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A Study on Response of Sugarcane Genotypes to Phosphorus Fertilizer in Western Guangdong, China

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Abstract: To optimize Phosphorus (P) fertilization, three sugarcane genotypes (ROC22, LC5135, and YT236) widely cultivated in western Guangdong, China were used for the experiment in which 5 levels of P fertilizer were set up to study the effects of their application. The results showed that: (1) P fertilization amount within 288 kg/hm^2 P_2O_5 could increase the plant height, stem diameter, and weight and yield of sugarcanes. The yield of ROC22 was 14% more than LC5136 and 33% more than YT236. (2) The sucrose yield of ROC22, YT236, and LC5136 increased firstly, followed by leveling off or no significant change with the increase of P fertilizer. The sucrose yield of ROC22 with 288 kg/hm^2 P_2O_5 was significantly higher than other treatments. The average yield of ROC22 was 15% higher than that of LC5136 and 35% higher than that of YT236. (3) The P fertilizer use efficiency of ROC22 and LC5136 increased firstly and then decreased and that of YT236 always decreased with increasing levels of P fertilizer application. Considering the yields of sugarcane and sucrose and the use efficiency of P fertilizer, the optimum P fertilizer amounts of ROC22 and LC5136 were 288 kg/hm^2 and that of YT236 was 192 kg/hm^2. The growth of ROC22 was better than that of LC5136 and YT236.

Keywords: Sugarcane, Yield, Sucrose Yield, Phosphorus Fertilizer, Fertilizer use Efficiency

Introduction

Sugarcane belongs to the genus *Saccharum* in the grass family and is a very necessary sugar crop. The total sugarcane planting area in China ranks third in the world (Huang *et al*., 2020). Sugarcane is the main raw material of China's sugar industry and the ratio of sugarcane to the total sugar output exceeds 70%. The sugarcane industry is of great significance to the agricultural efficiency and income increase of sugarcane-producing areas in China (Zu *et al*., 2018). Phosphorus is an essential nutrient element for the growth and development of sugarcane and the application of P fertilizer has a significant effect on sugarcane yield (Sousa *et al*., 2017). However, the P fertilizer cannot be overused. Too much phosphorus will affect the normal growth and development of sugarcane and reduce the yield and quality of yielded sugarcane (Mccray *et al*., 2012). In China, only 10-15% or even less of P fertilizer applied in large quantities can be absorbed and utilized by sugarcane, which not only increases production costs but also causes waste of resources and environmental pollution (Wu *et al*., 2020). Only proper and reasonable application of P fertilizer can promote the growth of sugarcane and improve its yield and quality (Mccray *et al*., 2012).

Zhanjiang is the main sugarcane producing area in Guangdong Province and the third largest sugarcane planting area in China. The annual planting area and sucrose yield account for more than 90% of the province (An *et al*., 2013). At present, the amount of P fertilizer application in the Zhanjiang sugarcane area is mostly 400~500 kg/hm^2, which is far higher than the world average. The cost of fertilizer has become the largest expenditure on sugarcane yield. Therefore, the long-term unreasonable application of fertilizer has seriously restricted the healthy development of the sugar industry in Guangdong Province and even the whole of China (Jiang *et al*., 2011). So, the author took the sugarcane area of Zhanjiang, Guangdong as the research area, set up 5 P fertilizer levels and 3 sugarcane genotypes to conduct field experiments, and explored the master sugarcane in the research area through the research on the agronomic characteristics, yield and phosphorus utilization efficiency of sugarcane. The appropriate amount of P fertilizer for the sugarcane genotypes can reduce production costs and environmental phosphorus pollution and provide an important theoretical and practical basis for the scientific application of P fertilizer and the selection of high-efficiency phosphorus utilization genotypes for sugarcane.

