

Effects of Faba Bean Root Exudates on Available Nutrients and Microbial Quantity in Purple Soil (Postprint)

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Abstract

To improve purple soil fertility and rationally utilize broad bean resources, this study first collected broad bean root exudates through solution culture method, and obtained concentrated solution via vacuum rotary evaporator, then conducted indoor soil incubation experiments, namely adding two levels [6 mL (low amount) and 12 mL (high amount)] of broad bean root exudate concentrate to three types of 60 g purple soils (acidic purple soil, alkaline purple soil, and neutral purple soil), and incubating them in darkness at 25 °C for 15 days, thereby exploring the effects of broad bean root exudates on available nutrients and microbial quantities in different purple soils. The results showed: across the three purple soils, compared with the control, after adding low and high amounts of broad bean root exudate concentrate, soil alkaline hydrolyzable nitrogen content and pH were both significantly reduced; while soil available phosphorus, available potassium, available iron, available zinc contents, and microbial quantities were all significantly increased, and this trend was enhanced with increasing addition amount of root exudate concentrate. Compared with the other two purple soils, the addition of broad bean root exudate concentrate to acidic purple soil showed the most pronounced decreasing effect on soil alkaline hydrolyzable nitrogen content and pH, and the most significant increasing effect on soil bacterial and fungal quantities, with increases of -32.00%, -4.51%, 3.51-fold, and 9.00-fold compared with the control, respectively. Compared with the other two purple soils, the addition of high amount of broad bean root exudate concentrate to alkaline purple soil exhibited the strongest activation effect on soil available phosphorus, available potassium, available zinc, and available iron contents, which were 4.48-fold, 2.04-fold, 147.10%, and 128.00% of the control, respectively. On neutral purple soil, the effects of adding high amount of broad bean root exudate concentrate on the above soil available nutrients and soil microbial quantities were intermediate between acidic purple soil and

alkaline purple soil. In summary, broad bean root exudates had different promoting effects on available nutrients (except soil alkaline hydrolyzable nitrogen and pH) and soil microbial activity in different purple soils, which has profound implications for purple soil fertility improvement.

Full Text

Effects of Faba Bean (*Vicia faba* L.) Root Exudates on Soil Available Nutrients and Microbial Populations in Different Purple Soils

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Abstract

To improve purple soil fertility and promote rational utilization of faba bean resources, this study investigated the effects of faba bean root exudates on available nutrients and microbial populations in different purple soils. Root exudates were collected via solution culture and concentrated using a vacuum rotary evaporator. A soil incubation experiment was then conducted by adding two levels of concentrated root exudate solution—6 mL (low) and 12 mL (high)—to 60 g samples of three purple soil types (acidic, alkaline, and neutral). The soils were incubated in darkness at 25 °C for 15 days. Results showed that, compared with the control, both low and high additions of faba bean root exudate significantly decreased soil alkali-hydrolyzable nitrogen content and pH, while significantly increasing available phosphorus, potassium, iron, zinc, and microbial populations across all three soil types. These effects intensified with increasing exudate concentration. Compared with the other two soils, acidic purple soil exhibited the most pronounced decreases in alkali-hydrolyzable nitrogen and pH, along with the greatest increases in bacterial and fungal populations (reaching 4.51 and 9.00 times the control, respectively). Alkaline purple soil showed the strongest activation effects on available phosphorus, potassium, zinc, and iron under high exudate addition, with increases of 4.48-fold, 2.04-fold, 147.10%, and 128.00% over the control, respectively. In neutral purple soil, the effects of high exudate addition on these parameters were intermediate between those observed in acidic and alkaline soils. In conclusion, faba bean root exudates differentially enhanced the availability of most soil nutrients (except alkali-hydrolyzable nitrogen and pH) and microbial activity across purple soil types, with significant implications for purple soil fertility management.

