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Phosphate-solubilizing bacteria and fungi in relation to phosphorus availability under different land uses for some latosols from Guangdong, China

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ABSTRACT

Some soil bacteria and fungi are known to solubilize phosphates and play an important role in supplying phosphorus (P) to plants. In this study, we characterized the phosphate-solubilizing bacteria and fungi as well as P availability in latosols from southern China under different land use practices. Three different latosols (*i.e.*, red soil, lateritic red soil and laterite red soil), each with four different land uses (*i.e.*, agricultural land, grass land, forest land and orchard land), from Guangdong Province, China, were chosen to determine the amounts of phosphate-solubilizing bacteria (PSB) and phosphate-solubilizing fungi (PSF) and their phosphate solubilizing abilities. Our results show that the amount of available P (AP) increased with the amount of PSB favored in solubilizing organic P (or PSBop), while the amount of PSF increased with the content of soil organic carbon (SOC). The average rates of phosphate solubilization were 28.23% for PSBop, 6.97% for PSF, and 0.16% for PSBip (PSB favored in solubilizing inorganic P). An increase in soil pH decreased the ability of PSB to solubilize phosphate in latosols. This ability occurred in the following order: PSBop > PSF > PSBip. No significant difference in the amount of PSF was observed among the four different land uses for the lateritic red soil and laterite red soil, whereas a profound significant difference was found for the red soil, with the highest number of PSF in the grass land. Reasonable linear correlations between the PSB and the AP and between the PSF and the SOC were obtained and could provide a good reference to characterize soil PSB and PSF. Additionally, PSBop was the best bacterial species to solubilize phosphate in the latosols.

1. Introduction

Phosphorus (P) is an essential nutrient for all forms of life and is one of the major macronutrients for plants. In agricultural practices, millions of tons of phosphatic fertilizers are intentionally applied to soils each year for plant growth. To be the most effective, efficient, and environmentally favorable, however, the entire applied mass of the phosphatic fertilizers should remain available to plants near the root zone. Unfortunately, a large portion of soluble inorganic phosphatic fertilizers applied to the soil is immobilized rapidly and becomes unavailable to plants (Goldstein, 1986; Chen et al., 2006). The immobilization of P presents serious problems for plant growth.

It has been reported that a considerable number of soil bacterial species, mostly those present in the rhizosphere, are effective in transforming inorganic and organic P from the soils into soluble forms available for plant uptake (Hilda and Fraga, 1999). In the past decades, numerous research efforts have been devoted to investigating the beneficial effects of phosphate-solubilizing bacteria (PSB) used as biofertilizers to improve plant growth and increase crop yield (Mba, 1994, 1996; Young, 1994; Young et al., 1998; Goldstein et al., 1999; Chen et al., 2006; Khan et al., 2010; Pereira and Castro, 2014; Obalum and Chibuike, 2017). This group of bacteria commonly includes *Pseudomonas*, *Azospirillum, Burkholderia, Bacillus, Enterobacter, Rhizobium, Erwinia, Serratia, Alcaligenes, Arthrobacter, Acinetobacter* and *Flavobacterium* (Kloepper and Schroth, 1978). They have been termed as the plant growth promoting rhizobacteria due to their ability to solubilize immobile P in soils (Kloepper and Schroth, 1978). Pereira and Castro (2014) investigated the effect of phosphate-solubilizing rhizobacteria on *Zea mays* growth in P-deficient agricultural soil. Their work indicated that the PSB have great potential to be used as biofertilizers in P-deficient soils, especially the *Pseudomonas* sp. EAV and *A. nicotinovorans* EAPAA, since both of them highly increase P availability. Khan

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et al. (2010) reviewed the role of phosphate-solubilizing fungi on plant growth. These authors determined that fungi have the ability to solubilize minerals for releasing P to enhance plant growth. Given the adverse environmental impacts of chemical fertilizers and their increasing costs, the use of PSB and PSF (phosphate-solubilizing fungi) is a promising alternative for sustainable agricultural practices.

The mechanism of phosphate solubilization by PSB is the release of low-molecular-weight organic acids, which through their hydroxyl and carboxyl groups chelate the cations bound to phosphate, thereby converting it into soluble forms (Kpomblekou and Tabatabai, 1994). However, P solubilization is a complex phenomenon that depends on many factors such as the nutritional, physiological and growth conditions of the culture (Reyes et al., 1999). There is experimental evidence to support the role of organic acids in mineral phosphate solubilization (Halder et al., 1990). Khan and Joergensen (2009) studied the occurrence and mechanisms of PSB and their role in crop production. These authors found that PSB can decrease soil pH by producing organic acid and thus enhance mineralization of organic P by acid phosphatases.

