Postprint of a Study on Nutrient Limiting Factors and Characteristics of Nutrient Uptake, Accumulation, and Distribution in Red Kidney Beans

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Abstract

Investigating nutrient limiting factors and the accumulation and distribution patterns of dry matter and nitrogen, phosphorus, and potassium in red kidney beans can provide a theoretical basis for rational fertilization and high-yield cultivation. Under field experiment conditions, using 'British Red' red kidney beans as test material, nutrient deficiency experiments were established, and plant samples from the complete fertilization zone were collected to analyze the dry matter mass, nutrient content, and accumulation amount in various organs at different growth stages. The results showed that combined application of nitrogen, phosphorus, and potassium significantly increased red kidney bean yield; compared with the complete fertilization treatment, the nitrogen-deficient, phosphorus-deficient, and potassium-deficient treatments reduced yield by 14.2%, 8.0%, and 11.3%, respectively, indicating that the limiting factors affecting red kidney bean yield were nitrogen > potassium > phosphorus. Throughout the entire growth period, the dry matter accumulation rate of red kidney beans first increased and then decreased; the dry matter accumulation amounts in roots, stems, pod walls, and seeds showed an increasing trend, while leaf dry matter showed a decreasing trend at harvest, with dry matter mass in different parts at harvest being seeds > stems pod walls > leaves > roots. As the growth stage progressed, nitrogen content in stems, leaves, and pod walls showed a decreasing trend, nitrogen content in seeds showed an increasing trend, while phosphorus and potassium contents in all organs showed a decreasing trend. The period from full flowering to pod-setting stage was the period of maximum nutrient accumulation, with nitrogen, phosphorus, and potassium absorption amounts accounting for 28.14%, 49.22%, and 56.20% of the total absorption throughout the entire growth period, respectively; different organs accumulated different amounts of nitrogen, phosphorus, and potassium, with seeds, leaves, stems, and roots all accumulating the most nitrogen, followed by potassium, and the least

phosphorus at maturity, while pod walls accumulated the most potassium, followed by nitrogen, and the least phosphorus. To produce 100 kg of red kidney beans requires supply of N 4.37 kg, P2O5 2.38 kg, and K2O 3.53 kg, with a ratio of 1:0.54:0.81.

Full Text

Nutrient Restrictive Factors, Nutrient Absorption and Accumulation of Red Kidney Bean

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Abstract

Kidney bean (*Phaseolus vulgaris*) is one of the main grain crops in China with important economical and nutritional values. Recently, the planting area of red kidney bean has been gradually increasing in Shanxi Province, China. However, the nutrient absorption characteristics and limiting factors of kidney bean were still not very clear. Nitrogen (N), phosphorus (P) and potassium (K) are essential nutrients for plant growth, and knowledge on periodic uptake, accumulation and allocation of N, P and K in different organs of kidney bean is important to implement nutrient management practices to ensure its sustainable production. There were several studies on effect of the fertilization and nitrogen application on yield of kidney bean. However, few studies have investigated the nutrient accumulation and distribution characteristics of kidney bean. In this study, field experiment was conducted with different nutrient application (N absence, P absence, K absence, NPK application and no fertilizer) using the red kidney bean variety 'British Red' as the materials in 2014. The nutrient restrictive factors, dry matter accumulation and nutrient uptake and accumulation of red kidney bean were investigated. The samples of NPK application treatment at different growth stages were collected for determining dry matter and nutrient contents in different organs, to illustrate the law of nutrient absorption. This is beneficial to provide theoretical basis for rational fertilization and high yield cultivation of red kidney bean. The results showed that NPK application treatment significantly increased yield of red kidney bean compared to absence of N, P, or K and no fertilizer treatments. Compared to NPK application treatment, yields of N-, P- or K-absence decreased by 14.2%, 8.0% and 11.3%, respectively, which indicated that the order of nutrient restrictive factors of red kidney bean yield was N > K > P. The dry matter accumulation rate of red kidney bean increased firstly and then reduced in the whole growth period. Dry matter accumulation of root, stem, pod shell and pea increased gradually throughout the whole growing period, while dry matter accumulation of leaf decreased at harvest stage. The order of dry matter weight in different organs at harvest was pea > stem pod shell > leaf > root. The contents of N, P and K of all investigated organs varied at different stages. N contents in steam, leaf and pod shell decreased gradually, and increased in pea throughout the whole period. The contents of P and K in different organs showed a decreasing trend in whole growth period. The highest nutrients level was observed from full-blooming to pod bearing stage, in which, the absorption contents of N, P and K accounted for 28.14%, 49.22% and 56.20% of the total content of whole growth period, respectively. The accumulation amount of N, P and K in different organs was various. The order of N, P, K accumulation was N > K > P in pods, leaves, stalks and stems, while it was order of K > N > P in pod skins. In conclusion, to produce 100 kilogram kidney bean pea, 4.37 kg N, 2.38 kg P O and 3.53 kg K O application with ratio of 1 0.54 0.81 were needed.