Keywords: Faba bean; Purple soil; Root exudate; Available nutrient; Microbial population

Introduction

Purple soil, a non-zonal soil formed from purple rock weathering under subtropical and tropical monsoon climates, is concentrated in the hilly regions and low mountainous areas below 800 m elevation in the Sichuan Basin. It represents the second most important cultivated land in Sichuan Province after paddy soil, with alkaline purple soil covering over 4 million hectares, neutral purple soil over 2.66 million hectares, and acidic purple soil over 2 million hectares. Although rich in mineral nutrients and highly valuable for agriculture, purple soil suffers from severe water and soil erosion due to its loose structure and susceptibility to weathering, with 48.8% of purple soil area affected by erosion. Coupled with population pressure and shrinking arable land, soil quality has deteriorated severely, leading to soil compaction, shallow plow layers, and declining water and nutrient retention capacity, which progressively reduces grain production. Therefore, improving and maintaining purple soil fertility has become an urgent requirement for sustainable agriculture in this region.

Root exudates, primarily low- and high-molecular-weight organic compounds secreted by plant roots during growth, serve as crucial mediators of material, energy, and information exchange between plants and soil. They represent the organic hub of the rhizosphere microecosystem and are key factors maintaining its vitality while playing important roles in substance migration and regulation. Previous studies have demonstrated that root exudates can activate soil phosphorus, promote nitrogen transformation from inorganic to organic forms, and enhance the availability of potassium, iron, and zinc. Soil microorganisms drive most biochemical transformations in soil and serve as important indicators of soil fertility. Root exudates provide abundant nutrients, energy, and carbon and nitrogen sources for soil microorganisms, significantly promoting microbial activity and influencing microbial community composition, abundance, and distribution.

Faba bean (*Vicia faba*) is an important economic crop and green manure, with China ranking first in global production area, particularly in Sichuan and Chongqing. Current research on faba bean has focused on disease control via root exudates, soil improvement effects as green manure, and yield and nutrient uptake in intercropping systems with wheat (*Triticum aestivum*) and maize (*Zea mays*). However, few studies have examined the effects of faba bean root exudates on soil fertility. This study therefore investigated the impacts of faba bean root exudates on different purple soils through soil incubation experiments to provide scientific evidence for purple soil fertility management and faba bean resource utilization.

Materials and Methods

1.1 Experimental Materials

Faba bean seeds were purchased from Henan Huafeng Grass Industry Technology Co., Ltd. Three types of purple soil were tested: acidic purple soil

collected from Yanzi Village, Simianshan Town, Jiangjin District, Chongqing; alkaline purple soil from Shuangjiang Village, Shuangjiang Town, Tongnan County, Chongqing; and neutral purple soil from Guanlong Village, Dashi Town, Hechuan District, Chongqing. Soils were sampled from the plow layer using multipoint mixing methods, air-dried, and stored. Basic physicochemical properties are presented in . The experiment was conducted from March to June 2014 in the Plant Nutrition Laboratory at Southwest University.

1.2.1 Collection of Faba Bean Root Exudates

Uniformly sized, plump faba bean seeds were surface-sterilized in 15% H₂O₂ for 15 minutes, rinsed with deionized water, and germinated on moist quartz sand in trays covered with wet filter paper at 25 °C in darkness. After germination, seedlings were grown under normal light until developing three leaves, then transferred to 1/2-strength nutrient solution for one week before full-strength nutrient solution. Plants were cultivated in 2 L pots (15 plants per pot, 10 pots total). Nutrient solution was replaced every 3 days, with aeration and 12-hour light periods (8:30-20:30) daily. The nutrient solution composition (mol · L⁻¹) was: K₂SO₄ 0.75 × 10⁻³; KCl 0.1 × 10⁻³; KH₂PO₄ 0.25 × 10⁻³; (NH₄)₂MoO₄ · 4H₂O 5.0 × 10⁻⁹; Ca(NO₃)₂ 2.0 × 10⁻³; MgSO₄ · 7H₂O 0.6 × 10⁻³; H₃BO₃ 1.0 × 10⁻⁵; CuSO₄ · 5H₂O 5.0 × 10⁻⁷; MnSO₄ · 7H₂O 1.0 × 10⁻⁶; Fe-EDTA 1.0 × 10⁻⁴\$.

Root exudates were collected 40 days after transplanting following established methods [17,23-24]. After 2 hours of light exposure, 15 plants per pot were removed from the nutrient solution, rinsed four times with deionized water, and transferred to 1 L beakers containing 450 mL deionized water. Roots were maintained under dark conditions for 4 hours to collect exudates. Exudates from all 10 pots were combined and concentrated 40-fold under vacuum at 40 °C, yielding a final concentrate from 150 plants. Each 0.75 mL of concentrate represented the 4-hour exudate production of a single plant. The concentrate was stored at -20 °C until use.

