



## Article

# Green Manure Amendment Increases Soil Phosphorus Bioavailability and Peanut Absorption of Phosphorus in Red Soil of South China

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**Abstract:** Peanut (*Arachis hypogaea* L.) is one of the most important crops produced worldwide. Peanut is the dominant crop in the typical upland red soil areas of China; however, phosphorus bioavailability in red soil is very low, which severely affects peanut production. To improve the phosphorus bioavailability, which substantially promotes the green development of peanut production, a peanut–green manure rotation field experiment was conducted with six treatments (milkvetch; radish; brassica rape; mustard rape; winter fallow and no-tillage), commencing in September 2017 in the red soil area of Jiangxi province, China. The results show that compared with no-tillage (NT) treatments, different green manure returning treatments had significant effects on soil pH, soil phosphorus components and available potassium content. The particulate phosphorus and soil available phosphorus contents in the green manure treatments were significantly higher than those in the winter fallow (WF) treatment. Compared with the WF treatment, the content of particulate phosphorus in brassica rape (BR), radish (R) and milkvetch (MV) treatments was significantly increased by 6.55%, 3.66% and 2.50%, respectively; the available phosphorus content in mustard rape (MR), BR, R and MV was significantly increased by 20.93%, 25.60%, 23.76% and 18.10%, respectively. In addition, the total phosphorus content of peanut shell in the MV and R treatment was significantly higher than that in the WF treatment, increasing by 33.47% and 60.66%, respectively. Compared with the WF treatment, the peanut biomass of MR, BR and R treatments increased significantly by 19.51%, 29.83% and 19.77%, respectively. The total phosphorus accumulation in all green manure treatments was higher than that in the WF treatment, and the MV treatment reached a significant level at 18.83%. Based on these results, the particulate phosphorus (PP) and available phosphorus were significantly affected by different green manure treatments; green manure amendment improves peanut phosphorus uptake. The use of green manure (especially milkvetch and brassica rape) can be recommended to improve phosphorus bioavailability and yield of peanut in red soil areas.

**Keywords:** soil phosphorus components; organic farming; winter fallow; green manure return; peanut production



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## 1. Introduction

Peanut (*Arachis hypogaea* L.) is one of the most important crops produced worldwide. In addition to its high nutritional value, it is one of the five most important oilseeds. Global peanut production has increased approximately 136%, from 16,719 (1000) MT in the 1970s to 39,526 (1000) MT in 2010–2013 [1]. In China, peanut has the highest yield among oil crops,

is the only crop with net export, and its share in the total domestic oil crop production has increased from 46.3% in 2010 to 50.4% in 2020 [2]. Peanut is the dominant crop in typical upland red soil areas in Jiangxi Province, China. The red soils in this region are derived from Quaternary red clay and have low inherent fertility, especially in respect of bioavailability of phosphorus [3]. To obtain high peanut yields, appropriate soil physical and chemical properties are required. However, due to the strong leaching of red soil, the serious phenomenon of desilicization and iron-rich aluminization, there is a strong fixation effect on phosphorus, thus reducing phosphorus bioavailability. The phosphorus fertilizer use efficiency in peanut production is about 10%~25% [4]. Consequently, the rate of phosphorus fertilizer application in the red soil region is 35% higher than the national average level [5]. The phosphorus bioavailability of soil will have a strong effect on peanut root growth and yield [6]. However, inordinate chemical fertilizer application is a huge threat to the environment and vastly increases production cost. The problem of how to promote the phosphorus absorption and utilization efficiency of peanuts is a major scientific challenge for the green development of peanut production in red soil regions [7,8].