Guangdong Province is located in southern China. Although there are various types of soils with distinct soil horizons and distribution patterns, the province has three major types of latosols, namely, red soil, lateritic red soil, and laterite red soil. These soils are distributed depending on latitude and altitude. In general, the red soil is situated from the central to north part of the province at 700 m above sea-level, the lateritic red soil is located from the central to south part of the province at < 800 m above the sea-level, and the laterite soil is distributed mostly in the Leizhou Peninsula (south part of the province). These three types of soils have low soil fertility and strong cation leaching potential and have been exploited for agriculture, orchard, forest, and grass land practices. Among the 74% of arable land in China, approximately 95% of the P content in the arable land is immobile and unavailable for plant uptake (Xu, 2004). The immobilization of P presents serious problems for plant growth. Therefore, a need exists to investigate the characteristics of PSB and PSF for solubilizing and mobilizing P in latosols.

Land use changes have many different impacts on soil microbial population, communities, and habitats through changes of soil chemical processes, soil structure, and hydrological regime. Impacts of land use on soil microbial biomass and community structure are most evident in the rooted topsoil, and the microbial biomass decreases with soil depth (Ekelund et al., 2001; Taylor et al., 2002). It has been reported that the soil microbial biomass is 4–5 times lower in arable land than in forest land and grass land in the topsoil (Van Leeuwen et al., 2017). However, no effort has been devoted to investigating the P availability produced by PSB and PSF under different land uses.

The goal of this study was to ascertain the impacts of land uses on the distribution and P solubilizing ability of PSB and PSF from latosols in Guangdong Province, China. Our specific objectives were to: (1) determine the amounts of PSBop (PSB favored in solubilizing organic P), PSBip (PSB favored in solubilizing inorganic P), and PSF presented in three different latosols (*i.e.*, red soil, lateritic red soil, and laterite red soil) under four different land uses (*i.e.*, agricultural land, orchard land, forest land, and grass land); (2) compare the distributions of PSB and PSF among the four different land uses with each land use under three different types of latosols; (3) determine the relationships of the amounts of PSB and PSF with certain soil properties; and (4) identify the PSB and PSF strains with a high ability to solubilize phosphate from the latosols.

2. Materials and methods

2.1. Study site and soil sampling

Guangdong Province is located in southern China between 20°13′ and 25°31′N and between 109°39′ and 117°19′E with a total inland area of 178,000 km^2 (Fig. 1). Its northern and central regions belong to the subtropical area, while its southern region (or Leizhou Peninsula) is in the tropical area. The northern region is located in or near the mountain area with high elevation, while the southern region, especially the southeast coastal area, is situated in the river delta alluvial with low elevation. The average annual precipitation ranges from 150 to 200 cm, and the mean annual temperature is 19 °C in the northern region and 23 °C in the southern region. The land uses in this province largely consist of agriculture (3,120,000 ha), forestry (10,025,000 ha), grass land (27,100 ha), and orchard (84,000 ha) in addition to residential and commercial areas. Rice, vegetables, and tropical fruits are the major crops in this province.

Three different geographical districts (*i.e.*, the Shaoguan, Guangzhou, and Leizhou districts), each representing one soil type, within Guangdong Province were selected in this study. The Shaoguan district is for red soil, the Guangzhou district is for lateritic red soil, and the Leizhou district is for laterite red soil (Fig. 1). Four different land uses (*i.e.*, grass land, forest land, agricultural land, and orchard land) from each district were chosen to collect soil samples at three sampling sites for each land use. The major soil physical and chemical properties are given in Table 1. The sampling sites were randomly selected and positioned with GPS. Five samples from three different locations in each site were collected during spring 2008 at a depth interval of 15 cm for a total soil depth of 45 cm using augers. The samples collected from each site were then mixed thoroughly to obtain one representative soil sample. The soil samples were placed in a cooler, shipped to the lab and stored in a freezer at 4 °C. All sampling activities were conducted in accordance with the Standard Operating Procedures for the collection and analysis of soil samples (NSICSA, 1978).

2.2. PSB and PSF isolation and measurement of their P solubilizing ability

Approximately 20 g of soil sample and 200 mL of deionized water were poured into a 250 mL volumetric flask. The flask was then shaken for 30 min in a mechanical shaker and was settled for approximately 10 min. Approximately 10 mL of supernatant was harvested, and the serially diluted samples were plated on Pikovsaia medium containing 5 g of tricalcium phosphate (TCP) as the sole phosphorus source for selectively screening the bacteria and fungi that have the ability to release inorganic phosphate from tricalcium phosphate (Nautiyal et al., 2000). Uninoculated plates and *E. coli* inoculated plates served as controls. The experiment was performed for 7 d in triplicate. After incubation, the pH of the medium was measured with a pH meter equipped with a glass electrode. Cell numbers were estimated by the standard plate count method, and the amount of available phosphate was measured by the Mo-blue method (Watanabe and Olsen, 1965; Lin and Zhao, 2001) every two days. The latter method measured the abilities of PSB and PSF to solubilize phosphate. Differences among treatments were statistically analyzed with a two-way ANOVA showing the main effects of land use, soil type and their interactive effects (Table 2) using SPSS 25 (Statistical Product and Service Solutions, SPSS). All of the treatments were significant except for PSBop in the soil type group.