1.2.2 Soil Incubation Experiment

The soil incubation experiment followed the method of Sun et al. [24]. Two exudate treatments were established: high (12 mL root exudate concentrate) and low (6 mL concentrate + 6 mL deionized water), with 12 mL deionized water as the control (CK). Sixty grams of air-dried, 80-mesh sieved acidic, alkaline, or neutral purple soil were placed in 100 mL beakers. Solutions were evenly dripped onto soils to maintain moisture at approximately 80% of field water capacity. Each treatment was replicated four times. Soils were incubated in darkness at 25 °C for 15 days, with daily water loss replenished by weight using neutral deionized water. At the end of incubation, all soil from each replicate was removed and prepared for analysis according to standard methods.

1.3 Measurement Indicators and Methods

Soil alkali-hydrolyzable nitrogen was determined by the diffusion method, available potassium by NH_4Ac -flame photometry, available phosphorus by the Olsen method, available zinc and iron by DTPA extraction-atomic absorption spectrophotometry, and pH by water extraction and pH meter [25]. Microbial populations were quantified by plate count methods: bacteria on beef extract peptone agar, actinomycetes on modified Gause' s No. 1 medium, and fungi on Martin' s Bengal streptomycin medium [26].

1.4 Data Processing

Data were analyzed using SPSS 18.0 and Microsoft Excel 2007 software.

Results

2.1 Effects of Faba Bean Root Exudates on Purple Soil Nutrient Content

As shown in , addition of 6 mL and 12 mL faba bean root exudate concentrate significantly decreased soil alkali-hydrolyzable nitrogen content in acidic, alkaline, and neutral purple soils compared with the control, with the magnitude of reduction increasing with exudate concentration. In acidic purple soil, alkali-hydrolyzable nitrogen decreased by 32.00% and 24.40% with 12 mL and 6 mL additions, respectively; in alkaline purple soil, corresponding decreases were 6.00% and 2.50%; and in neutral purple soil, 25.40% and 12.50%. Thus, the nitrogen reduction effect was most pronounced in acidic purple soil.

Soil available phosphorus increased significantly in alkaline and neutral purple soils with both 12 mL and 6 mL additions, with the enhancement increasing with exudate concentration. In acidic purple soil, only the 12 mL addition significantly increased available phosphorus compared with the control, while the 6 mL treatment showed no difference. The 12 mL and 6 mL treatments increased available phosphorus to 1.33-fold and 1.14-fold of control in acidic soil, 4.48-fold and 3.06-fold in alkaline soil, and 1.49-fold and 1.24-fold in neutral soil, respectively. These results indicate that faba bean root exudates had the strongest phosphorus activation effect in alkaline purple soil.

Similarly, soil available potassium increased significantly in alkaline and neutral purple soils with both exudate additions, with enhancement increasing with concentration. In acidic purple soil, only the 12 mL addition significantly increased available potassium. The 12 mL and 6 mL treatments increased available potassium to 1.88-fold and 1.41-fold of control in acidic soil, 2.04-fold and 1.56-fold in alkaline soil, and 1.62-fold and 1.37-fold in neutral soil, respectively. Thus, potassium activation was also strongest in alkaline purple soil.

Available iron content increased significantly with both 12 mL and 6 mL additions in acidic purple soil, while in alkaline and neutral purple soils, only the 12

mL addition produced significant increases over the control. The 12 mL treatment increased available iron by 15.60% in acidic soil, 28.00% in alkaline soil, and 17.30% in neutral soil, demonstrating the strongest iron activation effect in alkaline purple soil. For available zinc, neither exudate addition significantly affected acidic purple soil, while the 12 mL addition significantly increased zinc in alkaline soil, and both additions increased zinc in neutral soil. The 12 mL treatment increased available zinc by 6.73% in acidic soil, 47.10% in alkaline soil, and 17.90% in neutral soil, again showing the strongest effect in alkaline purple soil.