The application of green manure in agricultural production is crucial to ensuring food security, improving the ecological environment, saving energy and reducing consumption [9]. Previous studies have found that the content of available phosphorus in soils of arable land increases significantly after green manure amendment [10,11]. Planting green manure in winter conforms to the crop rotation systems employed in the red soil region, making effective use of light, temperature, water and soil resources of winter fallow fields to produce a large amount of high-quality green manure, thereby improving the bioavailability of phosphorus and nutrients of red soil [5,12]. Therefore, the application of green manure crops in the red soil area with low phosphorus bioavailability to improve the phosphorus bioavailability of the red soil, substantially promotes the green development of peanut production. However, at present, both the characteristics of phosphorus absorption by peanut plants and the best mechanism of returning green manure to the field for the subsequent improvement of phosphorus bioavailability in red soils are still unclear, and further research is needed. Despite this urgent need, however, there are few reports of research on the effect of green manure on soil phosphorus bioavailability and peanut production in red soil. We hypothesized that:

- (i) Green manure incorporation in red soil can increase soil phosphorus bioavailability in peanut–green manure rotation systems, although different green manure species may display differing abilities to mobilize soil phosphorus;
- (ii) Growing and returning green manure increases biomass production and phosphorus accumulation of peanut.

To test these hypotheses, a peanut–green manure rotation field trial was conducted to study the effects of different treatments on the yield of peanut and phosphorus bioavailability. Four different species of green manure were compared against winter fallow and no-tillage treatments in the red soil region of south China.

## 2. Materials and Methods

### 2.1. Experimental Site

This study was initiated in September 2017 at the field experimental base of the Chinese Academy of Agricultural Science in Hongrang village, Zhanggong town, Jinxian city, Jiangxi province, China. The base is at 28°21′10″ N, 116°11′6″ E and an altitude of 26.7 m (Figure 1). It has a typical humid subtropical monsoon climate, with abundant water and heat resources. The rainfall is mainly concentrated from April to August. The annual average rainfall is 1858 mm, the annual average evaporation is 1150 mm, the annual average temperature is 17.92 °C, the annual effective radiation is 660.42 MJ m<sup>-2</sup> and the frost-free period is 262 days. The soil texture is sandy loam and it had the following chemical characteristics: Soil total organic matter (SOM) was 17.42 g kg<sup>-1</sup>, pH (H<sub>2</sub>O:soil = 5:1) was 5.34, alkali-hydrolyzable nitrogen was 98.98 mg kg<sup>-1</sup>, available phosphorus was 6.50 mg kg<sup>-1</sup> and available potassium was 55.53 mg kg<sup>-1</sup>. Peanut is one of the primary

crops in the region, Jiangxi province being one of the main red soil areas of China. Data in this manuscript were collected from October 2019 to September 2020.



**Figure 1.** Location of the experimental site.

## 2.2. Experimental Design and Field Management

The experimental design was based on the random block design. Planting mode was peanut (*Arachis hypogaea* L.)–green manure rotation, with 4 green manure species: milkvetch (*Astragalus sinicus* L., MV) (yujiangdaye), radish (*Raphanus sativus* var. *Longipinnatus*, R.) (aizaoluo No.1), brassica rape (*Brassica napus* L., BR) (zhongyoufei No.1), mustard rape (*Brassica juncea*, MR) (zhongjieyou No.1), as well as winter fallow and no-tillage. This equates to six treatments, with three replicates each, spanning a total of 18 plots. All of the green manure was sown in the second week of October in each year. The aboveground biomass was cut into 10–20 cm at the stage of flowering of oilseed rape in the second week of March and returned into the 15–30 cm soil layer by grubbing machine and rotary tillers machine. Peanut was sown 20 days after green manure return and harvested in the first week of September.

The chemical fertilizer used in the experiment comprised urea (46% N), superphosphate (12%  $P_2O_5$ ) and potassium chloride (60%  $K_2O$ ). An equal amount of fertilizer was applied as base fertilizer in all plots in the green manure season (N: $P_2O_5$ : $K_2O$  was 15:0:0  $kg\ hm^{-2}$ ). In the peanut season, the application rate of N,  $P_2O_5$  and  $K_2O$  fertilizer in all plots was 60, 90 and 135  $kg\ hm^{-2}$ , respectively. The full standard quantities of phosphorus and potassium fertilizers of the peanut season were used as base fertilizer, while 60% of standard nitrogen fertilizer was used as base fertilizer and 40% applied as topdressing in the budding stage.

