Research Findings

Photo 1. Pepper plants grown on yellow soil in China. Photo by the authors.

Enrichment of Compound NPK Fertilizer with Polyhalite Enhances Pepper *(Capsicum annuum)* Yield and Quality on Poor Yellow Soils in Southwest China

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Abstract

Pepper (*Capsicum annuum*) is one of the major vegetable crops grown on the yellow soils of southwest China. While the vegetable crops in the area are intensively fertilized with a uniform compound nitrogen (N), phosphorus (P), and potassium (K) fertilizer at a composition ratio of 15-15-15 (N-P_2O_5-K_2O), secondary macronutrients such as calcium (Ca) and magnesium (Mg) are usually ignored. Under the rainy subtropical climate of the region, soil Ca and Mg are rapidly depleted, crops suffer from imbalanced mineral nutrition, and consequently, farmers fail to realize the economic potential of the crop. Two principal steps were examined in the present study: adjustment of the NPK ratio according to pepper crop requirements; and, adding polyhalite to the compound NPK blend, as a supplementary Ca and Mg fertilizer. Two experiments

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were conducted at two sites: Chongqing and Guizhou. Each experiment included four treatments: T1 – farmer's practice, applying compound NPK fertilizer at 15-15-15; T2 – NPK 15-15-15 with supplementary polyhalite; T3 – NPK 16-8-18; and T4 – NPK 16-8-18 with polyhalite. In all treatments, the seasonal N and K_2O doses were kept quite similar at 248-260, and 248-284 kg ha^{-1}, respectively, while P_2O_5 dose was 248 or 164 kg ha^{-1}, in treatments T1 and T3, or T2 and T4, respectively. Polyhalite comprised 19-23% of the total fertilizer blend of T2 and T4, and provided 63-68, and 23-28 kg ha^{-1} of CaO and MgO, respectively. The adjustment of the NPK ratio alone gave rise to a substantial increase in the agronomic P use efficiency without having much impact on pepper productivity or yield. However, the addition of supplementary polyhalite increased the aboveground biomass and fruit yield, and significantly enhanced the agronomic use efficiency of both N and P. In addition, polyhalite increased crop Ca and Mg uptake and their distribution to plant organs, while replenishing the soil reserves of these nutrients. Polyhalite application also increased fruit K, Mg, and vitamin C contents, thus enhancing the produce quality. All economic parameters were improved dramatically as a result of polyhalite application, with the return on investment (ROI) ranging from 15-27. The supplementary application of polyhalite, which provides four essential nutrients gradually released over a prolonged period, demonstrates the principles that should dominate the required modification of the fertilization approach in vegetable cultivation on the yellow soils: balanced soil nutrition; adjustment to crop requirements; and, use of slow- or controlled-release fertilizers.

Keywords: Capsicum annuum; magnesium; nutrient use efficiency; Polysulphate; vitamin C.

Introduction

Pepper (*Capsicum annuum*) cultivation area in China is steadily expanding. With the second largest production area for vegetables in China, after Chinese cabbage (China Agricultural Yearbook, 2015), pepper is a key crop in agricultural and rural economic development. As one of the dominant production areas for pepper cultivation, Southwest China has the largest cultivation area, accounting for 29.3% of the national total pepper cultivation area and 19.5% of the national total pepper production. However, the average regional yield is only 79.3% of the national average yield (National Vegetable Industry, 2014). In addition, the southwest region is also a major consumer of peppers, and spiciness is one of the characteristics of the region's food culture (He and An, 2004). Therefore, it is important to conduct research on improving pepper quality and yield in southwest China in order to increase regional production and economic benefits to farmers.

For a long time, driven by economic considerations, excessive application of macronutrient fertilizers has been very common in vegetable production. Currently, the total amounts of nitrogen (N), phosphorus (P), and potassium (K) applied to open field vegetables are 2.7, 5.9 and 1.5 times higher than recommended (Huang *et al.*, 2017). Over-reliance on compound NPK fertilizers and the absence of other essential nutrients may often lead to a disrupted nutrient allocation ratio (Zhu *et al.*, 2005; Yu *et al.*, 2013). Ti *et al.* (2015) concluded that fertilizer use efficiency in Chinese open field vegetables was extremely low, with an N use efficiency of only 25.9%, seriously upsetting the sustainable development of agroecosystems (Vitousek *et al.*, 2009; Zhang *et al.*, 2015). In addition, long-term deficient input of secondary macronutrients, such as calcium (Ca), magnesium (Mg), and others, has extremely interfered with the crop-soil balance of these nutrients (Liu *et al.*, 2005; Cakmak and Yazici, 2010). Yellow soil, one of the typical soil groups in southwest China (China Soil Science Database http://vdb3.soil.csdb.cn/), is characterized by rapid weathering rates, high acidity, and poor capacity for fertilizer retention. Due to heavy rainfalls in the region, soils are very susceptible to Ca^{2+} and Mg^{2+} depletion by leaching (Gransee and Fuhrs, 2013). Li *et al.* (2018) found that Mg losses to leaching on a yellow soil ranged from 105-244 kg ha^{-1}, 2-3 times higher than on red soils. Therefore, the crop biomass Mg content is generally lower (Li, 1994), and in a similar way, vegetable Ca content is low (Zhang *et al.*, 2011). This has become a primary limiting factor of pepper crop yield and its nutritional quality (Brodowska and Kaczor, 2009; Ma *et al.*, 2015).