2.2 Effects of Faba Bean Root Exudates on Purple Soil pH

As shown in , addition of 12 mL and 6 mL faba bean root exudate concentrate significantly decreased soil pH in alkaline and neutral purple soils compared with the control, with the reduction increasing with exudate concentration. In acidic purple soil, both additions significantly reduced pH, though the two concentrations did not differ significantly. The pH reductions with 12 mL and 6 mL additions were 4.51% and 3.25% of control in acidic soil, 1.73% and 0.58% in alkaline soil, and 3.21% and 1.20% in neutral soil, respectively. Thus, the pH reduction effect was greatest in acidic purple soil.

2.3 Effects of Faba Bean Root Exudates on Purple Soil Microbial Populations

As shown in , in acidic purple soil, only the 12 mL addition significantly increased bacterial and fungal populations to 4.51-fold and 10.00-fold of control, respectively, while actinomycetes showed no significant change. In alkaline purple soil, both 12 mL and 6 mL additions significantly increased bacterial, fungal, and actinomycete populations, with the 12 mL treatment increasing them to 2.22-fold, 4.00-fold, and 2.02-fold of control, respectively. In neutral purple soil, both additions significantly increased bacterial and fungal populations, with the 12 mL treatment increasing them to 3.59-fold and 5.00-fold of control, respectively, while actinomycetes were unaffected. These results demonstrate that high concentrations of faba bean root exudates had the most pronounced effects on bacterial and fungal populations in acidic purple soil.

Discussion and Conclusion

Plants secrete low-molecular-weight organic acids, amino acids, and other compounds from their roots during growth, collectively termed root exudates. These exudates play crucial roles in mineral nutrient transformation and microbial activity in soil. The observed significant decrease in soil alkali-hydrolyzable nitrogen following faba bean root exudate addition aligns with previous research [8,14]. This reduction likely occurs because root exudates promote microbial proliferation, and enhanced microbial metabolism increases demand for inorganic nitrogen, thereby decreasing soil alkali-hydrolyzable nitrogen content [8,14]. Al-

ternatively, root exudates may reduce soil urease activity, which catalyzes the conversion of organic to inorganic nitrogen and correlates positively with soil nitrogen availability [27–28]. The greatest nitrogen reduction in acidic purple soil may be attributed to its low pH, active microbial communities, and inherently lower urease activity.

Root exudates are critically important for enhancing phosphorus bioavailability in soil. This study demonstrated that faba bean root exudates increased soil available phosphorus content in a concentration-dependent manner, indicating their role in activating sparingly soluble phosphorus. Similar results have been reported for faba bean intercropped with maize, where organic acids and protons released from faba bean roots acidified the rhizosphere and mobilized insoluble phosphorus, promoting phosphorus uptake by maize [29]. Other studies have reported comparable effects with different plant species [30–32]. The increased phosphorus availability may be attributed to several mechanisms: (1) low-molecular-weight organic acids in root exudates reduce soil pH [34], increasing the solubility of insoluble phosphorus compounds; (2) organic acids chelate Al^{3+} , Fe^{3+} , and Ca^{2+} , forming complexes that enhance cation availability and promote phosphorus release from Al-P, Fe-P, and Ca-P complexes [35]; and (3) root exudates may increase soil phosphatase activity, which reflects improved phosphorus supply [28]. The strongest phosphorus activation effect in alkaline purple soil may be related to its higher content of sparingly soluble phosphorus compounds such as Ca-P, though further investigation is needed.

Compared with nitrogen and phosphorus, soil potassium is more abundant, with soil representing a vast natural potassium reservoir. However, readily available potassium constitutes only 0.1%–2% of total potassium, while slowly available potassium accounts for 2%–8%, and mineral potassium unavailable to crops comprises 90%–98% of soil potassium. This study showed that faba bean root exudates significantly increased soil available potassium, consistent with previous findings [36]. This effect likely results from the high organic acid content in root exudates [18,37]. Dissociated H^+ from organic acids can promote dissolution of insoluble minerals through acid dissolution and form hydronium ions similar in size to K^+ , thereby replacing lattice potassium and releasing K^+ [37]. Additionally, small organic acids with adjacent carboxyl and hydroxyl groups readily form metal-organic complexes with mineral structure cations, accelerating mineral decomposition [37]. Low-molecular-weight organic acids thus effectively promote mineral potassium release through combined chelation and acidic hydrolysis mechanisms. Oxalic acid exhibits particularly strong complexing and hydrolytic capacity, while polybasic acids such as citric, malic, and tartaric acids primarily act through complexation, and monobasic acids like lactic and acetic acids have limited effects. The greater potassium activation effect in alkaline purple soil may be attributed to its higher mineral potassium content and total potassium levels, though this requires further verification.