Materials and Methods

Study Materials and Field Conditions

The tested *Saccharum officinarum* genotypes were the Xintaitang 22 (ROC22), Liucheng 5136 (LC5136), and Yuetang 236 (YT236), which are widely cultivated in South China. The tested Nitrogen (N), Phosphorus (P) and potassium (K) fertilizers were urea (containing N 46%), calcium magnesium phosphate (containing P_2O_5 12%), and potassium chloride (containing K_2O 60%). The test site was set up in the field of Zhanjiang Agricultural Reclamation Research Institute, Guangdong, where sugarcanes had been planted continuously for more than 9 years. The soil in the field was basalt matrix latosol and the soil pH was 4.94, organic matter was 18.34 g/kg, total nitrogen content was 0.98 g/kg, alkali hydrolyzed nitrogen was 69.64 mg/kg, available phosphorus was 11.15 mg/kg, available potassium was 75.57 mg/kg.

Experimental Methods and Design

The experiment was a two-factor split-plot design. The main factors were different sugarcane genotypes, namely ROC22, LC5136, and YT236. The secondary factors were 5 levels of P fertilizer, that were the non-phosphate treatment (P0), 96 kg/hm^2 P_2O_5 treatment (P1), 192 kg/hm^2 P_2O_5 treatment (P2), 288 kg/hm^2 P_2O_5 treatment (P3) and 384 kg/hm^2 P_2O_5 treatment (P4). Each of the sugarcane genotypes with 5 levels of P fertilizer, a total of 15 treatments and there were three repeated plots in each treatment, so a total of 45 plots. The plot was a three-row area with a row length of 8 m and spacing of 1 m and an area of 24 m^2 a plot. Planting density of sugarcanes was102000 plants/hm^2. Nitrogen (N) of 351 kg/hm^2 and potassium oxide (K_2O) of 324 kg/hm^2 were applied for each plot. The N fertilizer was applied by basal fertilizer (30%) and topdressing (70% during the jointing hill up period), the P fertilizer was used by basal fertilizer (60%) and topdressing (40%) and the K fertilizer was applied by basal fertilizer (40%) and topdressing (60%).

Survey and Analysis Items

The experiment was carried out from March 2015 to December 2015. A total of 15 sugarcane plants with relatively uniform growth were selected from each treatment as the observation plants to investigate their agronomic attributes. Dead leaves were collected to determine the total P uptake of leaves. The plant height, stem diameter, and productive stem number were investigated in early November 2015. The 9 plant samples were taken from each treatment to measure their biomass, sucrose content, and P uptake for calculating the use efficiency of P fertilizer.

At the beginning of December 2015, the yield, sucrose yield, and partial productivity of P fertilizer were calculated when the sugarcanes were harvested:

$$Use\ efficiency\ of\ P\ fertilizer(\%) = \frac{Plant\ P\ absorption\ form\ fertilization\ area(g) - Plant\ P\ absorption\ form\ no\ fertilization\ area(g)}{P\ fertilization\ amount(g)}$$

$$Yield(kg/hm^2) = weight\ of\ single\ stem(kg) \times Number\ of\ production\ stems(plant/hm^2)$$

$$Sucrose\ yield(kg/hm^2) = Sucrose\ content(\%) \times yield(kg/hm^2)$$

$$Partial\ productivity\ of\ P\ fertilization(kg/kg) = \frac{Yield\ of\ P\ fertilization\ area(kg)}{Pfertilization\ amount(kg)}$$

Data Processing

The test data was processed by Excel 2007 and SSPS13 software.

Results

The Effects of Phosphorus Application Rate on the Agronomic Attributes of Different Sugarcane Genotypes

As shown in Table 1, the amount of P fertilizer application has significant effects on the agronomic attributes of sugarcane genotypes e. As the amount of P fertilizer increased, the plant height of the three sugarcane genotypes increased significantly. In addition, the average plant height of the three sugarcane genotypes under different P fertilizer rates was significantly different. ROC22 was 5 and 44 cm higher than LC5136 and YT236, respectively. The phosphorus application rate had a significant impact on the stem diameter of sugarcanes as well. The stem diameter of ROC22 increased significantly with the increase in phosphorus application rate. The stem diameter of LC5136 treated with P2 and P3 was significantly larger than that treated with P1 and P4, and that treated with P0 was the least. The stem diameter of YT236 treated with P4, P3 and P2 were significantly larger than that treated with P1 and P1 was significantly larger than P0. The average stem diameters of the three sugarcanes under different P fertilizer rates were significantly different. LC5136 was 0.13 and 0.18 cm thicker than ROC22 and YT236, respectively. And the productive stem number was affected by P fertilizer rates as well. The number of the productive stem of ROC22 treated with P4 and P3 was significantly greater than that treated with P2, P1, and P0. The productive stem number of LC5136 treated with P4, P3, and P2 was significantly greater than that treated with P1 and P0. The productive stem number of YT236 treated with P3 and P2 was significantly greater than that treated with P1 and P0. The average productive stem number of the three sugarcanes under different P fertilizer rates was significantly different. YT236 was 12 and 45% more than ROC22 and LC5136, respectively.