Previous studies demonstrated that Mg fertilizer application on Mg-deficient soils can significantly increase the yield and mineral nutrient content in Chinese cabbage and onion, adding up to 20.4% and 38.0% to the yield, respectively (Klelber *et al.*, 2012; Huang *et al.*, 2016). In addition, Yang Yang and Tao (1994) found that Ca and Mg fertilization not only significantly increases tomato yield, but also strongly improves the fruit vitamin C and mineral nutrients contents. Similar to tomato, pepper belongs to the Solanaceae family of cash crops, which is characterized by high biomass and, consequently, high Ca and Mg requirements (Zhang, 2007). In a field study at He County, Anhui Province, Liu *et al.* (2017) revealed that pepper requirements throughout the reproductive period were 135 kg CaO ha^{-1} and 74.9 kg MgO ha^{-1}, respectively, higher than the requirement for the primary macronutrient P, which was 61 kg P_2O_5 ha^{-1}. Therefore, in terms of fertilizer management, pepper cultivation on yellow soils would require attention not only to the optimization of macronutrient formulations, but also to the adequate application of secondary macronutrients, such as Ca and Mg.

Polyhalite is a new natural fertilizer containing four essential nutrients: K, Ca, Mg, and S in sulfate forms (K_2SO_4, $CaSO_4$, and $MgSO_4$), and is composed of SO_3 (48%), K_2O (14%), CaO (17%), and MgO (6%). Polyhalite is adequately water soluble to release its mineral nutrients to the crop rhizosphere, but the rates of mineral release are more prolonged than commonly used fertilizers (Yermiyahu *et al.*, 2017; Yermiyahu *et al.*, 2019; Huang *et al.*, 2020). In addition, polyhalite has negligible chloride and sodium contents, and hence any risk of salt stress or salinization are considerably

Map 1. Location of the experiment sites in Hongming Village, Chongqing and Sanhe Village, Guizhou, China. *Source*: Google Maps.

lessened. These advantages make polyhalite a promising candidate as a complementary fertilizer for a wide range of crops and countries (Zhuo *et al.*, 2019; Bhatt *et al.*, 2021).

Matching nutrient supply to crop roots with the aboveground requirements and ensuring high efficiency and, subsequently, high productivity of the soil-crop system, necessitates a scientific approach (Chen *et al.*, 2011). At present, there are a few studies aimed at composing fertilizer formulae containing Ca and Mg for pepper production. In the present study, an NPK formula was adjusted to the estimated pepper crop requirements. This formula was enriched with polyhalite in order to supply the crop with Ca, Mg, and S. The two new formulae were examined compared with the usual NPK fertilizer, with and without polyhalite. The objective was to provide theoretical basis for high-yield and high-efficiency cultivation of pepper based on two field experiments, and to demonstrate the advantages of balanced fertilization on two typical yellow soils in southwest China.

Table 1. Basic physical and chemical properties of the soils at the two experiment sites.

Soil property	Units	Shizhu, Chongqing	Jinping, Guizhou
Soil type		Purpli-Udic Cambosols	Ultisol, fine
Clay (<2 µm)	%	13.8	45
Silt (2-20 µm)	%	26.7	43.5
Sand (20-2,000 µm)	%	59.5	11.5
pH		4.51	4.87
Organic matter	g kg^{-1}	13.1	23.2
Exchangeable Ca	mg kg^{-1}	279	945
Exchangeable Mg	mg kg^{-1}	31.3	48.8
Available K	mg kg^{-1}	65.0	91.0
Available N	mg kg^{-1}	208	268
Phosphorus (Bray)	mg kg^{-1}	31.9	24.9

Materials and methods

Location of field experiments

The first experiment was located at Hongming Village, Sanhe Town, Shizhu County, Chongqing (N 30°04′, E 108°10′). The second experiment was located at Sanhe Village, Dunzhai Town, Jinping County, Qiandongnan Miao and Dong Autonomous Prefecture, Guizhou Province (N 26°15′, E 109°15′). Both sites belong to the central subtropical humid monsoon climate zone, and the soil types are subclasses of the yellow soil group. The basic physical and chemical properties of the soils are given in Table 1. Soils at both experimental sites exhibited deficient or extremely deficient levels of exchangeable Ca and exchangeable Mg (Li, 1994; Zhang *et al.*, 2011).

Fertilizer formulae and treatments

Based on previous findings on pepper requirements of N, P and K (Liu *et al.*, 2017), a fertilizer formula was designed for pepper, with NPK ratio of 16-8-18 and supplementary K, Ca, Mg, and S in the form of polyhalite (Polysulphate®, ICL, Israel). The specific raw materials, fertilizers' composition, and application doses, are given in Table 2.

