Relative Agronomic Effectiveness of Some African Rock Phosphate Fertilizers in an Ultisol of Okinawa, Japan

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Abstract

A greenhouse experiment was conducted to compare the agronomic effectiveness of four phosphate rock (PR) fertilizers from Togo (TPR), South Africa (SAPR) and Morocco (MPR) with single super phosphate (SSP) for corn (*Zea mays L.*) on an acidic P-deficient ultisol in Okinawa. The P rates used were 0, 100, 200, and 300 mg P kg^{-1} soil and corn was grown for six weeks. The relative agronomic effectiveness (RAE) of each PR with respect to SSP was calculated. The dry matter yield (DMY) and P uptake followed the order SSP>MPR>TPR=SAPR=control. The RAE values ranged from 8 to 78% and were significantly correlated (r = 0.96**) with chemical reactivity of the PRs measured by extraction with ammonium citrate (pH 3). The DMY, P uptake and RAE values for MPR were statistically similar ($P < 0.05$) to SSP, suggesting that MPR can be used as a P source in Okinawa soils.

Introduction

The red soils of Okinawa are highly weathered utisols formed under conditions of intense weathering from parent material having low phosphorus (P) content. These soils occupy the widest area on the Island and represent an important resource for rain-fed agriculture. Generally, they have low pH, high contents of Fe and Al oxides and hydroxyoxides, low total P, extractable P, basic cations (Ca, Mg, and K) as well as other trace elements (Dodor & Oya, 2000; Dodor *et al.,* 1999). Due to the high contents of Al and Fe bearing minerals (Dodor & Oya, 2000), these soils have high P sorption capacities, hence P deficiency has been the major constraint to crop production on them. Therefore, adequate P fertilization is essential for economic and sustainable crop production in these soils. Consequently, large quantities of P fertilizer are applied to these soils to increase crop yield. However, the high cost of conventional water soluble P fertilizer represents a considerable cost to farmers. Furthermore, with increasing concern about the adverse effect of the excessive use of chemical P fertilizers on environmental quality, a search for effective alternative P source is imperative.

Under certain soil and crop conditions, the constraint of low P availability can be overcome by direct application of phosphate rock (PR). This may be an agronomically and economically attractive alternative to the use of soluble P fertilizers (Khasawneh & Doll 1978; Hammond *et al.,* 1986; Chien *et al.,* 1990; Chien *et al.*, 1992). Studies carried out on tropical soils to test the effectiveness of PRs for direct application to crops have shown that some PRs are or nearly as effective as water-soluble P fertilizers on acid unlimed soils

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(Rajan *et al.,* 1996). The most important soil factors necessary to promote the dissolution of applied PRs and hence the agronomic effectiveness of PR upon direct application have been identified as low pH and Ca in solution as well as high P sorption capacity (Dodor, *et al.*. 1999; Rajan *et al.,* 1996; Smith & Sanchez, 1982).

Laboratory incubation studies to determine the prospect of PR utilization in Okinawan soils have indicated that acidic conditions coupled with large Ca sink contributed highly to dissolution of PRs in the red soils of Okinawa (Dodor *et al.,* 1999). However, there is still some degree of uncertainty about the relative agronomic effectiveness of PRs when applied directly to these soils. This is because the use of PRs for direct application depends not only on dissolution but also on subsequent availability of the P released for plant growth. Technically, the need to conduct an in-depth study into the factors affecting the relative agronomic effectiveness of PR cannot be overemphasized. In this way, it may be possible to quantitatively evaluate amount of PR in terms of equivalent amount of super phosphate under local soil and climate conditions. Quantifying the P availability of soils amended with PR-based fertilizers in the greenhouse could be useful alternative in making recommendations on the best type and rate of PR fertilizer to use to obtain optimum agronomic and economic benefits.

The agronomic potential of different PR sources has been extensively evaluated in different agroecological zones (Chien *et al.,* 2003; Owusu-Bennoah and Acquaye 1996; Sagoe *et al.,* 1997). To date, no such study has been conducted on the important red soils of Okinawa. The objective of this study was therefore to evaluate the agronomic effectiveness of four PR fertilizers in comparison to single super phosphate in an acidic red soil of Okinawa Island.