Table 1: The agronomic attributes of sugarcanes under different phosphorus rate conditions

		Sugarcane genotypes			
Agronomic attributes	Treatment	ROC22	LC5136	YT236	Mean
Plant height (cm)	P0	259±6e	239±4e	217±4e	238±19e
	P1	271±4d	269±2d	230±4d	257±20d
	P2	287±3c	284±4c	245±3c	272±20c
	P3	309±2b	305±3b	258±2b	291±25b
	P4	319±4a	324±3a	275±3a	306±24a
	Mean	289±24A	284±30B	245±21C	
Stem diameter (cm)	P0	2.36±0.03e	2.53±0.03c	2.33±0.03c	2.41±0.10c
	P1	2.49±0.04d	2.68±0.07b	2.52±0.07b	2.56±0.10b
	P2	2.63±0.04c	2.83±0.03a	2.64±0.04a	2.70±0.10a
	P3	2.71±0.05b	2.87±0.03a	2.62±0.02a	2.74±0.11a
	P4	2.80±0.04a	2.74±0.04b	2.62±0.02a	2.72±0.08a
	Mean	2.60±0.16B	2.73±0.13A	2.55±0.13C	
Productive stem (plant/ hm^2)	P0	73910±493d	69840±572c	103550±1064c	82433±15949d
	P1	86700±1650c	72800±826b	106855±210b	88785±14858c
	P2	101600±1146b	76140±119a	109785±777a	95842±15211b
	P3	109285±2813a	75980±329a	109025±1208a	98097±16659a
	P4	108460±1869a	75870±550a	108345±1341ab	97558±16309a
	Mean	95991±14253B	74126±2603C	107512±2434A	

Note: Different small letters in the same column meant significant differences among phosphorus rate treatments ($P<0.05$). Different capital letters in the same line meant significant differences among different sugarcane genotype treatments ($P<0.05$)

The Influence of Phosphorus Application Rate on the Biomass of Different Sugarcane Genotypes

As shown in Fig. 1, the amount of P fertilizer has a significant impact on the biomass of different varieties of sugarcane. The biomass of three genotypes treated with P4, P3, and P2 was significantly greater than those of P1 and P0 and the biomass of the P1 treatment was significantly greater than that of P0. The plant biomass of three genotypes was significantly different under different P fertilizer levels and LC5136 was significantly greater than those of ROC22 and YT236 and ROC22 was significantly larger than YT236. The average biomass of LC5136 under the five P fertilizer rates was 23 and 50% higher than ROC22 and YT236, respectively.

Different small letters indicate significant differences among phosphorus rate treatments under the same genotype condition ($P<0.05$). Different capital letters meant significant differences among sugarcane genotype treatments under the same phosphorus rate condition ($P<0.05$).

The Effects of Phosphorus Application Rate on the Phosphorus Uptake of Different Sugarcane Genotypes

As shown in Fig. 2, the amount of P fertilizer has a significant impact on the phosphorus uptake of above-ground individuals of sugarcane varieties. With the increase in phosphorus application, the phosphorus uptake of ROC22 and YT236 increased significantly in the range of P0-P3 and there was no significant difference between P3 and P4 treatments. The phosphorus uptake of LC5136 increases significantly with the increase of phosphorus application.

Under five P fertilizer rates, the phosphorus absorption of LC5136 was significantly greater than those of ROC22 and YT236 and YT236's phosphorus uptake was significantly greater than ROC22 at P4 and P3 levels, while there was no significant difference between YT236 and ROC22 at P0-P2 levels.

