 4B, $P < 0.05$).

Soil types, organs, and their interactions have extremely significant effects on the distribution of P content in *P. chinense* seedlings (Table 2, $P < 0.001$). The highest total P content of *P. chinense* seedlings grown in acidic purple soil was 1.51 ± 0.02 g/kg, which was not significantly different from that of yellow soil, but higher than that of other soils (Figure 3C, $P < 0.001$). In acidic purple soil, the highest P content in leaves was 1.94 ± 0.04 g/kg, with significant differences among the four soil types (Figure 4C, $P < 0.001$). In yellow soil, the highest P content in stems was 1.31 ± 0.02 g/kg, with no significant difference from acidic purple soil, but both evidently higher than alkaline purple soil and red soil (Figure 4C, $P < 0.001$), with a significant difference between the two (Figure 4C, $P < 0.05$). The highest root P content in yellow soil was 1.51 ± 0.03 g/kg, which was obviously different in acidic purple soil (Figure 4C, $P < 0.01$), alkaline purple soil (Figure 4C, $P < 0.001$), and red soil (Figure 4C, $P < 0.001$). The four soil types showed sensible differences (Figure 4C, $P < 0.05$).

Effects of four soil types on the content characteristics of K, Ca, and Mg

Soil types, organs, and their interactions have a significant impact on the distribution of K content in *P. chinense* seedlings (Table 2, $P < 0.001$). The highest total K content of *P. chinense* seedlings grown in yellow soil was 14.95 ± 1.32 g/kg, which was higher than that in red soil ($P < 0.05$), alkaline purple soil ($P < 0.001$), and acidic purple soil (Figure 3D, $P < 0.001$). The highest K content of leaves in yellow soil was 27.60 ± 4.36 g/kg, clearly higher than that in red