## 2.3. Sampling and Analysis

Before green manure returning, a representative area of 1  $m^2$  was chosen in each plot and cut level with the ground in order to weigh yield of green manure and sample for nutrient testing at the same time. A peanut plant was sampled from each treatment and root nodules collected during the flowering stage for root nodule analysis. Peanut plant samples were taken during the harvest stage for yield calculation and nutrient testing. All plant samples were separated into leaf, seed, shell and roots, after which they were air dried, ground and sieved, then digested with  $H_2SO_4$ – $H_2O_2$  for nutrient testing. Phosphorus accumulation was calculated by the following equation:

$$PA = W_L \times P_L + W_S \times P_S + W_{SH} \times P_{SH} + W_R \times P_R$$

where  $W_L$  is the weight of leaf,  $W_S$  is the weight of seed,  $W_{SH}$  is the weight of shell,  $W_R$  is the weight of roots,  $P_L$  is the phosphorus content of leaf,  $P_S$  is the phosphorus content of seed,  $P_{SH}$  is the phosphorus content of shell,  $P_R$  is the phosphorus content of roots and PA is the phosphorus accumulation of peanut.

Mixed soil samples were collected after the peanut was harvested in each year. They were taken from the soil surface layer (0–20 cm) from 5 points in each plot using a soil borer. After removing animal and plant residues and pebbles, soil samples were air-dried and put

through a 100 or 200 mesh sieve for further analysis. SOM was measured by the  $K_2Cr_2O_7$  oxidation method, available N was measured by the Alkaline diffusion method, available phosphorus (AP) concentration of the samples was determined by the Olsen method after extraction with  $0.03 \text{ mol L}^{-1} \text{ NH}_4\text{F}$  and  $0.025 \text{ mol L}^{-1} \text{ HCl}$ , available K was measured by flame photometry after extraction with  $1 \text{ mol L}^{-1} \text{ NH}_4\text{OAc}$  and pH (1:10, soil to water rate) was determined with a pH meter [13].

For plant nutrient testing, total nitrogen concentration of the samples was determined by the Kjeldahl method, total phosphorus and total potassium were tested for by ICP (Germany) after extraction by heating digestion with  $\text{H}_2\text{SO}_4\text{-H}_2\text{O}_2$  [13]. For soil total phosphorus (STP), dry soil (2 g) was heated with 0.2 g sodium hydroxide at  $720^\circ\text{C}$  for 20 min. After cooling, the soil was washed out with distilled water. Then, 10 mL of  $4.5 \text{ M H}_2\text{SO}_4$  was added to the combined liquids and made up to 100 mL by adding distilled water. The extract was used for spectrophotometric analysis [14]. Total water-soluble phosphorus (TWSP) was determined by placing 2.00 g dry soil sample into 20 mL distilled water, oscillating under  $250 \text{ r min}^{-1}$  for 1 h, filtering through a  $0.45 \mu\text{m}$  filter, and digesting the filtrate with potassium persulfate. The extract was used for spectrophotometric analysis. Soil total phosphorus (STP) minus total water-soluble phosphorus (TWSP) equaled to particulate phosphorus (PP). Water-soluble inorganic phosphorus (WSIP) was determined by placing 2.00 g dry soil sample into 20 mL distilled water, oscillating under  $250 \text{ r min}^{-1}$  for 1 h, filtering through a  $0.45 \mu\text{m}$  filter, then using the extract for spectrophotometric analysis. Total water-soluble phosphorus (TWSP) minus water-soluble inorganic phosphorus (WSIP) equaled to water-soluble organic phosphorus (WSOP).

#### 2.4. Statistical Analysis

All data collected were statistically analyzed as a completely randomized design using ANOVA to test the differences in grain yield, soil nutrient contents, yield and yield components among treatments. Analysis of variance (ANOVA) was carried out to determine the differences between the measured parameters for different treatments. The least significant difference (LSD) at  $p = 0.05$  was used to elucidate any significant differences. All analyses were conducted using SPSS statistical software (ver. 11.0, SPSS, Chicago, IL, USA).