The two experiments similarly included four fertilizer treatments: T1 – the commonly used NPK fertilizer; T2 – the commonly used NPK fertilizer mixed with additional polyhalite; T3 – a specially

Table 2. Detailed description of the fertilizer treatments: nutrient application rate, fertilizer ratio, and the formulas of the fertilizer nutrient composition.

Treatment	Nutrient application rate					Fertilizer ratio				Fertilizer composition ratio
	N	P_2O_5	K_2O	MgO	CaO	Urea	Mono-ammonium phosphate	Potassium sulfate	Polyhalite	$N-P_2O_5-K_2O-MgO-CaO$
	-----------------*kg ha^{-1}*-----------------					----------------------%----------------------				
T1	248	248	248	–	–	28	38	34	–	15-15-15-0-0
T2	248	248	248	23.1	62.7	26	30	25	19	15-15-15-3.8-1.4
T3	260	164	284	–	–	36	21	43	–	16-8-18-0-0
T4	260	164	284	27.9	67.5	31	16	30	23	16-8-18-4.2-1.8

designed NPK fertilizer formulation for pepper; and T4 – the pepper NPK fertilizer mixed with polyhalite (Table 2). The experiments were planned in a random block design with four replicates. Each plot included border rows and was surrounded by a drainage ditch. The fertilizer dose was divided into four equal portions applied as a pre-planting base, and as a side dressing at bloom, early fruiting, and full fruiting stages. Field management practices were strictly consistent for all experimental treatments except for the difference in fertilizer application.

In Chongqing, pepper seedlings of the cultivar 'Jing Zhi Cui Mei' were planted on 27 April 2018, at spacing of 0.55×0.4 m. Experiment plot size was 5×2 m (10 m^2). Harvest took place on 18 August 2018. In Guizhou, pepper seedlings of the cultivar 'Xinxiang No. 8' were planted in May 2018, the experimental plot size was 5×4 m (20 m^2), and harvest took place on 26 August 2018. In both sites, the planting pattern was single-ridge mulching, and field management was carried out according to local farmers' practice.

Measurements

Soil samples were collected before tilling according to the S-shaped sample plan, air-dried and sieved. The basic physicochemical properties of the soil samples were determined according to conventional agrochemical analysis methods (Lu, 2000). Crop sampling area was set at 1.6×2.2 m (16 plants), and the commercial fruit yield was measured in three fixed plots from the time of fruiting to the time of crop harvest. Plant sampling was carried out during the pepper crop harvest period. Four representative plants were randomly selected from each plot, divided into stems, leaves, and fruits. After deionization and washing, the samples were dried in an oven at 105°C for 30 min, and then at 70°C until a constant weight was reached. Samples were then crushed with a stainless-steel grinder. A sample of 0.2 g was weighed and digested using HNO_3-H_2O_2. The concentrations of K, Ca, and Mg were then determined using ICP-OES (5110, Agilent, USA). Fruit vitamin C content was determined by the 2, 6-dichloroindophenol method (Lu, 2000).

Table 3. Effects of the fertilizer treatments on the dry biomass of leaves, stems, and fruit of pepper plants at harvest, and on the harvest index (HI). Values present are means of 4 replicates ±SD.

Test site	Treatment, $N-P_2O_5-K_2O-MgO-CaO$	Dry matter weight			HI
		Leaves	Stems	Fruits	
		---------------------------*kg ha^{-1}*---------------------------			
Shizhu, Chongqing	T1, 15-15-15-0-0	363 ± 6b	249 ± 27b	1,683 ± 138b	0.733
	T2, 15-15-15-3.8-1.4	397 ± 9a	397 ± 23a	2,541 ± 49a	0.762
	T3, 16-8-18-0-0	392 ± 14ab	315 ± 52ab	2,011 ± 47b	0.740
	T4, 16-8-18-4.2-1.8	416 ± 4a	364 ± 49ab	2,489 ± 202a	0.762
Jinping, Guizhou	T1, 15-15-15-0-0	386 ± 11b	530 ± 11b	1,446 ± 13b	0.612
	T2, 15-15-15-3.8-1.4	578 ± 61a	750 ± 55a	2,044 ± 46a	0.606
	T3, 16-8-18-0-0	488 ± 32ab	600 ± 50b	1,530 ± 54b	0.584
	T4, 16-8-18-4.2-1.8	596 ± 32a	813 ± 32a	2,156 ± 19a	0.605

Similar letters indicate no significant differences within an organ and site at $P<0.05$.

Calculations and data analyses

SAS 8.1 software was used for statistical analysis and significance of variances test, and Excel 2016 software was used for data processing and graphs.

Results

Yield and dry matter accumulation

Polyhalite, when added to the compound NPK fertilizer, the commonly used one or the one formulated for pepper (T2 and T4), gave rise to significant increases in the dry biomass of leaves, stems, and fruit (Table 3). These differences were highly significant compared to the common NPK fertilizer (T1), and a bit less pronounced compared to the improved NPK fertilizer (T3). Subsequently, the aboveground dry biomass at both experiment sites increased by 42-51% in response to the NPK+polyhalite mixtures, compared to T1, while improving the NPK formula alone resulted in biomass rise of only 11-18% (Fig. 1A). Notably, leaf biomass, but particularly stem biomass, were greater at Guizhou than at Chongqing (Table 3).