The rate of phosphate solubilized by each bacterial and fungal strain was calculated as:

$$R_{AP} = \frac{AP_{me} - AP_{in}}{TP} \times 100 \quad (1)$$

where R_{AP} is the rate of AP (available P) released from the soil (%), AP_{me} is the content of AP in the soil measured at the end of the experiment (mg/kg), AP_{in} is the content of AP in the background soil (mg/kg), and TP is the content of total phosphorus in the soil (mg/kg).

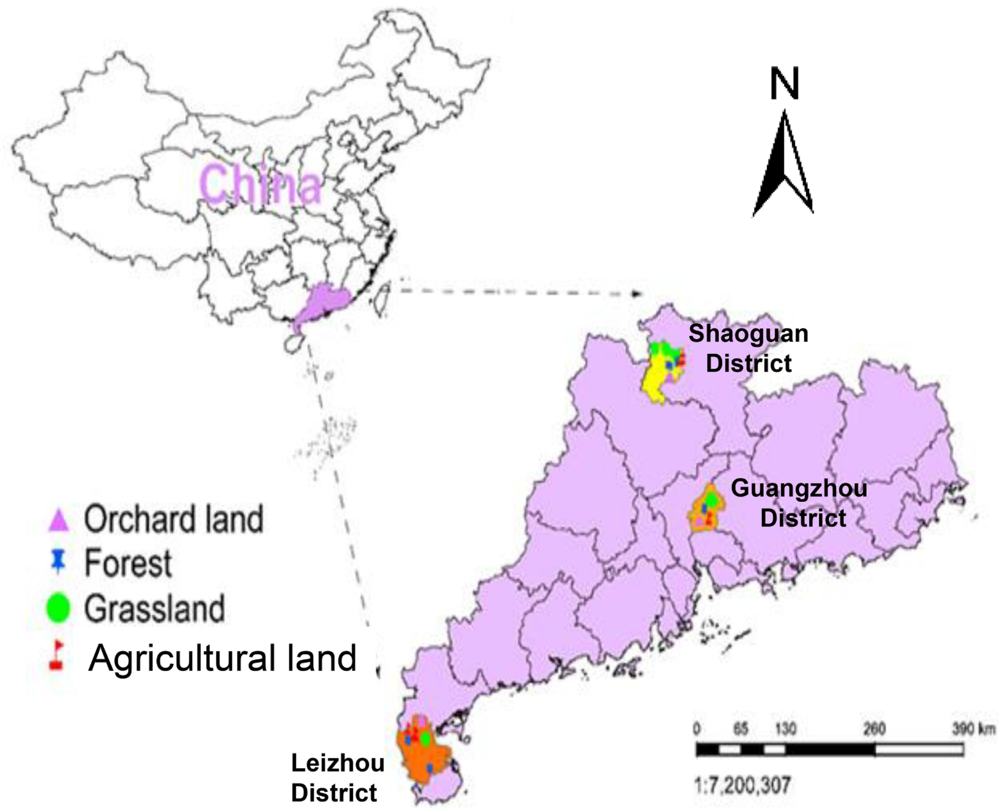

Fig. 1. Locations of soil sampling sites in Guangdong Province, China. Noted only the inland area for the province is shown in the map.

Table 1
Major physical and chemical properties of the soils used in this study.

Soil	Land use	Available K (mg/kg)	TK (g/kg)	TP (g/kg)	Available P (mg/kg)	TN (g/kg)	Available N (mg/kg)	Organic matter (g/kg)	Moisture content (%)	Organic carbon (g/kg)	pH
Red soil	Orchard	82.877533	27.39603	0.192907	7.76	1.345333	508.236	22.23087	18.88	12.89493	4.506667
	Agriculture	12.648047	27.44133	0.130093	5.9066667	1.067	162.6974	25.27577	21.174667	14.66112	6.483333
	Grass	39.536653	31.76893	0.148187	6.3133333	1.384667	235.1239	32.0313	16.795567	18.57964	5.016667
	Forest	72.539227	45.92793	0.10528	4.8033333	1.671	251.9902	24.3108	14.080333	14.10139	4.46
Lateritic red soil	Orchard	68.64119	51.85413	1.44	87.14	1.015333	223.2151	26.57573	17.059967	15.41516	4.986667
	Agriculture	135.90463	53.59683	0.701467	30.616667	0.944	189.9178	26.62957	15.3718	15.44638	4.72
	Grass	37.420677	19.80783	0.029427	1.1566667	0.671	66.362	16.35973	17.5711	9.489404	5.346667
	Forest	3.9823967	43.23017	0.069373	2.7933333	1.427333	572.4857	22.56117	20.534433	13.08652	4.366667
Laterite red soil	Orchard	141.3905	7.486467	0.36608	13.17	1.005	303.1031	27.73913	19.505833	16.08998	6.466667
	Agriculture	93.711047	6.852233	1.24392	63.08	1.123667	190.8644	23.67073	16.6708	13.73012	5.786667
	Grass	10.66897	4.518	0.215547	8.7033333	0.401667	104.0172	5.5049	23.61	3.193097	6.343333
	Forest	213.29467	8.5976	0.730427	30.99	2.037	433.1349	22.63873	21.514633	13.13152	5.226667