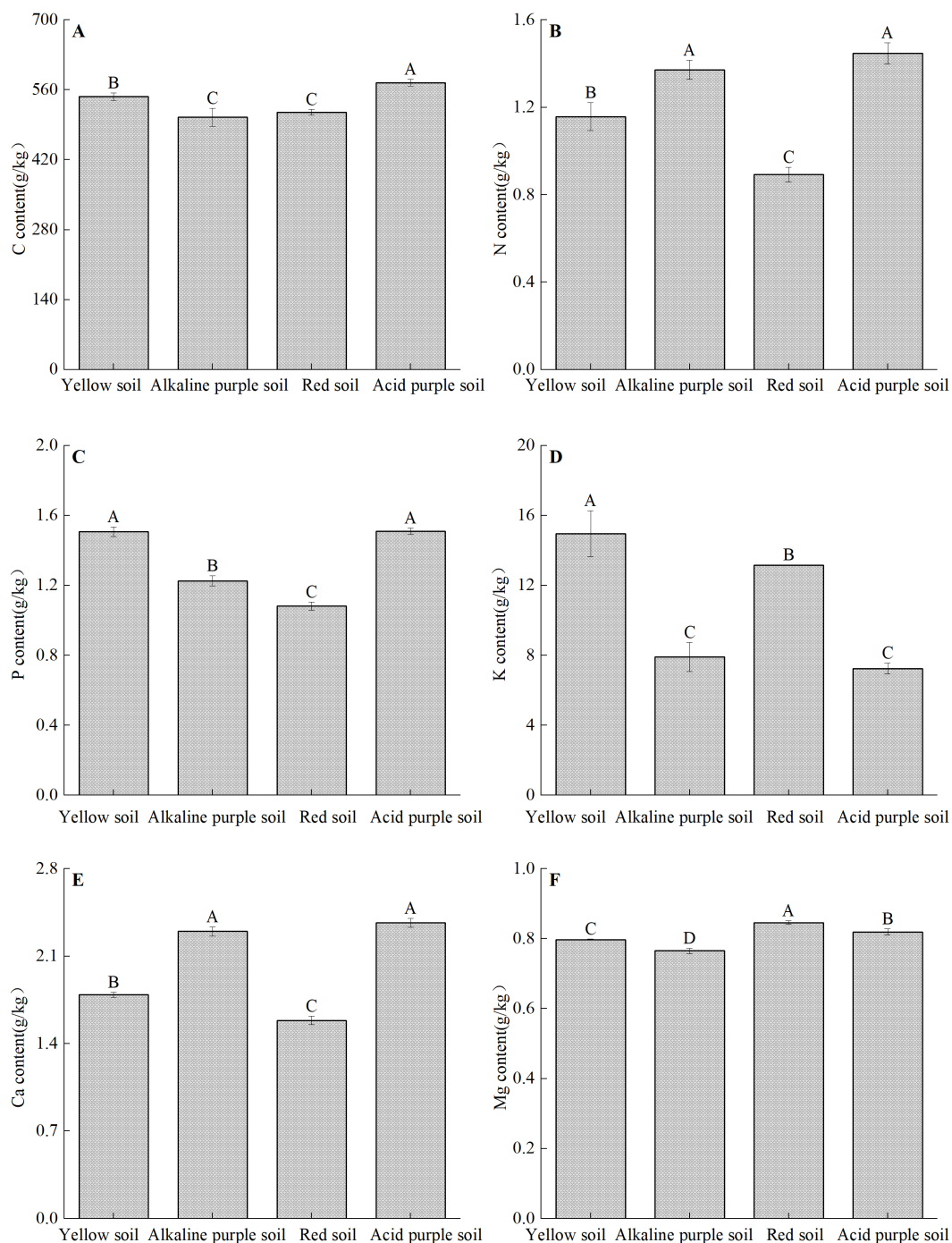


Figure 3. Effects of four soil types on total C, N, P, K, Ca and Mg contents in *P. chinense* seedlings.