It can also be seen from Fig. 2 that the amount of P fertilizer has a significant effect on the accumulation and distribution ratio of phosphorus in the three above-ground sugarcane stems. In general, with the increase in the amount of P fertilizer, the cumulative proportion of phosphorus in the stems of the three varieties of sugarcane increased, while the cumulative proportion of phosphorus in the leaves decreased and this trend of YT236 was clearer. The cumulative proportion of phosphorus in the stems of LC5136 increased by 22 and 24% compared with ROC22 and YT236 respectively. The cumulative proportion of leaf phosphorus of LC5136 was less than ROC22 and YT236.

Different small letters indicate significant differences among phosphorus rate treatments under the same genotype condition ($P<0.05$). Different capital letters meant significant differences among sugarcane genotype treatments under the same phosphorus rate condition ($P<0.05$).

The Effects of Phosphorus Application Rate on the Yield and Sucrose Yield of Different Sugarcane Genotypes

As shown in Table 2, the stem weights of ROC22 and LC5136 treated with P3 and P4 were significantly greater than those of P0 and P1. The stem weight of YT236 under P4, P3, P2, and P1 treatments was significantly greater than that of the control without P fertilizer (P0), while the stem weight of YT236 under P4, P3, P2, and P1 treatments had no significant difference. The stem weights of the three sugarcane genotypes under different P fertilizer levels were different significantly, LC5136 gained 15 and 69% more weight than ROC22 and YT236, respectively.

The amount of phosphorus applied also has an impact on the yield of the three genotypes of sugarcane. With the increase in phosphorus application rate, the phosphorus uptake of ROC22 and LC5136 increased significantly in the range of P0- P3 and there was no significant difference between P3 and P4 treatments. The phosphorus uptake of YT236 under P2 and P3 treatments was significantly greater than that of P1 and P0 and there was no significant difference between P2, P3, and P4. Under different P fertilizer levels, the average yields of the three varieties were significantly different and the yield of ROC22 was 14 and 33% higher than LC5136 and YT236 respectively.

The ROC22 sucrose content of the P1, P2, and P3 treatments was significantly higher than that of P0 and P4. There was no significant difference in the sucrose content of LC5136 under different P fertilizer rates. The sucrose content of YT236 showed a significant decreasing trend with the increase in phosphorus application rate. The average sucrose content of the three genotypes had no significant difference. With the increase in phosphorus application rate, the sucrose yield of ROC22 and YT236 increased first and then decreased. The sucrose yield of ROC22 reached the highest level at P3 (22620 kg/hm^2) and the sucrose yield of YT236 reached the highest at P2 (14214 kg/hm^2). The sucrose yield of LC5136 treated with P2, P3, and P4 was significantly greater than that of P1 and P0. The average sucrose yield of the three genotypes of sugarcane under different P fertilizer rates was significantly different, ROC22 was significantly greater than LC5136 and LC5136 was significantly greater than YT236. The sucrose yield of ROC22 was15 and 35% higher than that of LC5136 and YT236, respectively.

The Effects of Phosphorus Application Rate on the Fertilizer Utilization Efficiency of Different Sugarcane Genotypes

As shown in Table 3, the average phosphorus uptake of LC5136 per hectare showed a significant increasing trend with increasing P fertilization. The phosphorus uptake of ROC22 treated with P3 was significantly greater than that with P0, P1, P2, and P4. The YT236 with P3 and P4 was significantly larger than that with P2, P1, and P0. The average phosphorus uptake of the three genotypes under different P fertilizer rates was significantly different. LC5136 (63.20 g/hm^2) absorbed 19 and 44% more phosphorus per hectare than YT236 (53.16 g/hm^2) and ROC22 (43.92 g/hm^2), respectively.