3. Results

3.1. PSB and PSF distributions under different soil types and land uses

Comparison of the PSBop and PSBip distributions among the four different land uses for each type of latosols is shown in Fig. 2. There was no significant difference in the amount of PSBop for the orchard, agricultural, and grass lands in the red soil (Shaoguan District), while there was a profound significant difference in the amount of PSBop between the forest land and the other three land uses (Fig. 2A). A plot of AP against PSBop for all of land uses showed that the amount of PSBop in the soil increased with the AP content (Fig. 3A). There was no significant difference in the amount of PSBip between the orchard land and the agricultural land or between the grass land and the forest land. In contrast, there was a significant difference in the amount of PSBip between the orchard-agricultural lands and the grass-forest lands (Fig. 2A).

Unlike the red soil, there were significant differences in the amount of PSBop between the orchard land (0.069×10^6 cfu/g) and the agricultural land (0.539×10^6 cfu/g) for the lateritic red soil in Guangzhou District (Fig. 2B), although the amount of AP in the orchard land (87.14 mg/kg) was higher than that in the agricultural land (30.61 mg/kg). In other words, an increase in the amount of PSBop did not necessarily lead to a corresponding increase in AP. No significant difference was observed for the amount of PSBip among the four different land uses (Fig. 2B).

For the laterite red soil (Leizhou District), there was no significant difference in the amount of PSBop between the orchard land and the grass land or between the agricultural land and the forest land, whereas there was a significant difference in the amount of PSBop between the orchard and grass lands and the agricultural and forest lands (Fig. 2C). Analogous to the case of the lateritic red soil, there was no significant

Table 2
Statistical analysis of two-way ANOVA showing the main effects of land use and soil type on soil phosphate solubilizing bacteria and fungi and their interactive effects. PSBop denotes the phosphate solubilizing bacteria favored organic P and PSBip denotes the phosphate solubilizing bacteria favored inorganic P.

Source	Dependent Variable	Type III Sum of Squares	df	Mean Square	F	*P*	Partial Eta Squared
Land use	PSBop	5008016253.12[a]	3	1669338751.04	11.79	0.00	0.60
	PSBip	4655927330.15[b]	3	1551975776.72	16.09	0.00	0.67
	Fungi	3503159.22[c]	3	1167719.74	15.32	0.00	0.66
Soil type	PSBop	324985597.46	2	162492798.73	1.15	0.33	0.09
	PSBip	19546969271.67	2	9773484635.83	101.31	0.00	0.89
	Fungi	7990896.88	2	3995448.44	52.43	0.00	0.81
Soil type × Land use	PSBop	5801495383.80	11	966915897.30	6.83	0.00	0.63
	PSBip	9218846883.54	11	1536474480.59	15.93	0.00	0.80
	Fungi	6581007.19	11	1096834.53	14.39	0.00	0.78

[a] R Squared = 0.766 (Adjusted R Squared = 0.659).
[b] R Squared = 0.935 (Adjusted R Squared = 0.906)
[c] R Squared = 0.908 (Adjusted R Squared = 0.866)

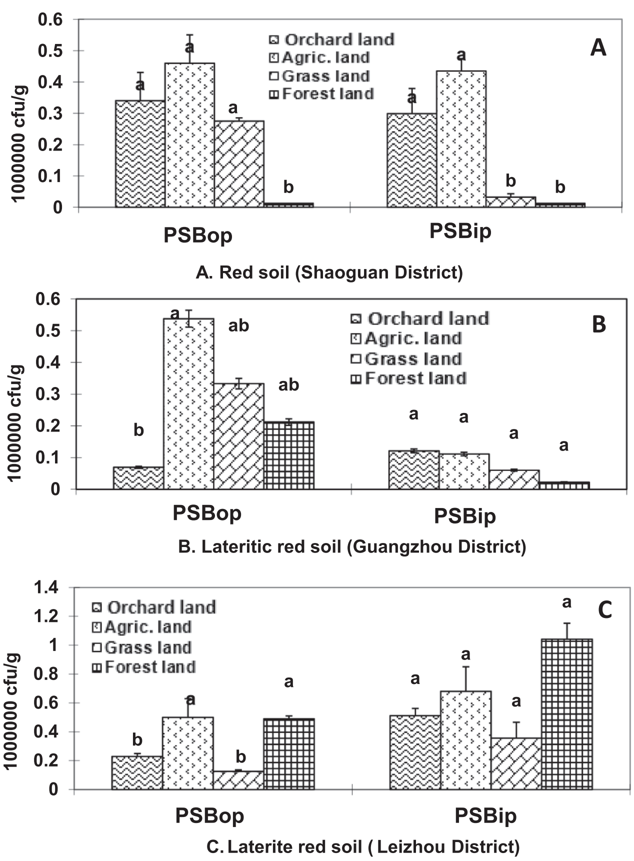

Fig. 2. Amount of PSBop and PSBip in four different land uses under three different type of soils.