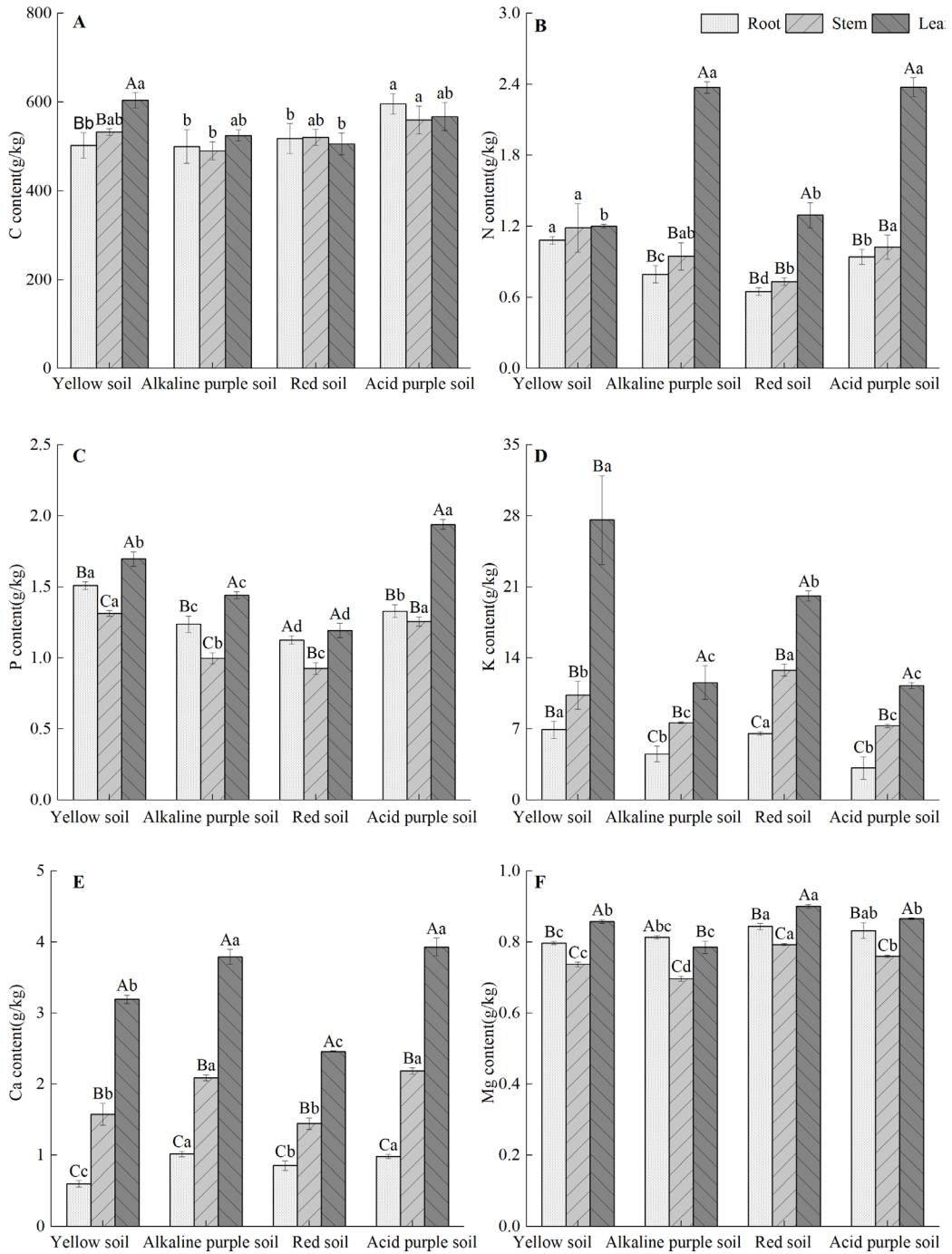


Figure 4. Effects of four soil types on C, N, P, K, Ca and Mg contents in different organs in *P. chinense* seedlings.

soil (Figure 4D, $P < 0.01$), alkaline purple soil (Figure 4D, $P < 0.001$), and acidic purple soil (Figure 4D, $P < 0.001$). In the stem, the highest K content in red soil was 12.81 ± 0.58 g/kg, significantly higher than that in yellow soil (Figure 4D, $P < 0.01$), alkaline purple soil (Figure 4D, $P < 0.001$), and acidic purple soil (Figure 4D, $P < 0.001$). The root K content of yellow soil was the highest at 6.92 ± 0.83 g/kg, which was not remarkably different from that of red soil, but significantly higher than that of acidic purple soil (Figure 4D, $P < 0.01$) and alkaline purple soil (Figure 4D, $P < 0.001$).

Soil types, organs and their interactions have extremely significant effects on the distribution of Ca content in *P. chinense* seedlings (Table 2, $P < 0.001$). The highest total Ca content of *P. chinense* seedlings grown in acidic purple soil was 2.37 ± 0.04 g/kg, which is higher than that in alkaline purple soil ($P < 0.05$), and other soils significantly (Figure 3E, $P < 0.001$). The highest Ca content in the leaves and stems in acidic purple soil was 3.93 ± 0.13 g/kg and 2.19 ± 0.05 g/kg, respectively. There was no significant difference compared to alkaline purple soil, but it was significantly higher than yellow soil and red soil (Figure 4E, $P < 0.001$). The Ca content of leaves grown in yellow soil was significantly higher than in red soil (Figure 4E, $P < 0.001$), but there was no significant difference in the stems. The highest root Ca content in alkaline purple soil was 1.02 ± 0.04 g/kg, and there was no significant difference compared to acidic purple soil, but it was evidently higher than in yellow soil (Figure 4E, $P < 0.001$) and red soil (Figure 4E, $P < 0.01$).

Soil types, organs, and their interactions have extremely significant effects on the distribution of Mg content in *P. chinense* seedlings (Table 2, $P < 0.001$). The highest total Mg content of *P. chinense* seedlings grown in red soil was 0.85 ± 0.01 g/kg, significantly higher than that of yellow soil ($P < 0.001$), alkaline purple soil ($P < 0.001$) and acidic purple soil (Figure 3F, $P < 0.01$). The highest Mg content of leaves

and stems in red soil was 0.90 ± 0.01 g/kg and 0.79 ± 0.005 g/kg, respectively. The Mg content of leaves in red soil was visibly higher than that in acidic purple soil (Figure 4F, $P < 0.01$), yellow soil (Figure 4F, $P < 0.001$), and alkaline purple soil (Figure 4F, $P < 0.001$). There were significant differences among the four soil types in the stem (Figure 4F, $P < 0.01$). The highest Mg content of the root in red soil was 0.84 ± 0.01 g/kg, which was not significantly different from that in acidic purple soil, but higher than that in yellow soil (Figure 4F, $P < 0.01$) and alkaline purple soil (Figure 4F, $P < 0.05$).