Table 2: The yield and sucrose yield of sugarcanes under different phosphorus rate conditions

		Sugarcane genotypes			
Yield	Treatments	ROC22	LC5136	YT236	Mean
The weight of stem (kg/plant)	P0	1.27±0.05c	1.51±0.03d	0.95±0.02b	1.24±0.25d
	P1	1.5±0.04b	1.67±0.03c	1.04±0.02a	1.41±0.28c
	P2	1.60±0.02a	1.75±0.05b	1.06±0.01a	1.47±0.32b
	P3	1.63±0.03a	1.88±0.03a	1.06±0.02a	1.52±0.36a
	P4	1.60±0.03a	1.91±0.02a	1.05±0.02a	1.52±0.38a
	Mean	1.52±0.14B	1.74±0.15A	1.03±0.05C	
Yield (kg/hm^2)	P0	93605±2914d	105235±2861d	98019±1038c	98953±5503d
	P1	130367±5364c	121834±3517c	111486±2297b	121229±8868c
	P2	162892±2150b	133495±3697b	116367±438a	137585±20491b
	P3	178179±7247a	142839±1674a	115557±1747a	145525±27458a
	P4	173919±5616a	144660±2208a	114141±3612ab	144240±26124a
	Mean	147792±33245A	129613±15347B	111114±7219C	
Sucrose content (%)	P0	10.82±0.72b	11.46±0.67ab	13.96±0.56a	12.08±1.55ab
	P1	13.41±0.99a	10.37±0.43b	12.73±1.00b	12.17±1.56ab
	P2	12.76±1.19a	13.07±1.11a	12.22±0.56b	12.68±0.94a
	P3	12.69±0.31a	12.08±1.58ab	10.68±0.58c	11.82±1.24ab
	P4	10.71±0.92b	12.93±0.33a	10.71±0.31c	11.45±1.22b
	Mean	12.08±1.36A	11.98±1.30A	12.06±1.40A	
The sucrose yield (kg/hm^2)	P0	10127±790d	12052±381b	13682±568b	11954±1628c
	P1	17520±1974c	12626±233b	14205±1386a	14784±2479b
	P2	20794±2012ab	17475±1973a	14214±605a	17494±3193a
	P3	22620±1122a	17268±2417a	12337±637b	17409±4660a
	P4	18666±2213bc	18709±524a	12233±675b	16536±3439a
	Mean	17945±4666A	15626±3078B	13334±1150C	

Note: Different small letters in the same column meant significant differences among different phosphorus rate treatments (P<0.05). Different capital letters in the same line meant significant differences among different sugarcane genotype treatments (P<0.05)

Table 3: The fertilizer utilization efficiency of sugarcane genotypes under different phosphorus rate conditions

		Sugarcane genotypes			
Utilization efficiency	Treatments	ROC22	LC5136	YT236	Mean
The P uptake of sugarcane (g/hm^2)	P0	29.04±1.67d	39.83±1.64e	40.68±2.36c	36.52±5.86e
	P1	38.02±1.51c	46.14±2.55d	51.46±2.51b	45.21±6.18d
	P2	47.58±2.31b	67.75±3.32c	51.30±2.50b	55.54±9.59c
	P3	54.74±1.00a	73.96±3.23b	59.41±3.11a	62.70±8.98b
	P4	50.24±1.94b	88.31±4.96a	62.93±1.79a	67.16±17.02a
	Mean	43.92±9.68C	63.20±18.75A	53.16±8.25B	
The use efficiency of P fertilizer (%)	P0	\	\	\	\
	P1	9.35±0.70a	6.57±1.17c	11.23±0.34a	9.05±2.15b
	P2	9.66±0.39a	14.54±0.94a	5.53±0.34c	9.91±3.94a
	P3	8.93±0.52a	11.85±0.63b	6.51±0.29b	9.09±2.36b
	P4	5.52±0.13b	12.62±0.89b	5.79±0.29c	7.98±3.52c
	Mean	8.36±1.78B	11.40±3.18A	7.27±2.44C	
Partial productivity of P fertilizer (g/kg)	P0	\	\	\	\
	P1	1357.98±55.9a	1269.10±36.63a	1161.31±23.9a	1262.80±92.38a
	P2	848.40±11.20b	695.29±19.26b	606.08±2.28b	716.59±106.72b
	P3	618.68±25.16c	495.97±5.81c	401.24±6.07c	505.29±95.34c
	P4	452.91±14.62d	376.72±5.75d	297.24±9.41d	375.63±68.03d
	Mean	819.49±357.40A	709.27±358.40B	616.47±348.60C	