The NPK+polyhalite fertilizers brought about 42 and 36% increase in fresh pepper fruit yield in Chongqing, and 41 and 52% increase in Guizhou, compared to the common NPK treatment (Fig. 1B). The improved NPK formula (T3) gave rise to only 14.5%, and to less than 2% yield increase in Chongqing and Guizhou, respectively. Interestingly, pepper fruit yields were considerably higher at Chongqing than at Guizhou in all treatments (Fig. 1B), while no such differences were observed in the aboveground biomass (Fig. 1A). In addition, polyhalite application enhanced the harvest index (HI) at Chongqing but not at Guizhou (Table 3).

Nutrient uptake and distribution

Generally, the different fertilizer treatments had various effects on the nutrient concentration and distribution among major pepper plant organs at harvest (Fig. 2). First, substantial differences occurred in K concentrations between the two sites, which were much higher at Chongqing in all three plant organs (Fig. 2A,B). Leaf K concentration that ranged from 30-36 g kg^{-1} DM at Chongqing, and from 17-20 g kg^{-1} DM at Guizhou, tended to be greater than in the two other organs, however, fruit K concentration was considerably high, ranging from 22-28 g kg^{-1} DM at Chongqing, and at about 14.5 g kg^{-1} DM at Guizhou. The direct effect of the fertilizer treatments on organ K concentration seemed quite weak and inconsistent, although some statistical differences were observed (Fig. 2A,B).

While leaf Ca concentrations were generally similar at both sites, ranging from 14-23 g kg^{-1} DM, stem Ca concentrations were much lower at Guizhou than at Chongqing, 1.5-2 vs. 9-13 g kg^{-1} DM, respectively (Fig. 2C,D). At both sites, fruit Ca concentrations were much lower than in the two other plant organs, ranging from 0.39-0.61 g kg^{-1} DM. Unexpectedly, polyhalite application reduced leaf Ca concentrations at both sites, a trend that was also observed in the stems. Similar to Ca, leaf Mg concentrations were quite similar at both sites (3.3-4.2 g kg^{-1} DM), while stem Ca concentrations were substantially higher at Chongqing than at Guizhou, 3.5-4.4 vs. 1.2-1.7 g kg^{-1} DM, respectively (Fig. 2E,F). Contrary to what was measured for Ca, fruit Mg concentrations were relatively high at both sites and ranged from 1.85-2.08 g kg^{-1} DM. The fertilizer treatments had very small effects on the organs' Mg concentration, excluding a tendency of polyhalite to reduce leaf and stem Mg concentrations,

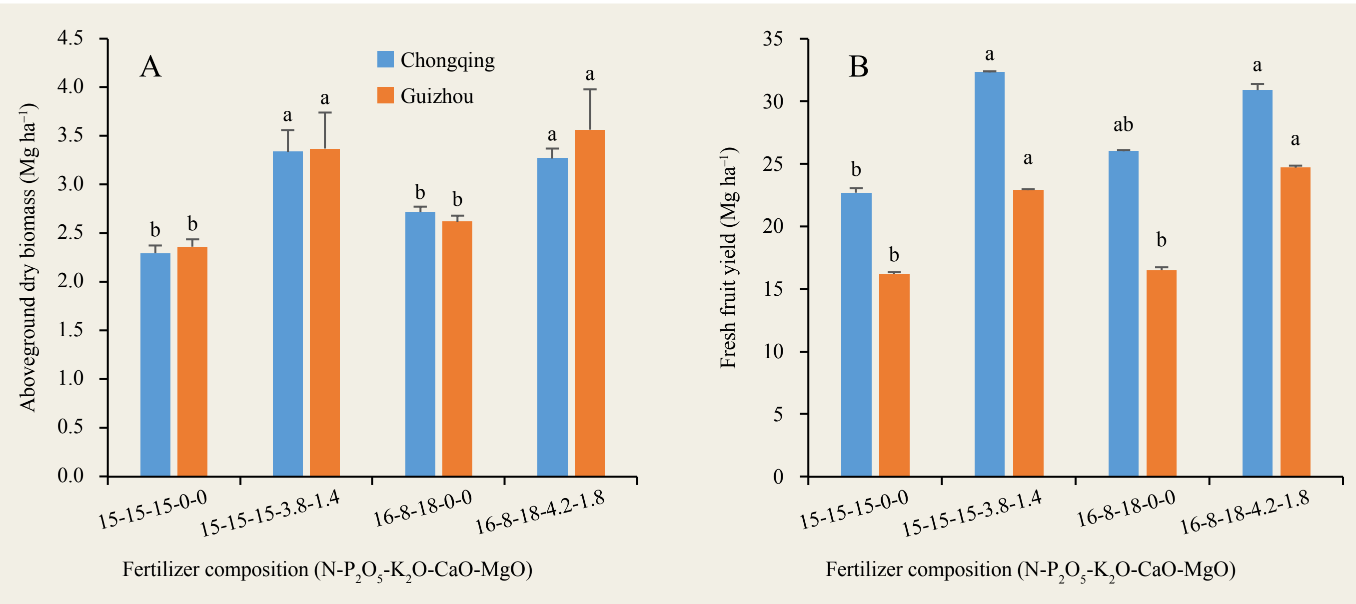

Fig. 1. Effects of fertilizer treatments on the aboveground dry biomass (A) and on the fresh fruit yield (B) of pepper crops grown at two experiment sites in southwest China on yellow soils. Similar letters indicate no significant differences within a site at P<0.05.