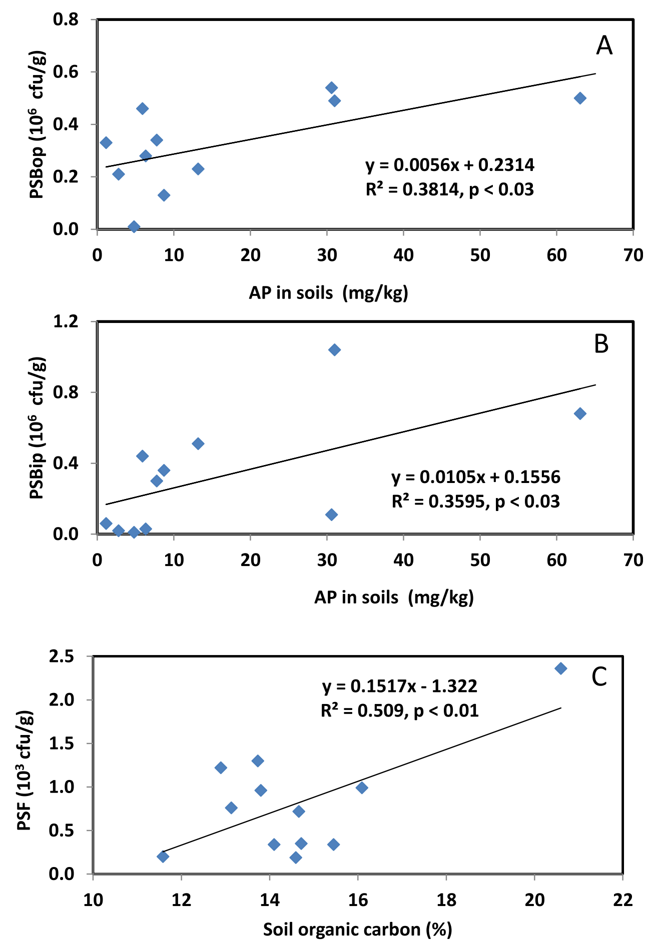

Fig. 3. Relationships of PSBop (A) and PSBip (B) to soil AP content as well as relationship of PSF to soil organic carbon.

difference in the amount of PSBip in the laterite red soil among the four different land uses, although the amount of AP in the agricultural land (63.08 mg/kg) was higher than that in the other three land uses (8.70–30.99 mg/kg).

Fig. 4 compared the amount of PSF distributions among the four different land uses per type of latosols. No significant difference in the amount of PSF was observed among the four different land uses for the lateritic red soil and laterite red soil, while a profound significant difference was found between the orchard and grass lands and the agricultural and forest lands for the red soil. The high number of PSF in the grassland could be attributed to the high content of SOC in the same land use. A plot of the number of PSF against the SOC content showed that there was, in general, a reasonable linear correlation between the number of PSF and the SOC content (Fig. 3C).

Among the three types of latosols, the average number of PSBop was larger than that of PSBip in the red soil and lateritic red soil, but the opposite was true in the laterite red soil. More specifically, the average numbers of PSBop and PSBip were, respectively, 0.27 × 10^6 cfu/g and 0.20 × 10^6 cfu/g for the red soil, 0.29 × 10^6 cfu/g and 0.08 × 10^6 cfu/g for the lateritic red soil, and 0.34 × 10^6 cfu/g and 0.65 × 10^6 cfu/g for the laterite red soil.

It is very interested to note that a higher number of PSBip was found in the laterite red soil from all of the four different land uses (Fig. 5). Our data analysis showed that the higher number of PSBip in the laterite red soil did not have a linear correlation to the soil nutrients or

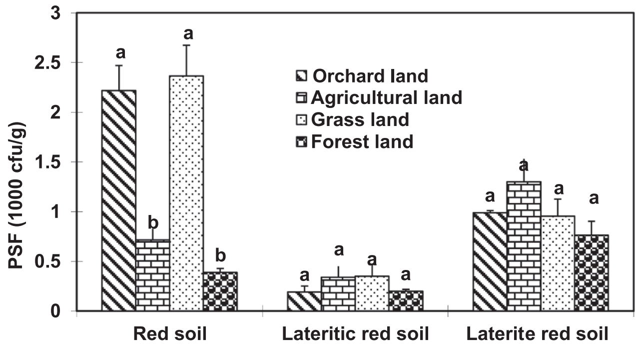

Fig. 4. Amount of PSF in four different land uses under three different type of soils.