### 3. Results

#### 3.1. Analysis of the Meteorological Data of the Experimental Site

The precipitation and temperature at the experimental site during experimental periods are shown in Figure 2. Compared to the average value of the last ten years, the precipitation was lower, while the average temperature was higher during the green manure sowing stage and the seedling stage (from October to December in 2019) in the experimental period.

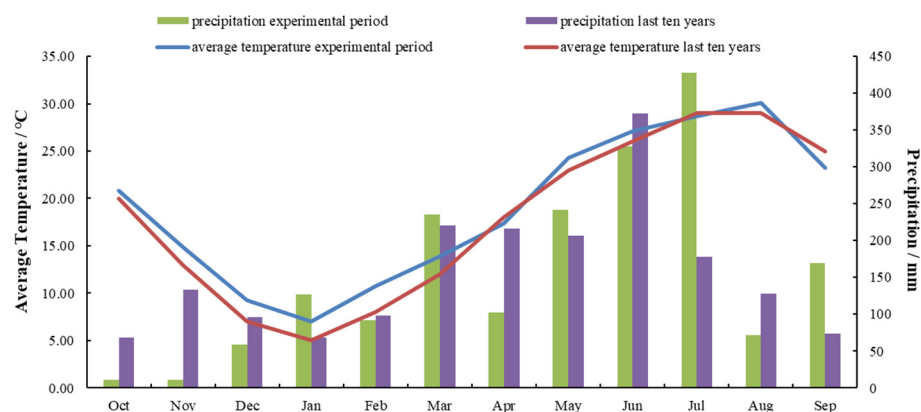
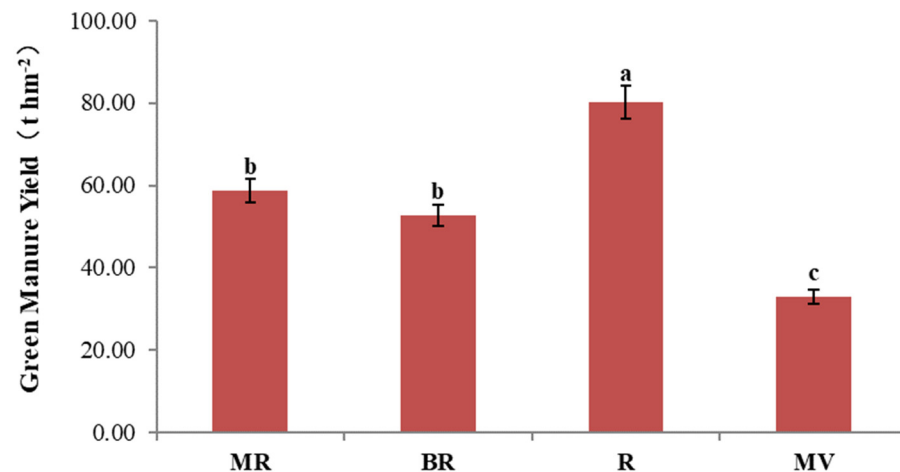


Figure 2. Meteorological data of the experimental site.

### 3.2. Green Manure Yield and Nutrient Accumulation

The highest yield of green manure was shown in radish (R), significantly higher than MR, BR and MV (Figure 3). Comparing between yields of MR and BR, there were no significant differences; while the yield of MV was significantly lower than the yield of other tested green manure.



**Figure 3.** Comparison of different green manure yield. Legend: Values followed by different letters represent significant differences between different green manure species ( $p < 0.05$ ); MR—mustard rape, BR—brassica rape, R—radish, MV—milkvetch.