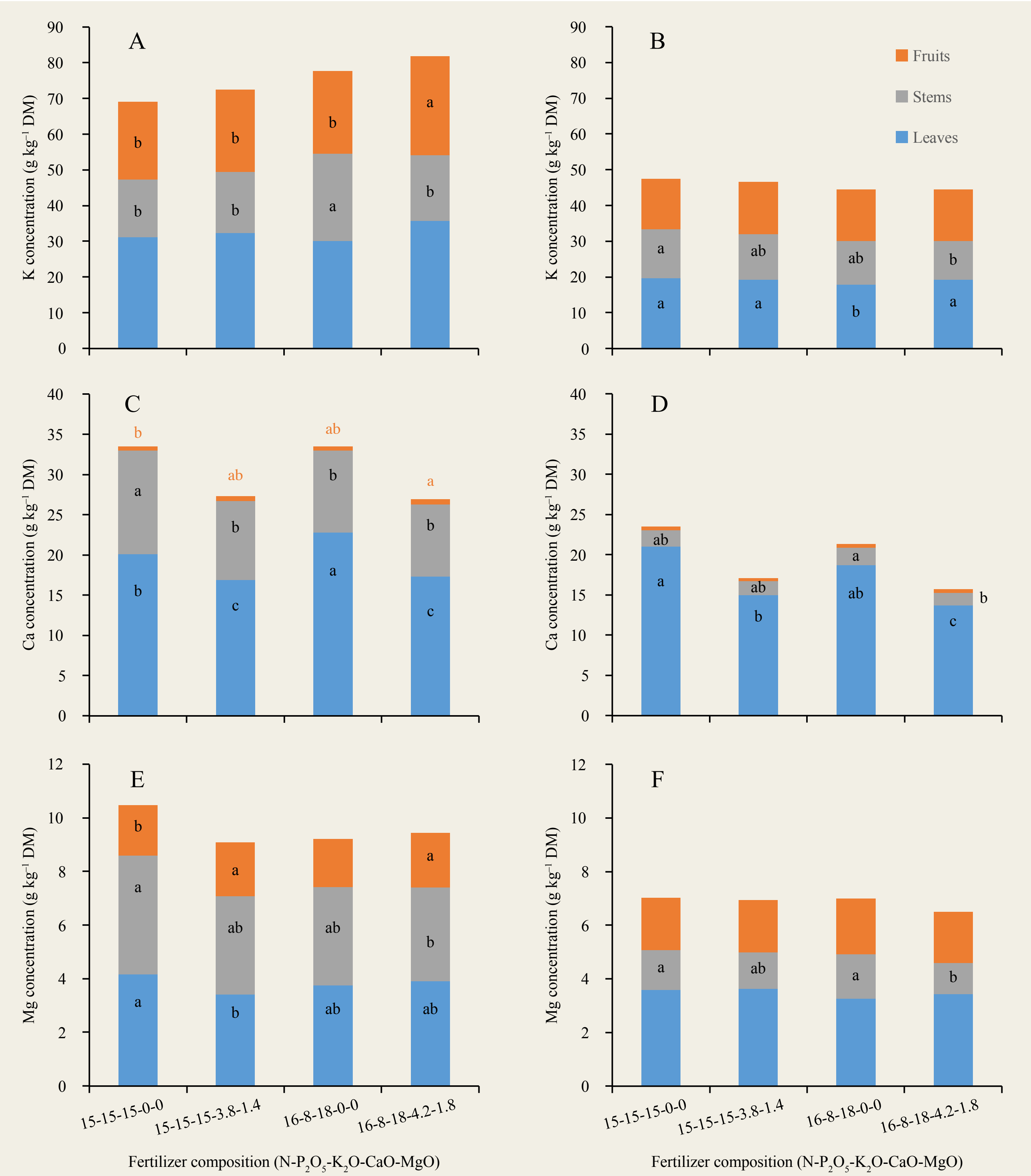

Fig. 2. Effects of fertilizer treatments on K (A and B), Ca (C and D), and Mg (E and F) concentration in pepper leaves, stems, and fruit, at two experiment sites, Chongqing (A,C,E) and Guizhou (B,D,F). Similar letters indicate no significant differences within a plant organ and site at P<0.05; no letters indicate no significant differences. For detailed description of the treatments T1-T4, refer to Table 2.

and to increase it in the fruit. Nevertheless, this tendency was not always clear.