Micronutrient deficiencies, particularly iron and zinc, commonly occur in calcareous soils and significantly affect crop growth. These deficiencies are associated

with soil pH, calcium carbonate content, and water status. This study demonstrated that faba bean root exudates reduced soil pH while increasing available iron and zinc, consistent with previous research [10,11]. Lower pH increases H^+ concentration in soil solution, which can displace Fe and Zn from soil surfaces [38-40]. Root exudates also chelate iron and zinc through complexation [39], and may form stable complexes with Ca^{2+} , reducing Ca^{2+} concentration and decreasing calcium compound adsorption and fixation of zinc, thereby releasing soil zinc [39]. The enhanced activation of zinc and iron by high concentrations of faba bean root exudates in alkaline purple soil may be related to the abundance of iron and zinc forms susceptible to complexation, though specific mechanisms require further investigation.

Soil microorganisms play vital roles in organic matter degradation, inorganic transformation, nitrogen fixation, plant nutrition, and soil fertility maintenance, making them crucial for soil ecosystem balance. The abundance of fungi, bacteria, and actinomycetes serves as an important biological indicator of soil fertility [13,41]. This study showed that faba bean root exudates increased populations of all three microbial groups, consistent with previous reports [23,42-43], because the abundant sugars, amino acids, and vitamins in root exudates provide ample nutrients for microbial growth and reproduction. However, some studies have reported different effects; for example, Chinese onion root exudates increased bacterial and actinomycete populations but decreased fungal populations [44], possibly due to differences in exudate composition or soil type. The most significant increases in bacterial and fungal populations in acidic purple soil may be attributed to its pH being more favorable for microbial proliferation.

In summary, addition of faba bean root exudate concentrate decreased soil alkali-hydrolyzable nitrogen content and pH while increasing available phosphorus, potassium, iron, zinc, and microbial populations. High concentrations of faba bean root exudates produced significant enhancement effects, though the magnitude varied among purple soil types. These findings demonstrate that cultivating faba bean can activate unavailable phosphorus, potassium, iron, and zinc in purple soils and enhance microbial activity. The activation effects were most pronounced for phosphorus, potassium, zinc, and iron in alkaline purple soil. This study provides important scientific evidence for purple soil fertility management and rational faba bean utilization. However, as root exudates were collected using solution culture, the results may differ from those obtained under soil culture or field conditions and require further validation.

References

- [1] Lin C W, Tu S H, Huang J J, et al. Effects of hedgerows on soil erosion and soil fertility on sloping farmland in the purple soil area[J]. *Acta Ecologica Sinica*, 2007, 27(6): 2190-2198
- [2] Zhu B, Chen S, You X, et al. Soil fertility restoration on degraded upland of purple soil[J]. *Acta Pedologica Sinica*, 2002, 39(5): 743-749
- [3] Zhang D D, Liang X H, Wang J. A review of plant root exudates[J]. *Chinese*