Materials and methods

Soil characteristics

The soil used in this study was developed over phyllite and classified as Oku series (local classification) and Typic paleudult (USDA classification), or Nitisol (FAO/UNESCO classification). A bulk surface (0–15 cm) sample was collected from uncultivated field in northern Okinawa, air-dried and passed through 2 mm sieve prior to greenhouse experiment and chemical analysis. Table 1 lists relevant chemical and physical properties determined according to the following procedures. Soil pH was measured in 1:2.5 soil-water suspensions. Organic carbon was determined by the wet oxidation

TABLE 1

Some chemical and physical properties of the Typic Paleudults soil used

pH	4.2
Organic matter (g /kg)	51.8
Troug P (mg /kg)	12.5
Total P (mg /kg)	40.8
P sorption capacity (mg /kg)	1045
Standard P requirement (mg /kg)	729
Exchangeable Ca (cmol_c /kg)	0.14
Exchangeable Mg (cmol_c /kg)	0.11
Exchangeable K (cmol_c /kg)	0.10
Exchangeable Na (cmol_c /kg)	0.11
Effective CEC (cmol_c /kg)	8.09
% Ca saturation	1.70
Free Fe oxide (g /kg)	10.45
Free Al oxide (g /kg)	3.25
Clay content (g /kg)	446

procedure of Kosaka *et al.* (1959). Total P content of the soil was determined by digestion with concentrated sulfuric acid and hydrogen peroxide, and available P was extracted with 0.001 M H_2SO_4 (Troug, 1930). In all cases, P concentration was measured on neutralized extracts by color development performed by the ammonium molybdate-ascorbic acid blue method (Murphy & Riley, 1962). Particle size analysis was done by the hydrometer method after removal of organic matter (Gee & Bauder, 1986).

Exchangeable bases extracted by neutral NH_4OAc (pH 7) were determined by atomic absorption spectrophotometer (Ca, Mg and Na) and flame emission (K). Cation exchange capacity (CEC) was determined after the soils were washed free of excess saturating salt by organic solvents and amounts of index cation (NH_4^+) adsorbed was displaced by 1N KCl. Ammonium in the KCl extract was determined by Nelson (1983) procedure. Oxides of Fe and Al were extracted with dithionite-citrate-bicarbonate (Mehra & Jackson, 1960). The concentration of Fe and Al in the extract was determined by Inductively Coupled Plasma-Mass Spectrometry (ICP-MS).

Phosphate sorption maximum was obtained by using the procedure of Fox and Kamprath (1970). Duplicate 3 g of < 2 mm sieved sample of the soil was equilibrated in 30 ml of 0.01 M $CaCl_2$ containing 0 to 200 μg P ml^{-1} at 25 °C for 6 days. Two drops of toluene were added to suppress microbial activity and the suspension shaken for 30 min twice daily. At the end of the equilibrating period, the soil suspension was centrifuged and filtered. Phosphorus in the supernatant solution was determined by the procedure of Murphy and Riley (1962). The amount of P sorbed by the soil was calculated as the difference between the amount of P added and the amount remaining in solution. The P sorption maximum was estimated from a Langmuir sorption isotherm plot of the data and standard P requirement calculated as the amount of P sorbed at 0.2 mg P L^{-1} in equilibrium solution.

Characterization of the P sources

The African PR fertilizers used in the present experiment were Togo PR (TPR), South Africa PR (SAPR), and Morocco PR (MPR). Single super phosphate (SSP) was included for comparison purposes. The PR fertilizers were passed through 100 mesh (150 μm) and SSP was in a fine powder form. The origin, chemical reactivity of the PRs as measured by extraction with 2% citric acid, 2% formic acid (Hoffman & Mager, 1953), NH_4^+ citrate *p*H 3 (Chien & Hammond 1978) and some chemical characteristics shown in Table 2, were previously reported by Dodor *et al.* (1999).