Nutrient accumulation for each type of green manure is shown in Table 1. The total amount of all three nutrients (N, P and K) in different green manure crops was the highest in R, at  $40.35 \text{ kg hm}^{-2}$ , followed by BR and MR. Although the differences among those three treatments are insignificant, they are significantly higher than MV at  $20.67 \text{ kg hm}^{-2}$ . In terms of nitrogen accumulation, MV was significantly higher than other green manures, with nitrogen accounting for 61.26% of its three nutrient accumulations, while phosphorus and potassium accounted for 5.46% and 33.28%, respectively. The nitrogen accumulation of the other three green manures was between  $10 \text{ kg hm}^{-2}$  and  $11 \text{ kg hm}^{-2}$ , the phosphorus accumulation was between  $1.75 \text{ kg hm}^{-2}$  and  $2.68 \text{ kg hm}^{-2}$ , and the potassium accumulation was between  $18.41 \text{ kg hm}^{-2}$  and  $27.88 \text{ kg hm}^{-2}$ . The ratio of nitrogen, phosphorus and potassium in MV was approximately 12:1:6, and the ratio of the three nutrients in MR, BR and R was 4:1:7; 6:1:14 and 4:1:12, respectively. Phosphorus value in MR and R was significantly higher than in MV; potassium value in BR and R was significantly higher than in MV.

**Table 1.** Differences in nutrient accumulation of green manure species ( $\text{kg hm}^{-2}$ ).

Green Manure Species	N	P <sub>2</sub> O <sub>5</sub>	K <sub>2</sub> O	Total
MR	10.97 b	2.68 a	18.41 ab	32.05 a
BR	10.65 b	1.75 ab	25.01 a	37.41 a
R	10.06 b	2.41 a	27.88 a	40.35 a
MV	12.66 a	1.13 b	6.88 b	20.67 b

Legend: Data values followed by different letters represent significant differences between different green manure species ( $p < 0.05$ ); MR—mustard rape, BR—brassica rape, R—radish, MV—milkvetch, N—nitrogen.

### 3.3. Effect of Different Green Manure Treatments on Soil Properties and Soil Phosphorus Nutrients

The effects of different treatments on soil properties are shown in Table 2. Compared with no-tillage (NT) treatments, different green manure returning treatments had significant effects on soil pH. The pH of MR, BR, R and MV soils decreased significantly by 9.24%, 7.23%, 8.74% and 11.76%, respectively. There was no significant differences in pH between



the green manure return and winter fallow (WF) treatments. There were also differences found in soil organic matter content between different treatments. Compared with the WF treatment, the differences in organic matter content of the green manure treatments were not significant. Compared with the NT treatment, the organic matter content of the green manure returning treatment had a decreasing trend. Among them, the organic matter content of the BR treatment decreased significantly by 22.68%. There was no significant difference in available nitrogen content among different treatments. Compared with the NT treatment, the available potassium content of the MR, BR, R and MV treatments was significantly increased by 20.93%, 25.60%, 23.76% and 18.10%, respectively. There was no significant difference in the content of available potassium between the WF treatment and the green manure returning treatment or NT treatment.

**Table 2.** Effects of different treatments on soil basic properties.

Treatment	pH	SOM g kg <sup>-1</sup>	Alkaline Hydrolysis N mg kg <sup>-1</sup>	Available K mg kg <sup>-1</sup>
MR	5.40 ± 0.14 b	17.80 ± 0.73 ab	115.95 ± 11.07 a	126.89 ± 17.65 a
BR	5.52 ± 0.13 b	17.01 ± 0.41 b	114.45 ± 11.53 a	117.16 ± 14.85 a
R	5.43 ± 0.09 b	17.69 ± 1.40 ab	110.33 ± 3.53 a	129.33 ± 21.86 a
MV	5.25 ± 0.23 b	17.43 ± 3.14 ab	111.82 ± 11.02 a	112.16 ± 13.29 a
WF	5.43 ± 0.29 ab	17.67 ± 4.21 ab	115.14 ± 25.40 a	95.31 ± 15.71 ab
NT	5.95 ± 0.27 a	22.00 ± 3.04 a	120.65 ± 13.13 a	78.90 ± 10.30 b

Legend: Data are expressed as means ± standard deviation; values followed by different letters represent significant differences between different treatments ( $p < 0.05$ ); MR—mustard rape, BR—brassica rape, R—radish, MV—milkvetch, WF—winter fallow, NT—no-tillage, SOM—soil organic matter, N—nitrogen, K—potassium.