Keywords: Red kidney bean; Nutrient restrictive factor; Dry matter; N; P; K; Nutrient accumulation

Introduction

Kidney bean (*Phaseolus vulgaris*) is a major minor grain crop in China, primarily distributed in northern regions and southwestern high-altitude, cold areas, with extensive cultivation [1]. Shanxi Province is one of China' s main kidney bean production areas. Nitrogen, phosphorus, and potassium are essential nutrients for plant growth, and their absorption and utilization directly affect crop development and yield. Understanding nutrient absorption and accumulation patterns can effectively regulate crop growth, improve yield, and enhance quality. Previous studies have shown that crop nutrient absorption and utilization of N, P, and K vary depending on crop type, variety, yield level, and fertilizer application rate [2-6]. Rational planting density combined with increased N and P fertilization and K supplementation can significantly improve kidney bean yield [7-8]; the yield increase effect of kidney bean varies with nitrogen fertilizer type, and nitrogen use efficiency and nitrogen uptake differ among varieties [9]; nitrogen application significantly increases pod number, 100-grain weight, and improves quality of red kidney bean [10-12]. These studies have mainly focused on the effects of fertilization and nitrogen application on yield and agronomic traits of kidney bean, while research on nutrient limiting factors and characteristics of nutrient absorption, accumulation, and distribution remains scarce. Red kidney bean, a type of kidney bean, has seen its planting area gradually expand in Shanxi in recent years due to its high nutritional and economic value [13]. This study used red kidney bean as experimental material, determined fertilizer application rates based on farmer practices combined with soil test results, established N, P, and K deficiency experiments to identify nutrient limiting factors, and systematically investigated dry matter accumulation, N, P, and K contents, and nutrient absorption-accumulation-distribution characteristics by collecting plant samples at different growth stages from the complete NPK treatment area, aiming to provide a theoretical basis for rational fertilization and high-yield cultivation of red kidney bean.

1. Materials and Methods

1.1 Experimental Site

The field experiment was conducted in 2014 at the Dryland Water-saving Agricultural Experimental Station of the Research Center for Dryland Agriculture, Shanxi Academy of Agricultural Sciences, located in Yangqu County. The station is situated in the ridge zone between Xinzhou and Jinzhong basins, characterized by a warm temperate continental monsoon climate with distinct seasons. The average annual temperature is 6–7°C, annual precipitation is 441.2 mm, and the frost-free period is approximately 120 days. The soil is cinnamon soil. The 0–20 cm soil layer contained organic matter 14.41 g · kg ^{1}, total nitrogen 0.95 g · kg ^{1}, alkaline hydrolyzable nitrogen 40.4 mg · kg ^{1}, available phosphorus 17.05 mg · kg ^{1}, available potassium 107.12 mg · kg ^{1}, and pH 8.25.

1.2 Experimental Design

The experiment included five treatments: CK (no fertilizer), PK (N deficiency, with P O 120 kg · hm ^{2} and K O 100 kg · hm ^{2}), NK (P deficiency, with N 90 kg · hm ^{2} and K O 100 kg · hm ^{2}), NP (K deficiency, with N 90 kg · hm ^{2} and P O 120 kg · hm ^{2}), and NPK (complete fertilization, with N 90 kg · hm ^{2}, P O 120 kg · hm ^{2}, and K O 100 kg · hm ^{2}). The experiment was arranged in a randomized complete block design with three replications, with plot size of 28 m^2. The N, P, and K fertilizer rates were determined based on farmer practices combined with soil test results. The tested red kidney bean variety was 'British Red' , planted at a density of 110,000 plants · hm ^{2} with two plants per hole. All fertilizers were applied as a single basal dose in spring. Sowing occurred on April 30 and harvest on August 26. Each plot was harvested separately, threshed, and yield was measured.

Plant sampling: Whole plants were sampled at the seedling stage (June 14), squaring stage (July 1), full-bloom stage (July 19), pod-bearing stage (August 8), and maturity stage (August 26). In each plot, 10 uniform plants were selected from above-ground parts, fresh weight was measured, and plants were separated into roots, stems, leaves, pod shells, and peas, then washed. Samples were killed out at 105°C for 30 minutes in an oven, dried at 60–70°C, and dry weight was measured.