Greenhouse experiment

Amounts of SSP or PR to give 100, 200, and 300 mg P kg^{-1} soil were weighed out and mix thoroughly with three (3) kg of air-dried soil placed in plastic pots. Lime was not applied and the amounts of P added were calculated on the basis of total P content of each P source. Uniform levels of urea, KCl and $MgSO_4$ were added to all pots to supply 200 mg N kg^{-1}, 150 mg K kg^{-1} and 30 mg Mg kg^{-1}. A basal nutrient solution was added to provide 3 mg of Cu kg^{-1} as $CuSO_4$. $5H_2O$, 6 mg of Zn kg^{-1} as $ZnSO_4.7H_2O$ and 1 mg of B kg^{-1} as $Na_2B_4O_7.10H_2O$. All treatments, including a

TABLE 2

Origin, reactivity scales and chemical composition of PR sources

PR source[a]	*Origin*	*Type of deposit*	*2% vitric acid*	*2% formic acid*	*NH_4 citrate (pH 3)*	*P*	*Ca*	*Mg*	*K*
			—— soluble P (%) ——			*mg/kg*	*—— g/kg ——*		
Morocco PR	Khouribga, Morocco	Sedimentary	2.3	14.7	4.0	140	344	2.12	0.88
Togo PR	Hahotoe, Togo	Sedimentary	2.1	7.3	3.2	152	363	0.42	1.11
South Africa PR	Palfos, South Africa	Igneous	1.2	2.4	3.2	171	380	4.08	0.44

[a] All the PRs were ground to 150 µm (100 mesh).

no-P control, were arranged in a randomized block design with 3 replications in the greenhouse. The pots were sown with pre-soaked seeds of the indicator crop (*Zea mays L.*) at a rate of four seeds per pot and thinned to three plants per pot after germination. The pots were watered as required to maintain soil moisture at about 70% of field capacity. The plants were grown for a total of six weeks and the above-ground portion was harvested. After the first cropping, the soils were allowed to rest for two and half months, after which they were spread out and the roots carefully hand-picked, air-dried and repotted for a second cropping of maize to evaluate the residual effectiveness of the P fertilizers. All the nutrients, except P, were added to each pot as described above in the first experiment.

Soil and plant analysis

The harvested plant materials were oven-dried at 70 °C for 78 hrs and weighed so as to measure the dry-matter (DM) yield. The plant materials were ground to pass a 2-mm screen and digested with H_2SO_4-H_2O_2 and elemental concentration determined using ICP-MS. Phosphorus uptake by the plants was calculated by multiplying the P concentration in the tissue and DM yield per pot. Soils were sampled after harvest and analyzed for pH, exchangeable bases (Ca, K, and Mg) and P as described above.

Statistical analysis of data

Analysis of variance (ANOVA) was performed to determined significant differences in DM yield and P uptake between the various treatments. The ANOVA was based on factorial arrangement in a randomized complete block design in which the effects of replication, P source, P rate and the interaction of P source and P rate (source x rate) were accounted for as sources of variance. All statistical analysis were performed using the general linear model procedure in SAS 9.1 (SAS Institute Inc., Cary, USA).

The relationship between DM yield or P uptake and applied P was evaluated by a linear statistical model in the form:

$$Y = \beta_0 + \beta_i X, \qquad\qquad 1$$

where *Y* is the DM yield or P uptake obtained with SSP or PRs, and *X* is the rate of P applied. The relative agronomic effectiveness (RAE) of the PR fertilizers relative to SSP with respect to any of the measured parameters was calculated as the ratio of the two slopes (Chien and Hammond 1991):

$$\mathrm{RAE}\,(\%) = \beta_i/\beta_{SSP} \times 100, \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 2$$

where β_i is the regression estimate of the tested PR and β_{SSP} is the regression estimate of the standard fertilizer (SSP).

Results and discussion

The exchangeable cations (Ca, Mg and K) content of the soils are low, indication low fertility status (Table 1). The high P sorption capacity of the soil, coupled with the low % Ca saturation will provide suitable environment for dissolution of the PR fertilizers. The relationship between DM yield and level of P applied from the various sources for both cropping are shown in Fig. 1. The effectiveness of the P sources in increasing DM yield followed the order SSP = MPR > TPR > SAPR. Without P application, the DM yield was low, and MPR produced significantly more DM yield than the other PRs in both the first and the second cropping, with SAPR been the least effective. Single super phosphate gave higher DM yield than TPR or SAPR at all rates of applied P in the two crops. This low DM production by the three PRs is consistent with the results of Nnadi and Haque (1998) showing that triple super phosphate was more effective in promoting DM yield of lucera (*Medicago sativa*) grown on a high P fixing volcanic ash soil of Ethiopia compared with PR fertilizers. It is noteworthy that the mean DM yield across all P rates for SSP was, however not significantly different ($P > 0.05$) from that for MPR.