- Agricultural Science Bulletin, 2014, 30(35): 314-320
- [4] Dijkstra F A, Cheng W X. Interactions between soil and tree roots accelerate long-term soil carbon decomposition[J]. Ecology Letters, 2007, 10(11): 1046-1053
- [5] Zhang F S, Shen J B, Feng G. Rhizosphere Ecology: Process and Regulation[M]. Beijing: China Agricultural University Press, 2009: 158-163
- [6] Paul G C, Bokhtiar S M, Islam M J. Contribution of different green manuring to phosphate nutrition of sugarcane[J]. Bangladesh Journal of Sugarcane, 1999, 21: 76-80
- [7] Shen H, Yan X L, Zhao M, et al. Exudation of organic acids in common bean as related to mobilization of aluminum- and iron-bound phosphates[J]. Environmental and Experimental Botany, 2002, 48(1): 1-9
- [8] Landi L, Valori F, Ascher J, et al. Root exudate effects on the bacterial communities, CO₂ evolution, nitrogen transformations and ATP content of rhizosphere and bulk soils[J]. Soil Biology and Biochemistry, 2006, 38(3): 509-516
- [9] Li T X, Ma G R, Zhang X Z. Root exudates of potassium-enrichment genotype grain amaranth and their activation on soil mineral potassium[J]. Chinese Journal of Applied Ecology, 2006, 17(3): 368-372
- [10] Zuo Y M, Chen Q, Zhang F S. The mechanisms of root exudates of maize in improvement of iron nutrition of peanut in peanut/maize intercropping system by ¹⁴C tracer technique[J]. Acta Agriculturae Nucleatae Sinica, 2004, 18(1): 43-46
- [11] Hu X Y, Li X Y, Xie Z C. Differences of Zn uptake in various pakchoi cultivars and relationship between Zn uptake and root exudates[J]. Plant Nutrition and Fertilizer Science, 2002, 8(2): 215-219
- [12] Zhang X Z, Li T X, Wang Y D. Relationship between growth environment and root exudates of plants: A review[J]. Chinese Journal of Soil Science, 2007, 38(4): 785-789
- [13] Zheng S Z, Xiao Q L, Wu W D, et al. Relationship among microbial groups, enzyme activity and physico-chemical properties under different artificial forestry in hilly red soil[J]. Chinese Journal of Eco-Agriculture, 2008, 16(1): 57-61
- [14] Fisk L M, Barton L, Jones D L, et al. Root exudate carbon mitigates nitrogen loss in a semi-arid soil[J]. Soil Biology and Biochemistry, 2015, 88: 380-389
- [15] Lu Y F, Zhou Y R, Nakai S, et al. Stimulation of nitrogen removal in the rhizosphere of aquatic duckweed by root exudate components[J]. Planta, 2014, 239(3): 591-603
- [16] Jiao B. Chinese Green Manure[M]. Beijing: China Agriculture Press, 1986: 27-28
- [17] Du C Z, Zhang J J, Zeng X Q, et al. Effects of different sowing dates on agronomic characters and yield of broad bean in Chongqing[J]. Bulletin of Agricultural Science and Technology, 2010(12): 86-89
- [18] Dong Y, Dong K, Zheng Y, et al. Allelopathic effects and components analysis of root exudates of faba bean cultivars with different degrees of resistance to *Fusarium oxysporum*[J]. Chinese Journal of Eco-Agriculture, 2014, 22(3): 292-299