The seasonal nutrient uptake was calculated from the organ biomass yield, multiplied by the nutrient concentration, at harvest. Therefore, both factors should be considered evaluating nutrient uptake. Polyhalite application increased leaf K uptake, reduced leaf Ca uptake at Chongqing but not at Guizhou, and increased leaf Mg uptake – only at Guizhou (Table 4). Stem K uptake was significantly increased by the pepper-NPK formula (16-8-18) at Chongqing, while polyhalite just tended to increase stem K uptake at both sites. While stem K uptake was greater somewhat at Guizhou, stem Ca uptake was about 3-fold greater there, compared to Chongqing (Table 4). However, polyhalite did not have any significant influence on stem Ca uptake at either site. Similarly, the fertilizer treatments did not affect stem Mg uptake. Fruit K uptake was twice as high at Chongqing and was significantly enhanced by the polyhalite+NPK fertilizer, with a slight advantage for the 16-8-18 NPK formula (Table 4). Similar patterns, though less pronounced, were observed for fruit Ca and Mg uptake. Overall, K uptake by the total aboveground crop biomass was substantially higher at Chongqing (Table 4). Both K and Mg uptake by the crop biomass were significantly promoted by the polyhalite+NPK fertilizers, whereas Mg uptake remained unaffected by the fertilizer treatments (Table 4).

The difference between nutrients input (application dose) and nutrients uptake by a crop may be expressed as surplus, or deficit in the case of a negative balance. At both sites, the pure NPK fertilizers (T1 and T3) promoted higher K surplus, and Ca and Mg deficit (Fig. 3). On the contrary, the mixed NPK+polyhalite fertilizers reduced K surplus, and furthermore, led to considerable Ca and Mg surplus (Fig. 3).

The fertilizer treatments also had significant effects on the agronomic efficiency of the macronutrients N and P. This parameter is expressed by the ratio between the produce (e.g., fruit) yield and the nutrient application rate (kg fruit kg^{-1} nutrient). While the agronomic N efficiency was unaffected by the NPK formula modification from 15-15-15 to 16-8-18, the added polyhalite gave rise to significant increases of this parameter at both sites (Fig. 4A).

The agronomic P efficiency underwent an even more dramatic influence (Fig. 4B); the substantial reduction in P input in the modified NPK formula (T3) gave rise to a significant increase in this parameter, from 92 and 66 (T1), to 160 and 102 kg kg^{-1}, at Chongqing and Guizhou, respectively. Nevertheless, the added polyhalite, and particularly with the advanced NPK formula (T4), brought the agronomic P efficiency to 189 and 151 kg kg^{-1}, at Chongqing and Guizhou, respectively (Fig. 4B).

Table 4. Effects of the fertilizer treatments on the seasonal K, Ca, and Mg uptake by leaves, stems, fruit, and total aboveground crop biomass at harvest at Chongqing and Guizhou experiment sites.

Parts	Treatment	K		Ca		Mg	
		Chongqing	Guizhou	Chongqing	Guizhou	Chongqing	Guizhou
		kg ha^{-1}					
Leaves	T1, 15-15-15-0-0	11.4 ± 0.73b	7.62 ± 0.16b	7.30 ± 0.12b	8.16 ± 0.90a	1.51 ± 0.03a	1.39 ± 0.12b
	T2, 15-15-15-3.8-1.4	12.8 ± 0.54ab	11.1 ± 0.92a	6.72 ± 0.20b	8.75 ± 1.26a	1.36 ± 0.04a	2.08 ± 0.15a
	T3, 16-8-18-0-0	11.7 ± 0.44ab	8.72 ± 0.66b	8.92 ± 0.20a	9.10 ± 0.57a	1.48 ± 0.16a	1.58 ± 0.09b
	T4, 16-8-18-4.2-1.8	14.9 ± 1.69a	11.5 ± 0.52a	7.19 ± 0.23b	8.14 ± 0.72a	1.62 ± 0.09a	2.05 ± 0.17a
Stems	T1, 15-15-15-0-0	4.04 ± 0.77b	7.30 ± 0.66a	3.25 ± 0.47a	1.09 ± 0.12a	1.11 ± 0.14a	0.79 ± 0.07a
	T2, 15-15-15-3.8-1.4	6.84 ± 0.54ab	9.49 ± 0.63a	3.91 ± 0.35a	1.27 ± 0.14a	1.45 ± 0.09a	1.02 ± 0.02a
	T3, 16-8-18-0-0	7.86 ± 1.63a	7.42 ± 0.97a	3.18 ± 0.45a	1.32 ± 0.18a	1.12 ± 0.10a	1.00 ± 0.14a
	T4, 16-8-18-4.2-1.8	6.77 ± 1.12ab	8.74 ± 0.33a	3.26 ± 0.36a	1.29 ± 0.08a	1.27 ± 0.14a	0.96 ± 0.07a
Fruits	T1, 15-15-15-0-0	36.6 ± 3.56c	20.3 ± 1.08b	0.88 ± 0.15b	0.61 ± 0.04b	3.17 ± 0.30b	2.82 ± 0.06b
	T2, 15-15-15-3.8-1.4	58.3 ± 1.47ab	29.7 ± 1.28a	1.45 ± 0.10a	0.67 ± 0.01ab	5.10 ± 0.10a	3.95 ± 0.08a
	T3, 16-8-18-0-0	46.6 ± 2.29bc	22.1 ± 0.80b	1.05 ± 0.01b	0.62 ± 0.04b	3.59 ± 0.19b	3.19 ± 0.32b
	T4, 16-8-18-4.2-1.8	69.1 ± 7.78a	31.1 ± 0.63a	1.50 ± 0.14a	0.84 ± 0.12a	5.06 ± 0.48a	4.09 ± 0.09a
Total above ground biomass	T1, 15-15-15-0-0	52.0 ± 4.76c	35.2 ± 1.53b	11.4 ± 0.70a	9.85 ± 0.87a	5.79 ± 0.44b	5.00 ± 0.11b
	T2, 15-15-15-3.8-1.4	78.0 ± 0.41ab	50.3 ± 2.36a	12.1 ± 0.48a	10.7 ± 1.15a	7.91 ± 0.13a	7.05 ± 0.17a
	T3, 16-8-18-0-0	66.2 ± 3.87bc	38.2 ± 2.23b	13.2 ± 0.55a	11.0 ± 0.58a	6.18 ± 0.41b	5.77 ± 0.55b
	T4, 16-8-18-4.2-1.8	90.8 ± 8.86a	51.3 ± 0.06a	12.0 ± 0.51a	10.3 ± 0.71a	7.94 ± 0.44a	7.10 ± 0.17a