The effects of different treatments on soil phosphorus components are shown in Table 3. The results showed that compared with the WF and NT treatments, soil total phosphorus (STP) content of the green manure treatments had an increasing trend, but the difference was not significant. The particulate phosphorus (PP) and available phosphorus were significantly affected by different green manure treatments. The particulate phosphorus and soil available phosphorus contents in the green manure treatments were significantly higher than those in the WF treatment. Compared with the WF treatment, the content of particulate phosphorus in BR, R and MV was significantly increased by 6.55%, 3.66% and 2.50%, respectively; the available phosphorus content in MR, BR, R and MV was significantly increased by 20.93%, 25.60%, 23.76% and 18.10%, respectively. Compared with NT treatment, the content of particulate phosphorus in MR, BR, R and MV was significantly increased by 2.80%, 10.60%, 7.60% and 6.40%, respectively, while there was no significant difference in the content of available phosphorus. The effects of different treatments on the water-soluble phosphorus (WSP), water-soluble inorganic phosphorus (WSIP) and water-soluble organic phosphorus (WSOP) contents of the soil had no obvious regularity, and the differences among different treatments did not reach a significant level.

**Table 3.** Effects of different treatments on components of soil phosphorus.

Treatment	STP g kg <sup>-1</sup>	WSP mg kg <sup>-1</sup>	PP g kg <sup>-1</sup>	WSIP mg kg <sup>-1</sup>	WSOP mg kg <sup>-1</sup>	AP mg kg <sup>-1</sup>
MR	0.523 ± 0.003 a	4.47 ± 2.59 a	0.514 ± 0.006 b	0.139 ± 0.000 a	4.281 ± 1.116 a	8.55 ± 3.06 a
BR	0.557 ± 0.046 a	3.48 ± 2.31 a	0.553 ± 0.048 a	0.125 ± 0.059 a	3.276 ± 0.201 a	8.88 ± 2.67 a
R	0.543 ± 0.032 a	3.48 ± 2.50 a	0.538 ± 0.0298 a	0.111 ± 0.048 a	3.401 ± 2.505 a	8.75 ± 1.38 a
MV	0.534 ± 0.001 a	2.45 ± 1.30 a	0.532 ± 0.002 a	0.104 ± 0.088 a	2.284 ± 1.223 a	8.35 ± 0.557 a
WF	0.522 ± 0.068 a	3.34 ± 0.21 a	0.519 ± 0.069 b	0.139 ± 0.087 a	3.149 ± 0.973 a	7.07 ± 0.139 b
NT	0.506 ± 0.034 a	4.32 ± 2.99 a	0.500 ± 0.008 b	0.125 ± 0.072 a	4.216 ± 0.816 a	8.84 ± 3.20 a

Legend: Data are expressed as means ± standard deviation; values followed by different letters representing significant differences between different treatments ( $p < 0.05$ ); MR—mustard rape, BR—brassica rape, R—radish, MV—milkvetch, WF—winter fallow, NT—no-tillage, STP—soil total phosphorus, TWSP—total water-soluble phosphorus, PP—particulate phosphorus, WSIP—water-soluble inorganic phosphorus, WSOP—water-soluble organic phosphorus.

### 3.4. Effect of Different Green Manure Treatments on Peanut Growth and Phosphorus Nutrient Absorption

The effects of different treatments on peanut growth and yield are shown in Table 4. The results showed that the green manure treatment, particularly MR, significantly increased the number of nodules per peanut plant and the weight of nodules per plant. Comparing the yield of peanut kernels of different treatments, the difference in performance between different green manure treatments was large: yields from MR and BR treatments were significantly higher than that from R, while there was no significant difference between all green manure returning treatments and WF treatments. Among green manure treatments, the peanut biomass of BR treatment was the highest, reaching 14,685 kg hm<sup>-2</sup>, and the peanut biomass of MV treatment was the lowest at 13,244 kg hm<sup>-2</sup>. Compared with the WF treatment, the peanut biomass of MR, BR and R treatments increased significantly by 19.51%, 29.83% and 19.77%, respectively, while the MV treatment increased peanut biomass by 17.09%, without reaching a significant level.