- [19] Zhang Q, Chen Z G, Cui H H, et al. Effects of horse bean straw on maize yield and utilization of soil nutrients[J]. Southwest China Journal of Agricultural Sciences, 2015, 28(2): 632-636
- [20] Geng S N. Research on the mechanism of legumes on the improvement of soil fertility in dry slope land of purple soil[D]. Chongqing: Southwest University, 2015: 23-29
- [21] Zhao P, Zheng Y, Tang L, et al. Effect of N supply and wheat/faba bean intercropping on N uptake and accumulation of wheat[J]. Chinese Journal of Eco-Agriculture, 2010, 18(4): 754-759
- [22] Li S M, Li L, Zhang F S. Effect of inoculation of arbuscular mycorrhizal fungi and rhizobium on the P uptake in faba bean/maize intercropping system[J]. Chinese Journal of Eco-Agriculture, 2005, 13(3): 136-139
- [23] Zhao X L, Liu X H, He J Z, et al. Effects of cotton root exudates on available soil nutrition, enzyme activity and microorganism quantity[J]. Acta Botanica Boreali-Occidentalia Sinica, 2009, 29(7): 1426-1431
- [24] Sun L, Chen B L, Zhou Z G. Effects of root exudates on available soil nutrition, Micro-organism quantity of Bt cotton in wheat-cotton intercropping system[J]. Cotton Science, 2007, 19(1): 18-22
- [25] Nanjing Agricultural University. Soil Agro-chemistry Analysis[M]. 2nd ed. Beijing: Agriculture Press, 1996: 23-45
- [26] Li F L, Yu Z N, He S J. Agricultural Microbiology Experiment Technology[M]. Beijing: China Agriculture Press, 1996: 69-72
- [27] Zhao J L, Cheng C Q, Gu X Y, et al. Effects of root exudates from *Mirabilis jalapa* on soil microenvironment[J]. Journal of Henan Normal University: Natural Science Edition, 2014, 42(3): 95-99
- [28] Li H N, Liu W X, Dai L, et al. Invasive impacts of *Ageratina adenophora* (Asteraceae) on the changes of microbial community structure, enzyme activity and fertility in soil ecosystem[J]. Scientia Agricultura Sinica, 2009, 42(11): 3964-3970
- [29] Li L, Li S M, Sun J H, et al. Diversity enhances agricultural productivity via rhizosphere phosphorus facilitation on phosphorus-deficient soils[J]. Proceedings of the National Academy of Sciences of the United States of America, 2007, 104(27): 11192-11196
- [30] Wu L K, Lin X M, Lin W X. Advances and perspective in research on plant-soil-microbe interactions mediated by root exudates[J]. Chinese Journal of Plant Ecology, 2014, 38(3): 298-310
- [31] Lan Z M, Lin X J, Zhang W G, et al. Effect of P deficiency on the emergence of *Astragalus* L. root exudates and mobilization of sparingly soluble phosphorus[J]. Scientia Agricultura Sinica, 2012, 45(8): 1521-1531
- [32] Yang L N, Aotegen B Y, Li Q F, et al. Effects of alfalfa root exudates on insoluble phosphorus in soil[J]. Pratacultural Science, 2015, 32(8): 1216-1221
- [33] Liu S P, Yang Z W. Plant root exudates[J]. Eco-Agriculture Research, 1998, 6(2): 36-38
- [34] Zhang D S, Wang Y Y, Tang L, et al. Effects of wheat and faba bean intercropping on available phosphorus of red soils and its relationship with rhizosphere soil pH[J]. Plant Nutrition and Fertilizer Science, 2013, 19(1): 127-133

- [35] Zhang A Q, He L Y, Zhao H E, et al. Effect of organic acids on inorganic phosphorus transformation in soils and its readily available phosphate[J]. *Acta Ecologica Sinica*, 2009, 29(8): 4061-4069
- [36] Zhan L P, Cong R H, Li X K, et al. Effects of low-molecular-weight organic acids on K^+ adsorption kinetics of red soil and yellow-cinnamon soil[J]. *Acta Pedologica Sinica*, 2012, 49(6): 1147-1157
- [37] Jiang C S, Yang J H, Wei C F, et al. Effects of low-molecular-weight organic acids on potassium release from purple rock[J]. *Plant Nutrition and Fertilizer Science*, 2002, 8(4): 441-446
- [38] Lu H L, Yan C L. Exudation of low-molecular-weight-organic acids by *Kandelia candel* (L) Druce roots and implication on heavy metal bioavailability in mangrove sediments[J]. *Acta Ecologica Sinica*, 2007, 27(10): 4173-4181
- [39] Zhang F S. Root exudates and their role in plant nutrition (a review)[J]. *Acta Agriculturae Universitatis Pekinensis*, 1992, 18(4): 353-356
- [40] Jones D L. Organic acids in the rhizosphere —A critical review[J]. *Plant and Soil*, 1998, 205(1): 25-44
- [41] Sun B, Zhao Q G, Zhang T L, et al. Soil quality and sustainable environment (III. The biological indexes for evaluation of soil quality)[J]. *Soil*, 1997, 29(5): 225-234
- [42] Liu C, Huang H J, Zhang C X, et al. The effects of root exudates from Johnsongrass on soil bacteria community diversity[J]. *Ecology and Environmental Sciences*, 2013, 22(7): 1124-1128
- [43] Ye Z Y, Tu Z L. Study on the secretion and the rhizospheric microorganisms of mulberry roots[J]. *Science of Sericulture*, 2005, 31(1): 18-21
- [44] Yang Y, Liu S W, Pan K, et al. Effects of Chinese onion' s root exudates on cucumber seedlings growth and rhizosphere soil microorganisms[J]. *Chinese Journal of Applied Ecology*, 2013, 24(4): 1109-1117

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