Effects of four soil types on C, N, and P stoichiometric characteristics

As shown in Figure 5A, soil types, organs, and their interactions had extremely significant effects on the C:N in *P. chinense* seedlings (Table 2, $P < 0.001$). The C:N ratios of roots cultured in red soil was significantly higher than those in yellow soil ($P < 0.001$), alkaline purple soil ($P < 0.05$) and acidic purple soil ($P < 0.05$). The stem C:N ratios with 711.64 ± 53.21 cultured in red soil were evidently higher than those in other soils ($P < 0.05$), and there was no obvious difference in stems among the other three soils. The leaf C:N ratios with 502.44 ± 8.27 cultured in yellow soil were significantly higher than those in red soil ($P < 0.001$), and their values were significantly higher than those in acidic purple soil and alkaline purple soil ($P < 0.001$). However, there were no significant differences between acidic purple soil and alkaline purple soil.

As shown in Figure 5B, soil types, organs, and related interactions had significant effects on the C:P ratios (Table 2, $P < 0.001$). The C:P ratios of roots grown in yellow soil was significantly lower than those in alkaline purple soil ($P < 0.05$), red soil ($P < 0.01$) and acidic purple soil ($P < 0.01$). The C:P ratios of stems cultured in red soil were 562.72 ± 37.47 , and significantly higher than those in alkaline purple soil ($P < 0.05$), acidic purple soil ($P < 0.01$),

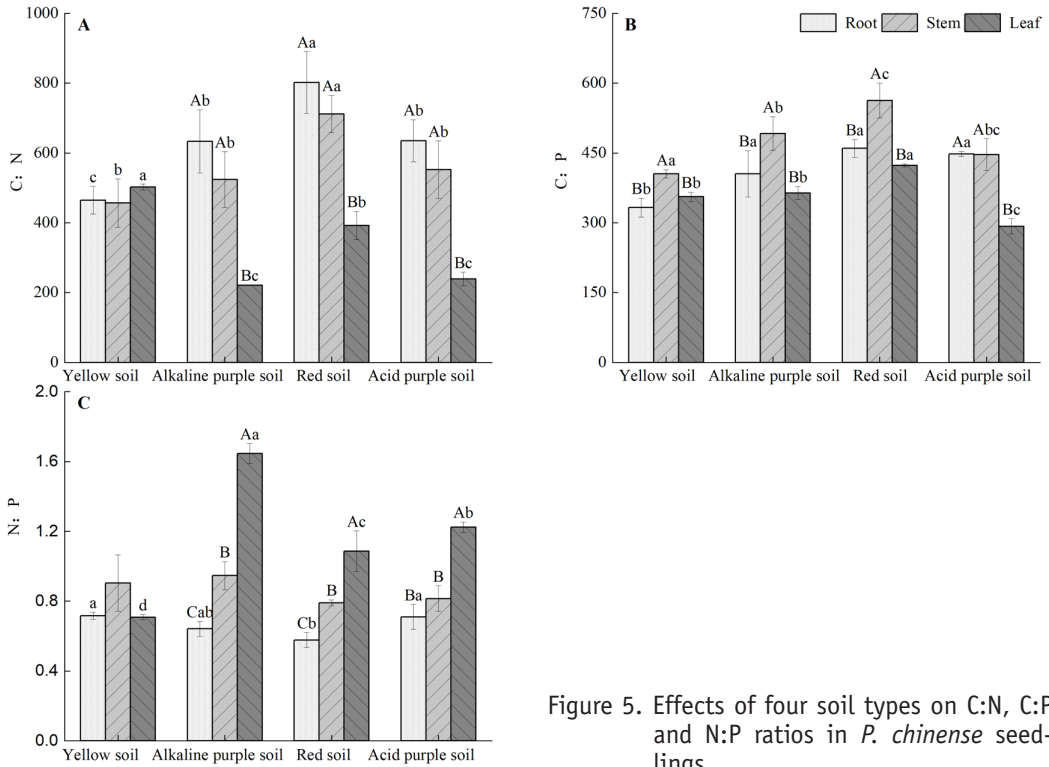


Figure 5. Effects of four soil types on C:N, C:P and N:P ratios in *P. chinense* seedlings.

and yellow soil ($P<0.001$). The C:P ratios of leaves cultured in red soil were 423.53 ± 3.26 , and evidently higher than those in alkaline purple soil ($P<0.001$), and yellow soil ($P<0.001$), with no significant difference between the two, both were significantly higher than in acidic purple soil ($P<0.001$).