Note: Different small letters in the same column meant significant differences among phosphorus rate treatments ($P<0.05$). Different capital letters in the same line meant significant differences among sugarcane genotype treatments ($P<0.05$)

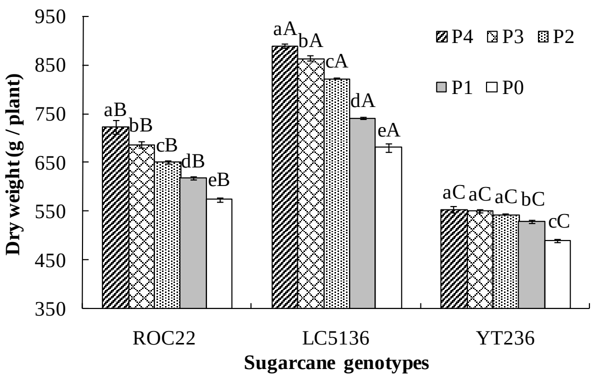

Fig. 1: The biomass of sugarcane genotypes under different phosphorus rate conditions

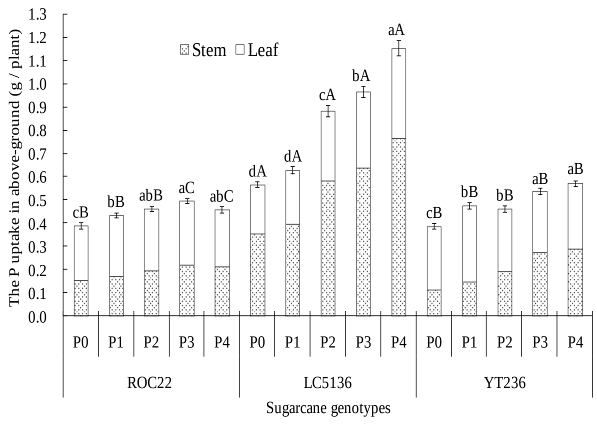

Fig. 2: The P uptake of sugarcane genotypes under different phosphorus rate conditions

The phosphorus application rate has a significant impact on the phosphorus utilization efficiency of three genotypes. The use efficiency of P fertilizer ROC22 with P1, P2, and P3 was significantly greater than that with P4 and the LC5136 with P2 was significantly greater than that with P1, P3, and P4. The use efficiency of P fertilizer of YT236 decreased significantly with the increase in fertilization rate. The average use efficiency of P fertilizer was significantly different between the treatments with different fertilizer rates and the P utilization efficiency of LC5136 (11.40%) was 3 and 4% higher than that of ROC22 (8.36%) and YT236 (7.27%), respectively.

The P fertilizer partial productivity of the three sugarcane genotypes decreased significantly with the increase of P fertilization. The average P partial productivity of the three genotypes under different P fertilizer rates was significantly different and ROC22 (819.49 g/kg) was 15 and 33% higher than LC5136 (709.27 g/kg) and YT236 (616.47 g/kg), respectively.

Discussion

In the process of traditional sugarcane planting, most farmers believe that P fertilizer is essential to increase sugarcane yield. So, they even prefer to apply P fertilizer regardless of cost for increasing sugarcane yield (Borges *et al*., 2019). However, the effect of P fertilizer application did not increase linearly with the increase of fertilizer amount and increased to a certain level and then showed a downward trend (Sousa *et al*., 2017), which is consistent with the results of this study.

The results of this study showed that P fertilizer application could increase the plant height, stem diameter and weight, and yield of sugarcanes to a certain extent, but the stem weight and yield of sugarcanes would decrease or have no obvious changes when the P fertilizer application reached a certain level. This is due to the imbalance of the ratio of nutrient elements caused by excessive amounts of P fertilizer and the photosynthetic intensity of sugarcane is weakened, the uptake of P is enhanced and carbohydrate consumption is increased, causing early or excessive consumption of sugarcane nutrients that is averse to increase the yield of sugarcanes, even reduce the yield (Albuquerque *et al*., 2016). Therefore, increasing the application of P fertilizer within a certain range can promote the growth of sugarcane and increase the yield. Appropriate fertilization for different sugarcane genotypes is the key to increasing the yield, so overuse of fertilization should be avoided for increasing the yield. Select the level of P application with higher sugarcane yield and lower fertilizer dose as the recommended fertilization rate for the local sugarcane planting industry, that was, the P application rate of 288 kg/hm^2 was more suitable for ROC22 and LC5136 and P fertilizer of 192 kg/hm^2 was a better choice for YT236.