**Table 4.** Effects of green manure return on the growth of peanut.

Treatment	Root Nodule Number Plant <sup>-1</sup>	Root Nodule Weight g Plant <sup>-1</sup>	Peanut Kernel Yield kg hm <sup>-2</sup>	Biomass kg hm <sup>-2</sup>
MR	10.81 a	0.141 a	3055 a	13,518 a
BR	9.00 a	0.120 ab	3431 a	14,685 a
R	8.63 ab	0.123 ab	2458 b	13,547 a
MV	7.27 b	0.102 b	2578 ab	13,244 ab
WF	7.11 b	0.119 ab	2805 ab	11,311 b

Legend: values followed by different letters represent significant differences between different treatments ( $p < 0.05$ ); MR—mustard rape, BR—brassica rape, R—radish, MV—milkvetch, WF—winter fallow.

The effects of different treatments on the absorption of phosphorus nutrients in peanuts are shown in Table 5. The results showed that compared with the WF treatment, the total phosphorus content of stems and leaves of peanut plants from all green manure treatments showed an increasing trend, while the total phosphorus content of peanut kernels had no obvious difference. The variation among different treatments on the total phosphorus content of peanut kernels, stems and leaves were not significant. However, the total phosphorus content of peanut shell in the MV and R treatments were significantly higher than that in the WF treatment, increasing by 33.47% and 60.66%, respectively, while the differences in BR and MR were not significant. The total phosphorus accumulation in all green manure treatments was higher than that in the WF treatment, and the MV treatment reached a significant level at 18.83%. Other green manure treatments showed a trend of increasing total phosphorus accumulation, but the difference was not significant.

**Table 5.** Effects of green manure return on phosphorus uptake of peanut.

Treatment	Phosphorus Content %			Phosphorus Accumulation kg hm <sup>-2</sup>
	Peanut Kernel	Stem and Leaf	Peanut Shell	
MR	0.4045a	0.1750a	0.0739ab	30.11ab
BR	0.4145a	0.1699a	0.0663b	31.72ab
R	0.4723a	0.2577a	0.0925a	30.80ab
MV	0.4596a	0.1857a	0.1113a	33.43a
WF	0.4174a	0.1330a	0.0693b	28.13b

Legend: values followed by different letters represent significant differences between different treatments ( $p < 0.05$ ); MR—mustard rape, BR—brassica rape, R—radish, MV—milkvetch, WF—winter fallow.

## 4. Discussion

### 4.1. Effect of Green Manure Returning on Bioavailability of Soil Phosphorus in Red Soil

Due to strong immobilization, phosphorus has poor mobility in soil. It is easily chemically fixed by ions, such as calcium, iron, and aluminum, in soil as forms of phosphorus

with low bioavailability. The effect of the fixation of phosphorus in red soil is stronger than in other soil types [5]. The planting and returning of green manure is an important measure for green production in red soil; it plays an important role in improving the bioavailability of phosphorus in red soil, preventing soil erosion and improving the ecological environment of farmland [15,16]. Existing studies have shown that in major food crops, such as wheat [17], rice [10], maize [18] and in orchards [19], the soil available phosphorus content increased significantly after the green manure was returned to the field. Therefore, adding green manure to red soil is an effective method to solve the problem of low phosphorus bioavailability in red soil [5,12].