Similar letters indicate no significant differences between treatments within an organ and site ($P<0.05$).
Detailed description of the fertilizer treatments is given in Table 2.

Vitamin C content

Pepper fruit are known to contain relatively high levels of vitamin C. Therefore, the concentration of this vitamin in pepper fruit is considered a quality parameter. As a rule, vitamin C contents at Guizhou were substantially higher than at Chongqing (Fig. 5). At Chongqing, all three modified fertilizer formulae brought about significant increases in vitamin C, compared to the common NPK control. At Guizhou, vitamin C tended to increase in response to the fertilizer modifications, but only T4, NPK 16-8-18 + polyhalite obtained a significantly higher concentration of vitamin C (Fig. 5).

Economic analyses

The purchase prices of inputs (e.g., fertilizers) and of the produce (pepper fruit) in China are dynamic and might significantly differ from one region to another, as well as over time. Therefore, any economic analysis should be considered real at location and time of execution. Converting the NPK formula from 15-15-15 to 16-8-18 reduced the fertilizer cost to the farmer, but the benefit was insignificant, 16 and 2% at Chongqing and Guizhou, respectively (Table 5). In contrast, adding polyhalite to the NPK formulas increased the farmer's benefit by 44 and 37% at Chongqing, and by 44 and 56% at Guizhou (T2 and T4, respectively). Consequently, the added values of the polyhalite treatments were substantially higher than that of the converted NPK (16-8-18) alone (Table 5). The ratio between the benefit and fertilizer cost increased at both sites as a result of the improved fertilizer treatment, but it was much lower at Guizhou due to the lower fruit yields there. The return on investment (ROI) in polyhalite was striking. Adding polyhalite to the formula raised the fertilizer cost by 1,010 and 1,168 CNY ha^{-1}, at T2 and T4, respectively; every invested CNY in polyhalite resulted in very positive ROI of 27.5 or 20 CNY at Chongqing, and 15.4 or 17.2 CNY at Guizhou, at T2 or T4, respectively (Table 5).

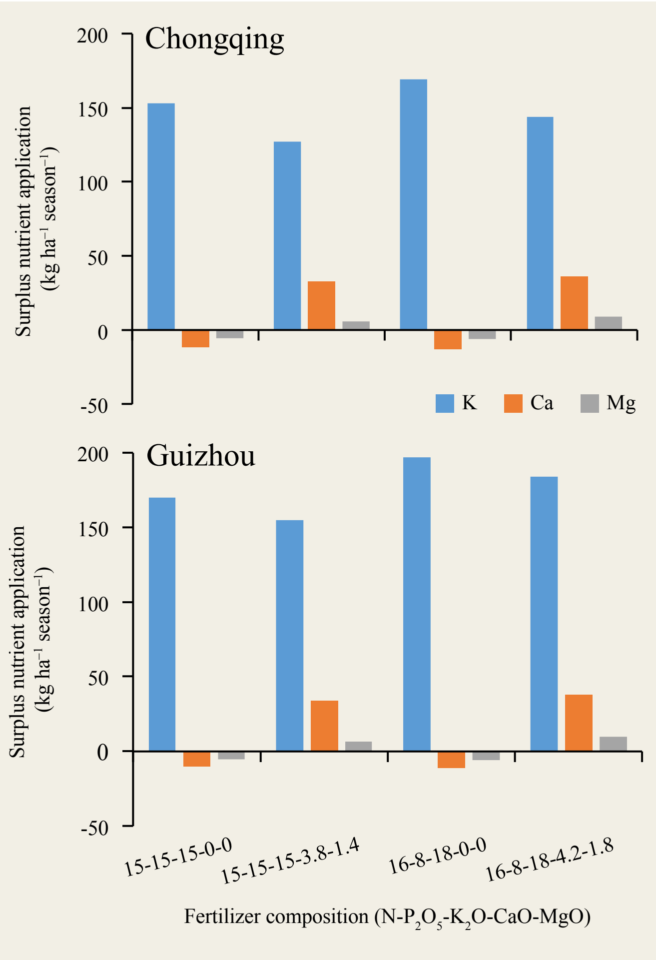

Fig. 3. Effects of fertilizer treatments on the seasonal balance between nutrient (K, Ca, and Mg) input and uptake by pepper crops at Chongqing and Guizhou experiment sites. Detailed description of the fertilizer treatments is given in Table 2.