The response of maize to P application as shown by P uptake values followed similar trend as DM yield, with SSP giving consistently superior values compared with TPR and SAPR (Fig. 2). There was a clear plant response to increasing rates of MPR and FPR and their P uptake values were significantly higher ($P < 0.05$) than the

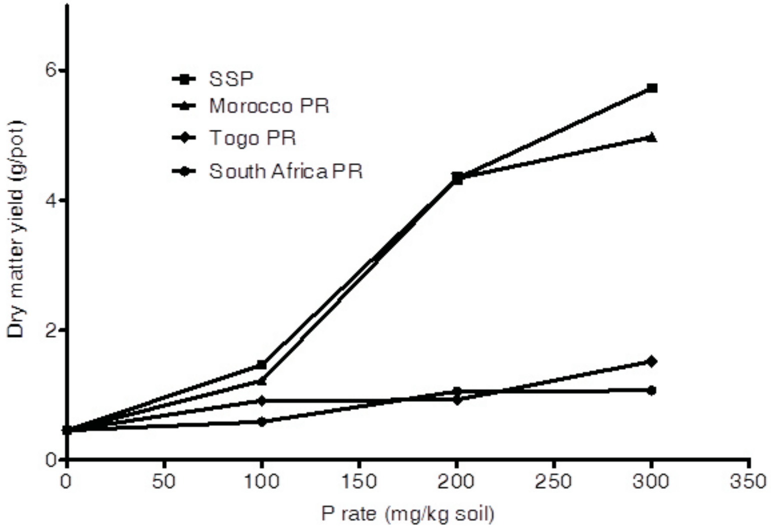

Fig. 1. Dry matter yield of corn obtained with phosphate rocks on ultsol in green house experiment

control in both cropping. The statistical analysis of data for DM yield and P uptake (Table 3) showed that the direct effect of P rate and sources as well as their interaction were all highly significant ($P < 0.01$). The response of maize to increasing rate of applied P was significant ($P < 0.05$) at all rates for SSP and MPR in the two crops. Except between 200 and 300 mg P kg^{-1} for TPR, no significant response to increasing rate of P application was obtained with TPR and SAPR.

The cumulative proportion of the applied P recovered by the maize was calculated as the additional P uptake by the tops over and above that of the control treatment for the three P rates of each fertilizer (Table 4). The P recovery values, expressed as a percentage of the total P applied, were generally low under the tested conditions. The low cumulative P recovery might be partially due to the high P sorption capacity of the soil used (Dodor & Oya, 2000). However, MPR performed well under the tested condition compared to SSP, especially during the first cropping.

The response of maize to the P sources in terms of increasing DM yield and P uptake was adequately described by a linear model ($r^2 > 0.97^{***}$). The RAE values for the various PR sources were calculated from the ratio of the marginal increase in DM

TABLE 3

Analysis of variance for DM yield and P uptake of maize in two successive cropping.†

Source of variation	*df*	*Dry-matter yield* First crop	*Dry-matter yield* Second crop	*P uptake* First crop	*P uptake* Second crop
Replication	2	0.02NS	0.01NS	12.91NS	0.60NS
P sources	3	16.30**	13.99.48**	1391.11**	8609.71**
P rates	2	19.32**	5.50**	13740.68**	3583.36**
P source x P rates	6	2.67**	1.46**	2103.07**	1237.68**
Error	25	0.02	0.01	9.57	5.37
CV (%)	5.60	5.39	5.70	5.61	
General mean		2.29	2.02	54.28	41.33

† The results are expressed as mean square from analysis of variance.

*,**, NS = Significant at 0.05 or 0.01 level of probability or not significant, respectively.