After the green manure is returned to the field, a series of physicochemical and biological reactions take place in the micro-zone of its residues during the process of decomposition, which will affect the bioavailability of soil phosphorus [20]. Green manure can provide a large carbon source, greatly improve the soil carbon and phosphorus ratio, and promote the growth and activity of microorganisms [21]. Microorganisms, in turn, can release organic acids, phosphatases and other substances to activate soil insoluble phosphorus as the form of microbial biomass phosphorus, thereby improving soil phosphorus bioavailability [22]. Additionally, returning green manure can decrease soil P loss due to soil surface runoff [23]. In this study, after 4 years of continuous green manure returning, compared with the winter fallow treatment, the content of particulate phosphorus in the green manure returning treatment significantly increased by 4.24% on average, and the available phosphorus content in the green manure returning treatment was significantly increased by 22.10% on average. The results of previous studies in rice and green manure rotation systems showed that the application of green manure significantly increased soil bioavailable phosphorus content by 25–30% [24], which is similar to the results of our research.

#### 4.2. Effect of Green Manure Returning on Peanut Yield in Red Soil

Currently, research into the effects of green manure has been mainly related to staple food crops [25–27]. Previous studies have reported that acid phosphorus and rice root enzyme activities contributed to the promotion of phosphorus absorption and accumulation in rice, enhancing rice tillering, root system growth, ear nutrient accumulation, and plant dry weight, all of which ultimately increases the rice yield [28,29]. Research into green manure returning in relation to peanut yield is rare, and the few related studies are mainly from China and India. It was found that compared with winter fallow treatment, wheat planted in winter and returned as green manure before peanut sowing increased the yield of peanut pods and seeds by 14.07% and 15.24%, respectively [30]. Compared with the single application of the full amount of compound fertilizer, the yield of peanut was still increased by 3.1%–7.2% after the application of 1500 kg hm<sup>−2</sup> green manure combined with 80%–90% of compound fertilizer [31]. In India, intercropping with green manure sesbania or green gram significantly increased peanut pod yield in the peanut-wheat rotation system [32].

However, studies have also shown that peanut yield is reduced by competition for soil nutrients, moisture and light between peanuts and intercropped green manure crops in a post-intercropping rotation experiment [33]. In addition, the difference in the types of green manure also had a significant effect on peanut yield. The effects of three green manures of triticale, ryegrass and *Orychophragmus violaceus* on peanut yield showed that the peanut pod yield from triticale treatment was the lowest, 655.21 kg hm<sup>−2</sup> and 425.00 kg hm<sup>−2</sup> lower than those of ryegrass and *Orychophragmus violaceus*, respectively [34]. In this experiment, compared with the winter fallow treatment, the rate of increase in peanut yield from different green manure returning was varying, and the difference in peanut biomass between the MR, BR, R and winter fallow treatment reached a significant level. Peanut kernel yield in MR and BR had an increasing trend, but the difference was not significant. In terms of phosphorus absorption and utilization by peanut, compared with the winter fallow treatment, the phosphorus accumulation of peanut plants in different green manure treatments showed an increasing trend, and the phosphorus accumulation



from MV treatment reached a significant level. This implies that the effects of green manure returning on peanut yield are quite different under different soil types and different green manure types in different regions. In addition to the fact that the soil available phosphorus content in all treatments in this experiment was lower than  $10 \text{ mg kg}^{-1}$ , indicating that soil phosphorus was in a state of serious deficiency, comparing the differences in soil available phosphorus content and peanut yield between different green manure returning treatments, it remains evident that the treatment with high available phosphorus content also has higher peanut yield.

## 5. Conclusions

The effect of different green manure returning on red soil phosphorus bioavailability is mainly manifested in the increase in particulate phosphorus content and available phosphorus content. After returning  $15\sim 22.5 \text{ t hm}^{-2}$  of green manure annually for 4 years, the increase in soil particulate phosphorus content was between 2.5%~6.55%, and the increase in soil available phosphorus content was between 18.10%~25.60%, notably higher when milkvetch and brassica rape were used. The phosphorus accumulation of peanut plants in milkvetch returning treatments was significantly higher than that in the winter fallow treatment. Green manure returning, particularly in the case of milkvetch, had a significant effect on phosphorus bioavailability, peanut biomass and phosphorus uptake in red soil.

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