As shown in Figure 5C, soil types, organs, and related interactions have significant effects on the N:P ratios (Table 2, $P<0.001$). The N:P ratios in roots cultured in yellow soil was 0.90 ± 0.16 , and was not significantly different from those in acidic purple soil. However, the values were significantly higher than those in red soil ($P<0.01$), and the differences between alkaline purple soil and other soils was not significant. In the stem, there were no significant differences among four soil types. The N:P ratios in leaves cultured in alkaline purple soil were 1.65 ± 0.05 , which was significantly higher than those in other soil

types ($P<0.001$). There were significant differences between the four soil types ($P<0.05$).

Redundancy analysis (RDA)

As shown in Figure 6, correlation analysis of soil nutrients, growth and nutrient indexes in *P. chinense* seedlings was studied using redundancy analysis. Soil pH had a significant negative impact on the content of Mg in stems and leaves (Figure 6B, 6C, $P<0.01$), and also had a negative impact on the C content in stems (Figure 6B, $P<0.05$). There was a significant positive correlation between soil pH and N:P in leaves (Figure 6C, $P<0.01$). Soil N had a significant positive effect on P content and biomass in stems and leaves (Figure 6B, 6C, $P<0.05$), and also had a similar effect on the C:N content in stems (Figure 6B, $P<0.01$) and Ca content in leaves (Figure 6C, $P<0.01$). Soil N inhibited C:P in leaves (Figure 6C, $P<0.01$). Soil OC significantly positively

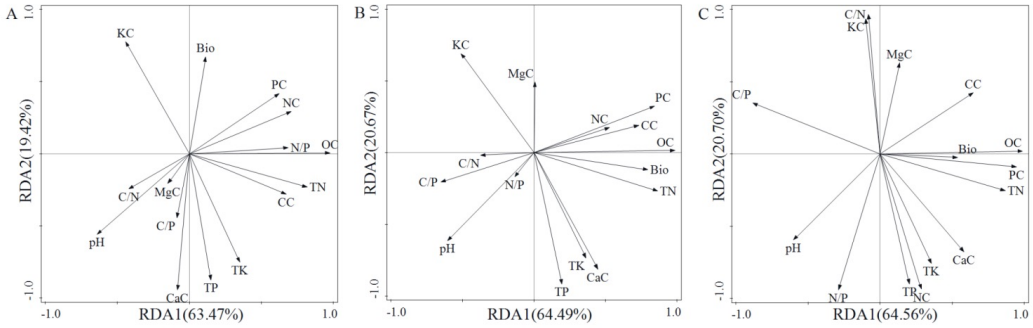


Figure 6. Redundancy analysis (RDA) of the relationship between soil nutrient factors and root (A), stem (B), and leaf (C) growth and nutrient indexes of *P. chinense*. pH=*Pondus Hydrogenii*, OC=Organic carbon, TN=Total nitrogen, TP=Total phosphorus, TK=Total potassium, Bio=Biomass, CC=C content, NC=N content, PC=P content, KC=K content, CaC=Ca content, MgC=Mg content.

correlated with the C content in the root, stem and leaf (Figure 6, $P < 0.05$). Moreover, it also significantly positively correlated with N in roots (Figure 6A, $P < 0.01$), biomass in stems (Figure 6B, $P < 0.01$) and Ca content in leaves (Figure 6C, $P < 0.05$). Soil OC significantly negatively correlated with C:P ratios in stems (Figure 6B, $P < 0.01$) and leaves (Figure 6C, $P < 0.05$). Soil P significantly inhibited the K content in the root, stem and leaf, but promoted the Ca content (Figure 6, $P < 0.01$). Mg content in stems and leaves was also affected by soil TP (Figure 6B, 6C, $P < 0.05$), showing a negative correlation trend. The effect of soil TK on the K content in roots, stems and leaves was significantly negatively correlated (Figure 6A, 6C, $P < 0.01$ and Figure 6B, $P < 0.05$), but significantly positively correlated with the Ca content in roots and stems (Figure 6A, 6B, $P < 0.01$). C content in roots (Figure 6A, $P < 0.05$) and N content in leaves (Figure 6C, $P < 0.01$) also showed a significant positive correlation with soil TK. Soil TK had a significant positive effect on C:P in roots (Figure 6A, $P < 0.05$), but it was opposite in leaves (Figure 6C, $P < 0.05$).