TABLE 4

Computed RAE values for DM yield and P uptake by maize

P source	*RAE (%)* *DM yield* First crop	*RAE (%)* *DM yield* Second crop	*RAE (%)* *P uptake* First crop	*RAE (%)* *P uptake* Second crop
SSP	100	100	100	100
MPR	89.5	35.3	78.2	29.6
TPR	15.8	11.8	13.4	6.3
SAPR	15.8	5.9	8.4	5.4

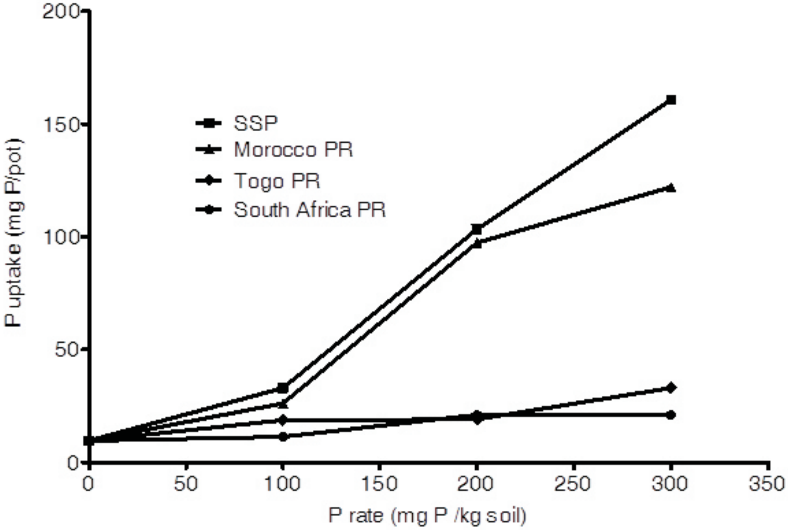

Fig. 2. Phosphorus uptake by corn as effected by different P sources

yield or P uptake from the PR sources compared with SSP (Table 4). Although the RAE values based on P uptake were not identical to those based on DM yield, the same trend was apparent. It should be noted that in pot experiment where adequate quantities of nutrients other than P are applied, P uptake may be a more sensitive indicator of relative agronomic performance of P fertilizers than DM yield. This is because of the differences in internal efficiency of P supplied to plant by different P fertilizers. Therefore, unless otherwise indicated, subsequent discussion of RAE values is on the basis of P uptake. It is also noteworthy that RAE values based on P uptake followed similar trend as DM yield, further justifying the use of P uptake values in the discussion.

Application of MPR was 78% as effective as SSP in inducing P uptake by maize (Table 4). It is interesting to note that comparison of the RAE values for MPR and SSP showed that the two were statistically similar ($P > 0.05$) in the first crop. During the second cropping, however, the response of maize to residual P from MPR decreased substantially relative to the residual response to SSP (Tables 4 and 5; Fig 2). This may indicate that MPR released a higher proportion of P which became available at the initial stages resulting in an earlier relative depletion of available P through crop utilization. Also, some of the solubilized P may have been fixed during the resting period (two and half months) resulting in reduced effectiveness of MPR even though its solubility might have been enhanced by the acidity of the soil (Chien *et al.,* 1980; Hammond *et al.,* 1986). This reduction in effectiveness coupled with the high initial P requirement of maize is probably the reasons for the poor performance of MPR during the second

TABLE 5

DM yield, P uptake and recovery by maize in two successive cropping

Phosphate source	*DM yield*		*P uptake*		*P recovered*
	First crop	*Second crop*	*First crop*	*Second crop*	
	g/pot		*mg/pot*		*%*
Control	0.46	0.73	9.61	12.93	–
SSP	3.84	4.11	99.01	94.26	26.18
MPR	3.51	1.97	81.86	38.44	15.03
TPR	1.12	1.07	23.56	19.48	3.53
SAPR	0.90	1.06	17.78	18.83	2.30
LSD (0.05)	0.72	0.54	20.25	15.52	–

Mean of three P rates and replications

cropping. Nevertheless, the result suggests that there was an initial benefit in direct application of MPR, however, this benefit tended to reduce during the following cropping when no P was applied.

The practical implication of the results of the present study is that increasing the frequency of direct application of MPR can be as effective as SSP in maintaining P levels in the soil for adequate plant growth in this soil. Furthermore, the physico-chemical properties of the Oku soil used in the present study is similar to most of the red and yellow soils of Okinawa. Result of the present study therefore, substantiates our previous assertion that the percent dissolution of MPR was high enough to be used as an alternative P source in Okinawan soils (Dodor *et al.*, 1999). Due to their low reactivity, the RAE values for TPR and SAPR were very low, suggesting that they are not suitable for direct application. The low reactivity of TPR is consistent with the results of Owusu-Bennoah & Acquaye (1996) who found that finely ground TPR gave lower yield than SSP.