1.3 Measurement Methods

Plant total nitrogen was determined by the Kjeldahl method using a FOSS 8400 automatic nitrogen analyzer after digestion with concentrated H SO . Total phosphorus and potassium were determined after HNO -HClO digestion: phosphorus by vanadium-molybdate yellow colorimetry using a Puxi General

TU-1901 UV spectrophotometer, and potassium by flame photometry using a 6400A flame photometer [14].

1.4 Data Analysis

Data were statistically analyzed using Microsoft Excel 2007 and SPSS 15 software.

2. Results

2.1 Nutrient Limiting Factors for Red Kidney Bean

As shown in Table 1 , compared with the CK treatment, fertilization increased red kidney bean yield by 13.4%–32.2%, with the NPK treatment showing significantly higher yield than other treatments. The N-deficient treatment differed significantly from P- and K-deficient treatments, while no significant difference was observed between P- and K-deficient treatments. Using the NPK treatment yield as the optimum, relative yields were calculated. N, P, and K deficiency reduced yield by 14.2%, 8.0%, and 11.3%, respectively, indicating that the order of nutrient limiting factors for red kidney bean yield was N > K > P. Regarding yield components, NPK application significantly increased 100-grain weight to 4.99–6.11 g, while no significant differences in 100-grain weight were found among N-, P-, K-deficient, and unfertilized treatments. The NPK treatment significantly increased pod number by 0.93–2.4 pods, while the N-deficient treatment showed no significant difference from the unfertilized treatment but was significantly lower than P- and K-deficient treatments, further demonstrating that N, P, and K fertilizers mainly affect yield through pod number.

Table 1 Effects of different fertilizer applications on the yield and yield components of red kidney bean

CK: no fertilizer; PK: N deficiency (P O 120 kg·hm ^{2}, K O 100 kg·hm ^{2}); NK: P deficiency (N 90 kg·hm ^{2}, K O 100 kg·hm ^{2}); NP: K deficiency (N 90 kg·hm ^{2}, P O 120 kg·hm ^{2}); NPK: complete fertilization (N 90 kg·hm ^{2}, P O 120 kg·hm ^{2}, K O 100 kg·hm ^{2}). Different letters in the same column indicate significant difference at the 5% level.

2.2 Dry Matter Accumulation and Distribution in Red Kidney Bean

As shown in Table 2 and Table 3 , dry matter accumulation in red kidney bean differed significantly among growth stages, showing an initial increase followed by a decrease: pod-bearing stage > full-bloom stage > maturity stage > squaring stage > seedling stage. Two peaks of dry matter accumulation per plant occurred during the growth period: the first from squaring to full-bloom stage (24.25% of total) and the second from full-bloom to pod-bearing stage (46.22% of total). Dry matter accumulation rates varied significantly among growth stages, with the lowest daily accumulation of 0.03 g per plant at the seedling stage, the highest of 1.30 g from full-bloom to pod-bearing stage, and an average of 0.75 g for the entire growth period. Leaves were the main site of dry matter accumulation from seedling to full-bloom stage, accounting for 52.4%–65.5% of whole-plant dry weight. After the pod-bearing stage, peas became the main site, accounting for 36.1%–45.7% of total dry weight. At harvest, dry matter per plant was 56.49 g, with pea yield of 25.84 g.

Regarding individual organs, root dry matter peaked at full-bloom stage then plateaued; stem dry matter peaked at pod-bearing stage then stabilized; leaf dry matter varied significantly among stages, reaching maximum at full-bloom stage then gradually decreasing to minimum at harvest, possibly due to withering and shedding of lower leaves not collected at late growth stages. From pod-bearing to maturity, pod shell dry matter changed slightly while pea dry matter increased significantly, becoming the main sink for dry matter distribution. At harvest, dry matter accumulation in different organs followed the order: pea > stem pod shell > leaf > root.

2.3 Dynamics of N, P, and K Contents in Red Kidney Bean Plants

Nitrogen content: As shown in Table 4 , root N content varied significantly among growth stages, gradually decreasing from seedling to pod-bearing stage then increasing to 10.21 g·kg^{1} at maturity, likely due to N remobilization. Stem N content increased from seedling to squaring stage then gradually decreased. Leaf N content decreased progressively with significant differences among stages, reaching the lowest value (9.12 g·kg^{1}) at harvest. Pod shell N content decreased while pea N content increased, reaching 29.5 g·kg^{1} at harvest, suggesting that delayed harvest could increase N content in red kidney bean seeds.