The increase in the C content inhibited K in roots (Figure 6A, $P < 0.01$), but promoted P in leaves (Figure 6C, $P < 0.01$). The content of C in roots significantly positively correlated with C:P (Figure 6A, $P < 0.05$),

and the content of N:P in leaves was significantly negatively correlated (Figure 6C, $P < 0.05$). N content significantly positively correlated with the P content in roots and stems (Figure 6A, 6B, $P < 0.01$), Ca content in leaves (Figure 6C, $P < 0.01$), and negatively correlated with the Mg content in roots and leaves ($P < 0.05$), and the K content in leaves (Figure 6C, $P < 0.01$). The N content in the root, stem, and leaf negatively correlated with C:N and C:P, but positively correlated with N:P ($P < 0.05$). P negatively correlated with the Mg content ($P < 0.01$) and Ca content in roots ($P < 0.05$), but positively correlated with the biomass in stems ($P < 0.05$) and Ca content in leaves (Figure 6C, $P < 0.01$). It negatively correlated with the C:P in the root, stem, and leaf (Figure 6, $P < 0.01$), and C:N in the root and stem (Figure 6A, $P < 0.01$, Figure 6B, $P < 0.05$), but positively correlated with the N:P in root (Figure 6A, $P < 0.05$). The Ca content in roots, stems and leaves decreased with the increase in K content ($P < 0.05$), while the Mg content in stems increased ($P < 0.05$). In addition, there was a significant negative correlation between the Mg content and Ca content in leaves (Figure 6C, $P < 0.05$). The Ca content in roots negatively correlated with the biomass (Figure 6A, $P < 0.05$).

Discussion

In this study, it was found that the biomass accumulation increased with the increase in soil organic matter and soil total N content, during the growth of *P. chinense* seedlings. The changing pattern is consistent with Knecht & Göransson (2004). The biomass of *P. chinense* seedlings cultured in acidic purple soil and yellow soil is higher, which may be due to higher organic matter content and N content than those in alkaline purple soil and red soil. In four soil types, the leaf biomass was significantly higher than that in the stems and roots, but there were no significant differences between them. The stem biomass cultured in acidic purple soil was obviously higher than that in other three soils, indicating that this soil is more suitable for the growth of *P. chinense*. Compared to yellow soil, there was a lower biomass of roots and a higher biomass of leaves in acidic purple soil. This may be due to the higher nutritional level of acidic purple soil than in yellow soil. Significant differences exist among plant species in carbon allocation strategies and tissue nutrient concentrations due to different soil conditions (Wardle *et al.*, 2004). Plants can adapt to changes in the nutritional environment by regulating the allocation of biomass (Minden & Kleyer, 2014). When nutrient levels are low, plants allocate more biomass to their roots, enabling them to absorb more nutrients. When the nutrient level is high, more biomass is allocated to the leaves, and the biomass share of the leaves increases. In summary, acidic purple soil has the best conditions for the growth of *P. chinense* seedlings, which is conducive to biomass accumulation.

Elements such as C, N, P, K, Ca, and Mg are the main carriers of plant life activities. They are not only components of the organic structure of plants, but also participate in enzymatic reactions or energy metabolism and physiological regulation (Tian *et al.*, 2019). The contents of C, N, P, and Ca in *P. chinense* seedlings in acidic

purple soil were significantly higher than those in the others, while the content of Mg was notably lower than that in red soil, and the content of K was evidently lower than that in yellow soil and red soil. This may be because acidic purple soil can provide sufficient nutrients, water, and air, ensure root respiration, promote nutrient absorption, and is suitable for growth and development, as shown by the distribution characteristics of the above element content. In contrast, the comprehensive quality of the other three soils is not as good as that of acidic purple soil.

This experiment studied the distribution characteristics of the elements C, N, P in different organs under the same soil conditions. The results showed that the content of C in different organs of *P. chinense* seedlings was higher, but the difference was not significant, similar to the results of Ding *et al.* (2022). The reason for the above results may be that C is a basic element that constitutes cells, tissues, and organs, providing energy for various life activities of plants, and is in high demand. Therefore, its content is high in plants (Ågren, 2008). In addition, *P. chinense* is at the seedling stage, with a relatively low degree of lignification in the stem, and a low content of C-rich polysaccharides, such as lignin and cellulose. The composition of C-containing components is similar to that of leaves and roots, resulting in no significant difference in the C content of the three organs. The contents of N, P, K, Ca, and Mg were relatively low, with significant differences among different organs. Leaves had significantly higher contents compared to stems and roots. The reason may be that stems and roots act as absorption and transportation channels for nutrients, and also have the function of storing water and nutrients (Fortunel *et al.*, 2012), which typically assume the supporting structure and fixation role. The leaf is the main organ for photosynthesis and respiration in plants (Yan *et al.*, 2023), and is the main component for respiratory metabolism. It carries

out physiological and biochemical activities, making the content of N, P, K, and Mg higher than those in stems and roots.