Yield is a concentrated expression of agronomic attributes of sugarcane and it is also one of the criteria for the quality of sugarcane genotypes (Franco *et al*., 2015). This research showed that the agronomic attributes and yields of the three sugarcane genotypes were significantly different. The plant height of ROC22 was 5 cm higher than LC5136 and 44 cm higher thanYT236.The stem diameter of LC5136 was 0.13 cm thicker than ROC22 and 0.18 cm thicker than YT236. The stem weight of LC5136 was 69% higher than YT236 and ROC22 was 48% higher than YT236. The productive stem numbers of YT236 were 45% higher than that of LC5136 and ROC22 was 30% higher than LC5136. Considering comprehensively, the agronomic attributes of ROC22, such as the plant height, stem weight, and productive stem were superior to LC5136 and YT236. Among them, the stem weight and productive stem are the main yield components of the sugarcanes, which directly affect the yield and economic benefits of sugarcanes (Tejera *et al*., 2007). The results also showed that the yield of ROC22 increased by 14, and 33% than LC5136, and YT236, respectively. Therefore, we recommend planting ROC22 in the study area instead of planting the LC5136 and YT236.

The high yield and quality of sugarcane are the main goal of planting sugarcanes and the quality of sugarcane is determined by the sugar content in the cane stem. The three major nutrients (nitrogen, phosphorus, and potassium) are particularly important for sugarcane growth, yield, and quality (Fortes *et al*., 2013). The nutrient supply of N, P, and K can improve the sugar content in cane stems (Anderson, 1990). The results also showed that the application of P fertilizer could increase the sucrose content of ROC22, but the sucrose content did not change significantly when the amount of P fertilizer was more than P1 and that with P4 even reduced significantly. The sucrose content of YT236 was significantly reduced with the amount of P increasing. But the effects of P fertilizer on LC5136 were not obvious, that may be because potassium is also very important for the growth and quality improvement of sugarcane, especially the potassium plays an important role in the carbohydrate metabolism process of sugarcane and the increasing of sucrose content and it is the main element to improve sugarcane quality (Esther Shekinah *et al*., 2012). Even if the phosphorus supply is sufficient, the sucrose content of sugarcane will not increase because of relatively insufficient potassium, especially the application of P fertilizer causes an imbalance in the ratio of nutrients, which can directly lead to the reduction of sugarcane quality (Albuquerque *et al*., 2016). This shows that excessive application of P fertilizer cannot effectively increase the sucrose content of sugarcane and the appropriate fertilization is also required, which should be used in conjunction with fertilizers such as nitrogen, phosphorus, and potassium to achieve the purpose of improving the sugarcane quality (Thomas and Scott, 1990).

The sucrose yield of sugarcane is mainly composed of sucrose content and sugarcane yield, so they directly determine the sucrose yield (Ferraro *et al*., 2009). The results showed that the sucrose yield of ROC22 and YT236 increased first and then decreased with the increase of P application. At the same time, the sucrose yield of LC5136 increased first and did not change significantly later. The sucrose yield of ROC22 with 288 kg/hm^2 P fertilizer (P3) was significantly higher than that with P0, P1, and P4, and the sucrose yield of ROC22 was significantly higher than that of the other sugarcane genotypes, which was 15, 35% higher than LC5136, YT236, respectively. Therefore, we recommend planting ROC22 with 288 kg/hm^2 P fertilization in the study areas to obtain higher sucrose yield and economic benefits.

The nutrient uptake of nitrogen, phosphorus, and potassium is crucial to the formation of dry matter in crops. Nitrogen and phosphorus are important nutrient elements for plant growth and yield, which affects the accumulation and distribution of dry matter during plant growth (Li *et al*., 2019a). In this study, the phosphorus uptake of the sugarcanes increased or increased first and then had no obvious change with the increase of P fertilizer, which was consistent with the changing trend of plant biomass. This result shows that there is a positive correlation between dry matter accumulation and phosphorus uptake of sugarcane plants (Zambrosi *et al*., 2016). In the same way, the whole biomass and phosphorus uptake of LC5136 were significantly greater than those of ROC22 and YT236.