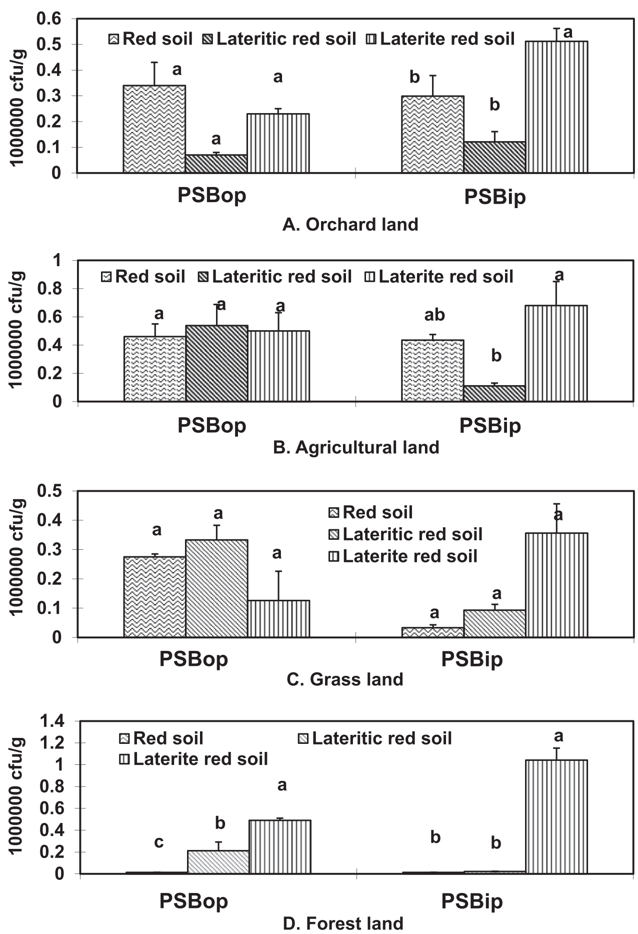

Fig. 5. Amount of PSBop and PSBip in three latosols under four different land uses.

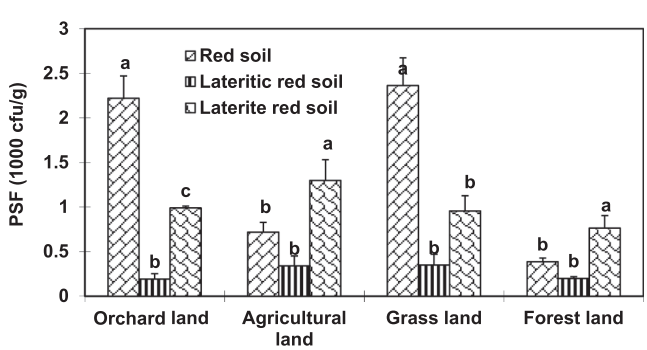

Fig. 6. Amount of PSF in three different latosols under four different land uses.

Table 3
Amount and rate of phosphate solubilized by PSBop at different pH. The negative values indicated some strains may not solubilize P rather than uptake AP.

Strain Name	Solubilized amount in AP (mg/kg)	Rate (%)	pH
BPSC33	12.05 ± 1.90	2.41	7.40 ± 0.07
BPSC22	5.40 ± 6.73	1.08	7.30 ± 0.08
BPSC21	17.87 ± 2.55	3.57	7.35 ± 0.10
BPSC14	21.47 ± 3.95	4.29	7.34 ± 0.13
BPSC17	11.58 ± 13.66	2.32	7.48 ± 0.10
BPSC35	4.73 ± 1.54	0.95	6.20 ± 0.00
BPSG15	81.92 ± 12.33	16.38	7.21 ± 0.18
BPSG38	8.72 ± 0.61	1.75	7.43 ± 0.01
BPSG23	111.48 ± 14.50	22.29	5.69 ± 0.38
BPSD41	116.31 ± 22.88	23.26	6.50 ± 0.20
BPGL18	83.72 ± 1.70	16.74	7.40 ± 0.34
BPGL31	6.86 ± 0.19	1.37	7.39 ± 0.05
BPGL17	−3.25 ± 1.28	−0.65	7.40 ± 0.02
BPGL23	4.04 ± 2.05	0.81	7.03 ± 0.10
BPGG22	−4.94 ± 1.86	−0.99	7.16 ± 0.15
BPGG24	80.35 ± 7.71	16.07	5.79 ± 0.38
BPGC23	4.05 ± 3.55	0.81	7.29 ± 0.07
BPGC24	−6.17 ± 1.03	−1.23	7.41 ± 0.12
BPGN114	28.51 ± 9.14	5.7	6.660.24
BPLN36	100.35 ± 8.79	20.07	5.02 ± 0.08
BPLG24	105.75 ± 4.48	39.15	6.08 ± 0.08

pH. Unlike PSBip and PSBop, there were more or less significant differences in the amount of PSF among the three different latosols for each land use (Fig. 6). For the orchard land, the amount of PSF was as follows: red soil > laterite red soil > lateritic red soil. For the agricultural land, there was no difference in the amount of PSF between the red soil and the lateritic red soil, but the amount of PSF in the laterite red soil was higher than that in the other two soils. For the grass land, there was no difference in the amount of PSF between the laterite red soil and the lateritic red soil, but the amount of PSF in the red soil was higher than that of the other two soils. For the forest land, there was no difference in the amount of PSF between the red soil and the lateritic red soil, but the amount of PSF in laterite red soil was higher than that of the other two soils.