The concentrations of C, N, and P in plants reflect their nutrient uptake, utilization efficiency, and adaptability to environmental stresses (Liu *et al.*, 2020). There is a close coupling relationship between the content of C, N, and P in different organs and their stoichiometric ratios, indicating that the stoichiometric ratios and nutrient utilization efficiency are closely related (Zhang *et al.*, 2022). The C:N and C:P ratios of different organs vary depending on their functions, and the C:N and C:P ratios of metabolic organs are lower than those of structural organs (Minden & Kleyer, 2014). Leaf nutrient concentrations, especially their stoichiometric ratios, have been shown to be related to the growth rate of plants. In this study, in red soil, alkaline purple soil, and acidic purple soil, the C:N and C:P ratios of leaves of *P. chinense* seedlings were smaller than those of roots and stems. However, the C:N of leaves in yellow soil was greater than that in roots and stems, and the C:P of stems was greater than that in roots and leaves. In addition, in red soil, the C:N and C:P ratios of *P. chinense* seedlings were significantly higher than those in the other three soil types. This indicates that *P. chinense* seedlings grown on red and yellow soil have a high investment in supporting structures, and may have adopted conservative nutrient utilization strategies during their growth, changing the distribution of carbon among different organs, reflecting environmental stress (Xie *et al.*, 2022).

From the perspective of plant nutritional requirements, N and P are particularly important among the various nutrients required by plants. They are nutrient-limiting indicators for biomass production and important factors limiting physiological activities, such as plant growth and reproduction (Güsewell, 2004). They are not only the components of many important organic compounds in plants, but also par-

ticipate in various metabolic processes in plants in various ways. In this experiment, N and P had significant effects on the C:N:P stoichiometric ratio in different organs. However, in this study, the nitrogen phosphorus ratio of *P. chinense* seedlings grown in four soil types is very small, far below 10. Studies have shown that there is a positive correlation between plant growth and primary productivity and nitrogen concentration (Peng *et al.*, 2011). In addition, studies have shown that when the N:P ratio <10, nitrogen fertilizer is applied to increase biomass. In other words, in this study, nitrogen has become a limiting factor for the growth and development of *P. chinense* seedlings, and nitrogen fertilizer should be applied to increase biomass and promote growth and development.

Conclusion

There are significant differences in the effects of different soil types on the growth and development, accumulation and distribution of nutrient elements and the stoichiometric ratio of *P. chinense* seedlings, and also in the roots, stems and leaves. The results showed that in a soil with a low nutrient level, the plant would distribute more nutrients to the root in order to absorb more nutrients. Compared with the other three soil types, acidic purple soil is more suitable for the early cultivation of *P. chinense*, which is conducive to the accumulation of biomass and C, N, P, Ca content. Proper increase in nitrogen fertilizer is conducive to more efficient growth and development of *P. chinense*. The contents and distribution of C, N, P, K and other elements in different organs of *P. chinense* seedlings are closely related to the functions performed by the particular organ. Among four soil type, the yellow soil and red soil were beneficial to the accumulation of K and Mg content in *P. chinense* seedlings, respectively, but alkaline purple soil is not suitable for the growth

of *P. chinense* seedlings. The growth rate and metabolism of *P. chinense* leaves at the seedling stage are faster than those of the stems and roots. However, N is the limiting element for the growth and development of *P. chinense* seedlings in the four soil types. In this study, the biomass and nutrient element accumulation and distribution of *P. chinense* seedlings were studied, and the effects of different soil types on the medicinal properties of *P. chinense* were further analyzed, which will help to screen the suitable soil types of the genuine medicinal material of *P. chinense*, and provides experimental data and theoretical support for expanding the cultivation area of *P. chinense*.

Acknowledgements. This research was supported by the National Standardization Project of Traditional Chinese Medicine (Grant No. 2YB221-Y-SC-41).

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