The order of effectiveness of the various P sources in increasing DM yield and P uptake corresponds to the reactivity of the P sources as measured by the chemical extraction in NH_4 citrate (pH 3) (Table 6). Regression analysis relating the solubility measurements of the PRs to DM yield and P uptake (excluding SSP) showed that the correlation coefficient values were higher for NH_4^+citrate than for 2% citric or formic acids (Table 6). This indicates that acid NH_4^+citrate could be used to predict agronomic potential of PR fertilizers in this soil. This result agrees with those of Chien & Hammond (1991) who found that P uptake by bean was better correlated with acid NH_4^+citrate compared to 2% citric and formic acids.

The effect of the P sources on P content of the soils as measured by the acid Troug reagent (0.001 M H_2SO_4) which is the standard extractant for determining P availability index in Okinawa is shown in Table 7. Results indicated that available P contents of the soils treated with PR fertilizers were significantly higher than the control. The level of extractable P was higher in soils receiving PRs than SSP. The higher levels of extractable P in soils receiving PR presumably resulted from

TABLE 6

Correlation coefficient (r) of solubility test with DM and P uptake by maize in two successive cropping

Extractant	DM yield		P uptake	
	First crop	*Second crop*	*First crop*	*Second crop*
2% Formic acid	0.967	0.855	0.93	0.859
2% Citric acid	0.763	0.731	0.881	0.739
Acid Ammonium citrate	0.921	0.997	0.943	0.996

TABLE 7

Soil Nutrient Content after two cropping with Maize

	pH	*Soil Nutrient Content*			
		Ca	*Mg*	*K*	*P*
		meq/100g		*mg/kg*	
Control	4.22	0.38	1.97	1.42	13.89
MPR	4.22	1.27	5.90	0.95	220.77
TPR	4.21	0.53	6.61	1.13	135.62
SAPR	4.23	0.43	7.11	1.13	50.59
SSP	4.21	2.09	5.12	0.88	64.88

Values are means of three P rates and replications

acidulation of the PRs during the extraction process, leading to gross overestimation of the amount of bioavailable P in soils treated with PRs (Kumar *et al*., 1994).

Application of PRs also increased soil Ca and Mg concentrations and decreased K concentration in the soil. Because the Oku soil used in the present study requires lime to raise its pH along with supplying other nutrients such as Ca for optimum crop production, this finding suggests that PR may also have potential agronomic values as an effective alternative source of calcium for crop nutrition and/or production in this soil. This result agrees with those of Hellums *et al.* (1989) showing that PRs with medium to high reactivity have a liming effect in addition to their use as a P source when directly applied to acids soils. The effect of PR treatment on soil exchangeable Ca were also reported by Chien *et al.* (1987) with an Oxisol in Cambodia. The application of all P sources increased Ca content of the maize considerably above the control and there was a trend for higher Ca content with increasing rate of applied P (Table 8). Concentration of Ca in plants that received MPR was generally similar to those that received SSP, whiles those that received TPR and SAPR had lower Ca contents. Concentrations of K and Zn in plants that received PR were generally similar to SSP and the control. Although plants that received TPR and SAPR showed poor growth (DM yield), they tended to have higher concentrations of Mg and Mn.

In conclusion, although this study was of a preliminary nature, the finding offer an

TABLE 8

Nutrient composition of maize as affected by P sources.

Phosphate source	*Ca*	*K*	*Mg*	*Zn*	*Mn*	*B*
	g/kg			*mg/kg*		
Control	1.03	31.01	2.38	1.45	1.10	1.41
SSP	2.73	32.16	1.22	1.08	0.73	0.68
MPR	2.68	33.37	1.57	1.11	0.85	0.86
TPR	1.41	31.43	2.15	1.45	1.07	1.01
SAPR	1.27	28.60	2.34	1.25	1.11	0.89

Mean of three P rates and replications

encouragement for further appraising the possibility of utilizing MPR as source P in large number of soils in Okinawa and elsewhere.

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