3.2. Amount and rate of phosphate solubilization

Tables 3–5 showed the amounts and rates of phosphate solubilization by different PSB and PSF strains and the associated soil pH levels. Among the 21 PSBop strains isolated from this study, the top three strains were BPLG24, BPSD41, and BPSG23, respectively, accounting for 39.15, 23.26, and 22.29% of phosphate solubilization rates. Among the 14 PSBip strains isolated from this study, the top three strains were BPLL25, BPSC12, and BPSD22, respectively, accounting for 0.18, 0.16,

Table 4
Amount and rate of phosphate solubilized by PSBip at different pH. The negative values indicated some strains may not solubilize P rather than uptake AP.

Strain Name	Solubilized amount in AP(mg/kg)	Rate (%)	pH
BPSC12	13.74 ± 1.24	0.16	3.80 ± 0.20
BPGN37	3.11 ± 3.70	0.04	4.27 ± 0.06
BPGN26	4.25 ± 3.77	0.05	3.93 ± 0.12
BPGG13	10.52 ± 0.27	0.13	3.83 ± 0.06
BPLL34	10.03 ± 0.89	0.12	4.13 ± 0.06
BPSD22	12.08 ± 0.32	0.14	3.87 ± 0.06
BPGN213	11.01 ± 1.24	0.13	4.77 ± 0.06
BPLL25	14.80 ± 0.82	0.18	4.10 ± 0.00
BPLC22	4.37 ± 0.50	0.05	3.50 ± 0.00
BPGN28	6.14 ± 0.15	0.07	3.90 ± 0.00
BPLC15	4.13 ± 2.29	0.05	4.50 ± 0.00
BPSG31	−4.68 ± 0.40	−0.06	4.17 ± 0.06
BPSL21	5.35 ± 0.16	0.06	3.97 ± 0.15
BPSG15	6.05 ± 0.66	0.07	4.0 ± 0.00

Table 5
Amount and rate of phosphate solubilized by PSF at different pH. The negative values indicated some strains may not solubilize P rather than uptake AP.

Strain name	Solubilized amount in AP (mg/kg)	Rate (%)	pH
FPSg$_2$2(4)	576.60 ± 18.85	6.86	3.40 ± 0.10
FPSg$_3$2	−91.664 ± 47.71	−1.09	3.90 ± 0.21
FPLL$_1$3	476.88 ± 31.18	5.67	3.40 ± 0.00
FPGL$_1$4	485.86 ± 66.45	5.78	3.4 ± 0.10
FPLG$_2$1	513.11 ± 20.39	6.10	3.5 ± 0.06
FPLG$_1$4(2)	563.68 ± 8.32	6.70	3.5 ± 0.06
FPSG$_2$1	581.10 ± 6.08	6.91	3.05 ± 0.05
FPGN$_2$1	585.59 ± 5.61	6.96	2.9 ± 0.06
FPSD$_2$2	575.76 ± 18.78	6.85	2.6 ± 0.10
FPLN$_3$2	436.061 ± 31.53	5.19	2.9 ± 0.12
FPSD$_3$4	497.79 ± 49.63	5.92	3.1 ± 0.15
FPGG$_2$2	578.85 ± 13.83	6.88	2.8 ± 0.06
FPLL$_3$3	594.01 ± 5.39	7.06	2.9 ± 0.01
FPSG$_3$1	580.569 ± 13.40	6.90	2.75 ± 0.05
FPGN$_3$4	571.139 ± 1.02	6.79	3.1 ± 0.06

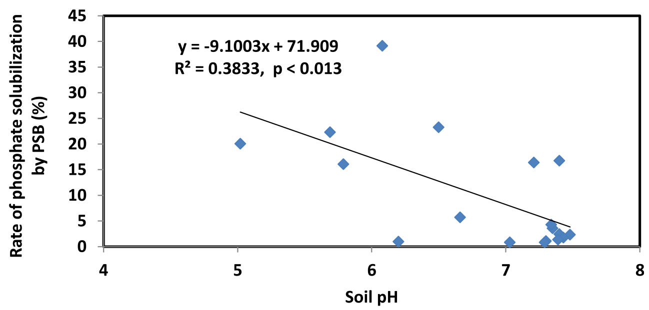

Fig. 7. Relationship of phosphate solubilization by PSB to soil pH.

and 0.14% of phosphate solubilization rates. Among the 15 PSF strains isolated from this study, the top three strains were FPLL$_3$3, FPGN$_2$1, and FPSG$_2$1, respectively, accounting for 7.06, 6.96, and 6.91% of phosphate solubilization rates. Comparison of Tables 3–5 showed that the phosphate solubilizing ability was as follows: PSBop > PSF > PSBip. The average rates of phosphate solubilization for the top three strains were 28.23% for PSBop, 6.97% for PSF, and 0.16% for PSBip. Our study revealed that PSBop was the best bacterial group for solubilizing phosphate from the latosols. A plot of soil pH against the rate of phosphate solubilization by PSBop showed a reasonable negative linear correlation (Fig. 7). That is, an increase in soil pH would decrease the rate of phosphate solubilization by PSBop.