Phosphorus content: Root P content showed an inverted "S" pattern, highest at seedling stage, gradually decreasing, then increasing to seedling-stage levels at pod-bearing stage before significantly decreasing to the lowest value (2.25 g·kg^{1}) at maturity. Stem P content decreased gradually, stabilizing from pod-bearing stage (2.56 g·kg^{1} at harvest). Leaf P content decreased gradually, stabilizing from full-bloom stage. Pod shell and pea P contents changed slightly, with pea P content of 7.13 g·kg^{1} at harvest.

Potassium content: Root K content showed the same trend as N content. Stem and leaf K contents decreased significantly across growth stages, reaching 7.12 g·kg^{1} and 6.84 g·kg^{1}, respectively, at harvest. Pod shell K content decreased while pea K content remained stable at 14.85 g·kg^{1} at harvest.

In summary, different nutrients showed varying contents in the same organ: N > K > P in roots, stems, leaves, and peas, while K > N > P in pod shells. Nutrient contents in different organs varied considerably across growth stages. At maturity, N content ranked as pea > leaf > stem > root > pod shell; P content as pea > leaf > stem > root > pod shell; and K content as pod shell > pea > stem > leaf > root.

2.4 Nutrient Uptake Characteristics of Red Kidney Bean

2.4.1 Nutrient Uptake Patterns Across Growth Stages As shown in Table 5 , N, P, and K uptake amounts in red kidney bean plants increased gradually, reaching maximum at harvest. Nutrient accumulation followed the order N > K > P, with average uptake of 124.39 $kg \cdot hm^{2}$ N, 28.86 $kg \cdot hm^{2}$ P, and 83.56 $kg \cdot hm^{2}$ K (ratio 4.31:1:2.89). Combined with Table 3, the period from full-bloom to pod-bearing stage represented both the maximum population stage and the period of greatest nutrient accumulation, with N, P, and K uptake accounting for 28.14%, 49.22%, and 56.20% of total uptake, respectively. Uptake rates were low in early growth due to small plant size, peaked from full-bloom to pod-bearing stage, then decreased. Therefore, adequate nutrient supply should be ensured when red kidney bean enters the flowering stage.

2.4.2 Nutrient Accumulation and Distribution Characteristics As shown in Table 6 -8, N, P, and K accumulation in red kidney bean plants increased progressively. Leaves were the distribution center for N, P, and K from seedling to full-bloom stage, while peas became the distribution center from pod-bearing stage onward. At maturity, N accumulation was greatest, followed by K, then P in peas, leaves, stems, and roots, whereas K accumulation was greatest, followed by N, then P in pod shells.

Nitrogen accumulation (Table 6): N accumulation in roots, stems, and leaves increased initially then decreased, peaking at full-bloom stage. Pod shell N accumulation decreased while pea N accumulation increased, reaching 83.91 $kg \cdot hm^{2}$ at harvest. Organ N accumulation ranked as pea > leaf > stem > pod shell > root. Distribution ratios in roots and leaves decreased progressively; stem distribution ratio increased initially then decreased, peaking at 33.82% at full-bloom stage. At harvest, N distribution ratios were 1.20% in roots, 11.70% in stems, 12.99% in leaves, 6.66% in pod shells, and 67.45% in peas.

Phosphorus accumulation (Table 7): P accumulation in roots, stems, and leaves increased initially then decreased, peaking at pod-bearing stage in roots and at full-bloom stage in stems and leaves. Pod shell P accumulation changed slightly while pea P accumulation increased, reaching 19.73 $kg \cdot hm^{2}$ at harvest. Organ P accumulation ranked as pea > stem leaf > pod shell > root. Leaf distribution ratio decreased progressively; root and stem distribution ratios increased initially then decreased, peaking at 4.87% and 43.94%, respectively, at full-bloom stage. At harvest, P distribution ratios were 1.14% in roots, 11.07% in stems, 10.93% in leaves, 8.40% in pod shells, and 68.46% in peas.

Potassium accumulation (Table 8): K accumulation in roots, stems, and leaves increased initially then decreased, peaking at full-bloom stage. Pod shell K accumulation showed no significant change while pea K accumulation increased progressively, reaching 42.22 $kg \cdot hm^{2}$ at harvest. Organ K accumulation ranked as pea > pod shell > stem > leaf > root. Distribution ratios in roots and leaves decreased progressively; stem distribution ratio increased initially then decreased, peaking at 47.67% at full-bloom stage. At harvest, K distribution ratios were 1.09% in roots, 10.71% in stems, 5.49% in leaves, 32.18% in pod shells, and 50.53% in peas.