The study showed that sugarcane mainly uptake phosphorus before the sugarcane jointing stage (early and mid-term) and phosphorus was distributed more in the leaves. The phosphorus stored in the leaves was transferred to the stems after sugarcane jointing to maintain the rapid growth of the stem, so that the accumulation of phosphorus in stems increased rapidly, while the distribution ratio of phosphorus in the leaves decreased rapidly (Coyne *et al*., 2004). The results showed that P fertilization has a significant effect on the P uptake and distribution in sugarcane stems and leaves. The cumulative proportion of phosphorus in the sugarcane stems increased with the increase of P fertilizer, while that in the leaves decreased. This may be related to the amount of P fertilizer and the fertilization method used in the test. In this study, P fertilizer was applied by 60% as base fertilizer and 40% as additional fertilizer (joint-growing period). The more phosphorus is supplied, the more phosphorus will be transferred from the leaf to the stem and the cane stems will absorb more phosphorus in the middle and late stages of sugarcane (Coyne *et al*., 2004). To improve the use efficiency of P fertilizer for sugarcane, it is recommended to improve both the amount and time of P fertilization.

The amount of P fertilizer has different effects on the P utilization efficiency of the sugarcanes. The phosphorus utilization efficiency of ROC22 and YT236 showed a decreasing trend with increasing P fertilizer. P fertilizer utilization efficiency significantly decreases because of the fixation, residue, and loss of phosphorus in latosol (Li *et al*., 2019b). It can be seen that P fertilization blindly will reduce the use efficiency of P fertilizer and increase the costs of planting sugarcanes and the risk of environmental pollution. We also found that the fertilizer utilization efficiency of LC5136 was different from that of the other two genotypes and showed a trend of first increasing and then decreasing. At the same time, the P fertilizer utilization efficiency of LC5136 was significantly higher than that of ROC22 and YT236 due to differences in phosphorus uptake of sugarcane genotypes (Sundara, 1994).

The partial productivity of P fertilizer reflects the marginal effect of crops absorption P from fertilizer and soil and is defined as the ratio of crop yield to fertilizer application (Cassman and Pingali, 1996). This research showed that the partial productivity of P fertilizer was negatively correlated with the amount of P fertilizer application (Li *et al*., 2019b). The P fertilization amount is an important factor that affects the partial productivity of P fertilizer. The partial productivity decreased when the P fertilization increased, but it was not a simple linear decrease, which showed that the amount of fertilizer was not the only factor that affected the partial productivity, it may also be related to crop yield or other factors. The yield will increase with the increase of phosphorus applied in a certain range, but the yield will not increase or decrease when fertilization exceeds the optimal amount. Therefore, excessive application of P fertilizer will cause lower partial productivity (Sundara, 1994). At the same time, the difference in sugarcane yields between genotypes also led to a significant difference in P fertilizer partial productivity and that of ROC22 was significantly greater than that of LC5136 and YT236. Therefore, selecting sugarcane genotypes with high-efficient fertilizer utilization and proper fertilization were important measures to improve the partial productivity of P fertilizer.

Conclusion

Considering the productive stem, sugarcane yield, sucrose yield, and P fertilizer utilization efficiency of sugarcane. The P fertilization amounts of ROC22 and LC5136 were 288 kg/hm2 (P3) and that of YT236 was 192 kg/hm2 (P2), which could be considered a reasonable P fertilizer rate. At the same time, the results showed that the planting performance of ROC22 was significantly better than that of LC5136 and YT236 and it is recommended to promote planting ROC22 in the study areas.

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Author's Contributions

Jin Li and Chao Zheng: Designed and performed the experiments, analyzed the data, and prepared the paper. Both authors contributed equally to this study.

Xianmin Wang and Yingbin Xue: Participated to collect the materials related to the experiment.

Tingting Duan: Designed the experiments and revised the manuscript.

Ethics

The authors declare their responsibility for any ethical issues that may arise after the publication of this manuscript.

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