4. Discussion

4.1. Effect of land uses on PSB and PSF

Land use has marked effects on soil microbial distributions through changes in soil structure, nutrient status, moisture regime, and microbial habitat. Although the exact reasons for the lack of a significant difference in the amount of PSBop among the four land uses, while a profound significant difference was seen in the amount of PSBop between the forest land and the other three land uses in the red soil, remain to be investigated, a possible explanation would be the TP content. The TP content from the forest land was much lower than that from the other lands (Table 1). The lower TP content in the forest land could limit the growth of PSBop. The reasonable linear correlations between PSBop and AP as well as between PSBip and AP (Fig. 3A and B) demonstrated that the PSB are favorable for releasing AP for plant growth. An attempt to locate literature reports to confirm the linear correlations was not successful. It is, therefore, apparent that little to no effort has been devoted to investigating this issue. Luo et al. (2001) investigated the effects of different fertilization methods on PSB activity in a cotton field and reported that nitrogen fertilizer could enhance the growth of PSB, although their study lacks detailed analysis. Our analysis, however, revealed that no correlations existed between the amount of PSB and other variables such as nitrogen, potassium, and SOC.

Although there was, in general, a linear correlation between the amount of PSBop and the amount of AP among the three different latosols, different results could be obtained for a specific type of soil. For example, the AP contents in agricultural land and grass land from the red soil were, respectively, 5.9 and 6.3 mg/kg, but the amounts of PSBop in agricultural land and grass land were, respectively, 0.44 and 0.03 × 10^6 cfu/g. In other words, an increase in the amount of PSBop would not necessarily increase soil AP. The fact that there was no significant difference in the amount of PSBip in the lateritic red soil among the four different land uses further confirmed that other soil factors also played an important role in the growth of PSB in addition to soil P. Furthermore, the fact that there was no significant difference in the amount of PSBip among the four different land uses indicated that a variation in PSB occurred with the soil types even for the same land use.

The high number of PSF in the grass land could be attributed to the high SOC content, which was confirmed by a linear correlation between the number of PSF and the SOC content (Fig. 3C). The results indicated that an increase in the SOC content would enhance the growth of PSF. A similar result was obtained by Rajeshkumar and Ilyas (2010). These authors found that an addition of carbon sources favored the growth of PSF to a certain extent.

Lin et al. (2002) studied the amount of PSB in the soils from four different types of ecosystems and found that the number of PSBop is much larger than that of PSBip. This finding was similar to our results, *i.e.*, the number of PSBop was larger than the number of PSBip in the red soil and lateritic red soil. A comparison of PSB and PSF among the three soil types further revealed that the number of PSB was two orders of magnitude larger than that of PSF (Table 2), although the exact reason remains unknown. Therefore, further study of these issues is warranted.

4.2. Effect of soil type on PSB and PSF

Soil type had discernible impacts on the distribution of PSB, and the amount of PSB was in the following order: laterite red soil > red soil > lateritic red soil. The higher number of PSBip in the laterite red soil did not have a linear correlation with the soil nutrients or pH. It seems that the soil temperature could play a role in the distribution of PSBip, as the laterite red soil is located in warmer (tropic) regions while the red soil and lateritic red soil are situated in subtropical regions. High temperature could stimulate the growth of PSBip. Therefore, further study is warranted to investigate this issue. The differences in the amount of PSF found in a given land use among different soil types demonstrated the complexity of soil factors affecting the growth of PSF. A thorough literature search revealed that little effort has been devoted to characterizing PSB and PSF in different latosols.

4.3. Solubilizing ability of PSB and PSF

PSBop was the best bacterial group for solubilizing phosphate from the latosols since the phosphate solubilizing ability was in the following order: PSBop > PSF > PSBip. In general, an increase in soil pH would decrease the rate of phosphate solubilization by PSBop. This finding was consistent with the results from Khan and Joergensen (2009). Khan and Joergensen (2009) studied the occurrence and mechanisms of PSB and their role in crop production. These authors found that PSB can lower soil pH by producing organic acid and thus enhance mineralization of organic P by acid phosphatases. Our further analysis also showed that a reasonable correlation existed between the soil pH and the rate of phosphate solubilization by PSB.

5. Conclusions

Among the three different latosols, the average number of PSBop was larger than that of PSBip in the red soil and lateritic red soil, but the opposite was true in the laterite red soil. Overall, the number of PSB was two orders of magnitude larger than that of PSF in the latosols. In general, the AP content increased with the amount of PSBop, and the amount of PSF increased with the SOC content. The linear correlations between the PSBop and the AP as well as between the PSF and the SOC could provide a way to characterize soil PSB and PSF, although other soil factors may also play an important role. The ability to solubilize phosphate was PSBop > PSF > PSBip. PSBop was the best bacterial group to solubilize phosphate from the latosols. Additionally, an increase in soil pH would in general decrease the ability of PSB to solubilize phosphate from latosols. Our research findings suggested that the use of PSB and PSF as biofertilizer is a promising alternative in sustainable agricultural practices. Further research is warranted to perform multiple regression and path analysis for a more accurate assessment when a sufficient dataset is available.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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