Based on N, P, and K uptake by aboveground plants at maturity, producing 100 kg of red kidney bean requires 4.37 kg N, 2.38 kg P O , and 3.53 kg K O (ratio 1:0.54:0.81).

Discussion

Numerous studies have shown that N, P, and K are the main factors affecting crop growth, with nitrogen being the primary nutrient limiting factor [2-6]. Li et al. [8] reported that fertilizer effects on red kidney bean ranked as N > P > K, while Gao et al. [15] found the order of fertilization factors affecting kidney bean yield was N > K > P. Chang et al. [11] suggested that N and P were the main factors affecting red kidney bean growth and yield. The differing orders of P and K effects on red kidney bean yield in previous studies may be due to variations in soil type, baseline soil nutrients, and fertilizer application rates. Under our experimental conditions, N and K deficiency (reducing yield by 14.2% and 11.3%, respectively) had more significant yield reduction effects than P deficiency, confirming that N and K are more limiting than P for red kidney bean yield.

This study showed that red kidney bean dry matter accumulation increased initially then decreased, consistent with trends in soybean (*Glycine max*) [16-17] and adzuki bean (*Vigna umbellata*) [18]. Dry matter accumulation rates varied significantly among growth stages, with the lowest daily accumulation of 0.03 g per plant at seedling stage and the highest of 1.30 g from full-bloom to pod-bearing stage, indicating this period is critical for dry matter accumulation and requires adequate nutrient supply. Before full-bloom, dry matter accumulated rapidly in roots, leaves, and stems; subsequently, accumulation in roots and stems decreased gradually, likely due to translocation of stored nutrients to seeds. The sharp decline in leaf dry matter accumulation after full-bloom may be related to withering and shedding of some leaves, which should be considered in future studies.

Crop biomass accumulation is closely related to nutrient accumulation. Nutrient absorption and accumulation form the basis of biomass accumulation and yield formation, and are important for rational fertilization. This study showed that red kidney bean biomass accumulation trends were consistent with N, P, and K accumulation curves, similar to findings in maize [19]. The full-bloom to pod-bearing stage is a period of concurrent reproductive and vegetative growth, with dry matter accumulation accounting for 46.22% of the total. N, P, and K uptake rates and accumulation peaked during this stage, representing 28.14%, 49.22%, and 56.20% of total uptake, respectively. Additionally, nutrient demand was also high from squaring to full-bloom stage, similar to adzuki bean [18]. Based on dry matter and nutrient accumulation characteristics, high red kidney bean yields require rational fertilization to achieve vigorous seedlings at seedling stage, and appropriate topdressing of N and K before flowering to ensure adequate soil nutrient supply. As a legume crop, red kidney bean has complex nitrogen nutrition, and optimal N application rates must consider nitrogen fixation factors. Song et al. [9] showed that optimal N rate depends on kidney bean variety. This study only examined nutrient uptake under balanced fertilization; further experiments are needed to determine optimal fertilizer rates and nutrient uptake characteristics under different fertilization regimes.

Conclusions

1) Combined N, P, and K application significantly increased red kidney bean yield, 100-grain weight, and effective pod number. N, P, and K deficiency reduced yield by 14.2%, 8.0%, and 11.3%, respectively, with nutrient limiting factors ranking as N > K > P.

2) Red kidney bean dry matter accumulation increased then decreased during the growth period, with two peaks from squaring to full-bloom stage and full-bloom to pod-bearing stage, accounting for 24.25% and 46.22% of total plant dry weight, respectively. Vegetative growth dominated from seedling to full-bloom stage, while peas became the main sink for dry matter accumulation after pod-bearing stage, accounting for 36.1%–45.7% of total plant dry weight, with individual plant pea yield of 25.84 g at harvest.

3) N, P, and K contents in roots, stems, and leaves decreased progressively with growth stage. N, P, and K accumulation trends were similar, with accumulation order of N > K > P. The full-bloom to pod-bearing stage was the period of maximum nutrient accumulation. Nutrient accumulation varied among organs: at maturity, N accumulation was greatest, followed by K, then P in peas, leaves, stems, and roots, while K accumulation was greatest, followed by N, then P in pod shells. Producing 100 kg of red kidney bean requires 4.37 kg N, 2.38 kg P O , and 3.53 kg K O (ratio 1:0.54:0.81).

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Note: Figure translations are in progress. See original paper for figures.