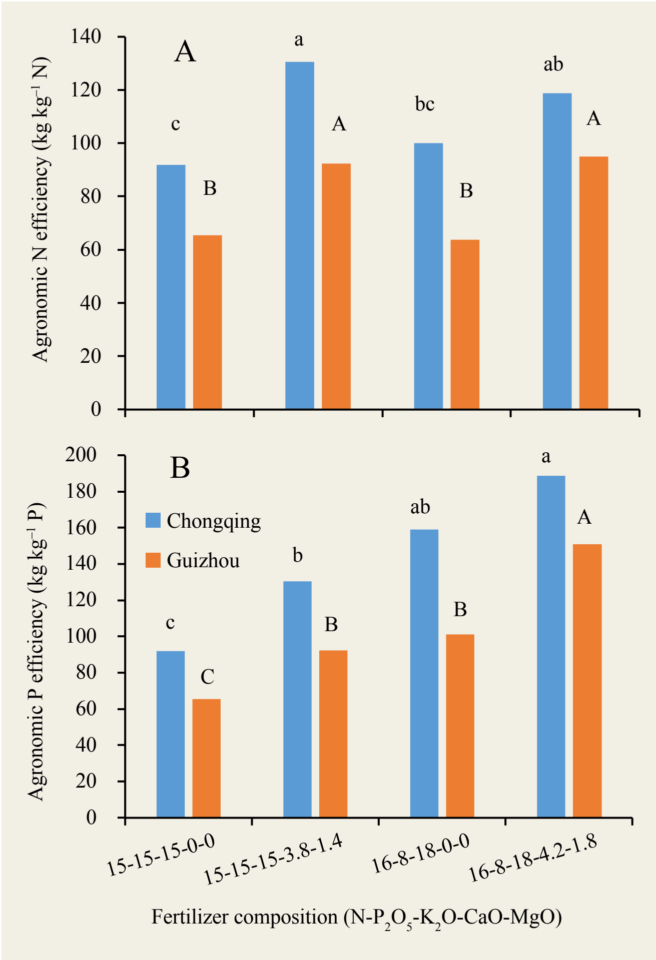

Fig. 4. Effects of fertilizer treatments on the agronomic efficiencies of N (A) and P (B) in pepper crops at Chongqing and Guizhou experiment sites. Similar letters indicate no significant differences between treatments (P<0.05) at Chongqing (small letters) and at Guizhou (capital letters).

Table 5. Economic analysis of the cost and return on investment (ROI) of fertilizer treatments employed in pepper cultivation at Chongqing and Guizhou, southwest China.

Sites	Treatments	Revenue	Fertilizer cost	Benefit	Added value	Benefit/cost ratio	Polyhalite ROI
		-----------CNY ha^{-1}-----------					
Shizhu, Chongqing	T1, 15-15-15-0-0	68,172 b	4,950	63,222 b	–	12.8	–
	T2, 15-15-15-3.8-1.4	96,987 a	5,960	91,027 a	27,805	15.3	27.5
	T3, 16-8-18-0-0	77,990 ab	4,830	73,160 ab	9,938	15.1	–
	T4, 16-8-18-4.2-1.8	92,559 a	5,998	86,561 a	23,339	14.4	20.0
Jinping, Guizhou	T1, 15-15-15-0-0	40,572 b	4,950	35,622 b	–	7.2	–
	T2, 15-15-15-3.8-1.4	57,153 a	5,960	51,193 a	15,571	8.6	15.4
	T3, 16-8-18-0-0	41,304 b	4,830	36,474 b	852	7.6	–
	T4, 16-8-18-4.2-1.8	61,697 a	5,998	55,699 a	20,077	9.3	17.2

Similar letters indicate no significant differences between treatments within a site ($P<0.05$).
Detailed description of the fertilizer treatments is given in Table 2.

Discussion

In the current agricultural practices used to grow pepper on the yellow soils of southwest China, the application doses of N, P_2O_5, and K_2O are rigid and even (15-15-15), and targeted at the lower level of fertilizer cost rather than at the crop requirements. In addition, farmers ignore the input of secondary but essential nutrient elements, such as Ca and Mg. Calcium and Mg are both essential secondary elements for the normal growth and development of vegetables, and the Ca and Mg requirements of peppers both exceed P requirements (Ma *et al.*, 2010a). Due to the regional characteristics of highly intensive agriculture, high temperature and precipitation regimes, and a high degree of soil acidification (Table 1), the leaching problems of soil Ca and Mg nutrient are very serious in the region. Consequently, soil Ca and Mg deficiencies are very common. Thus, the current fertilization practices result in low fertilizer use efficiency and increase the environmental burden, while the crop potential of yield and quality remains unrealized (Lu *et al.*, 2011).

In the present study, two different steps were examined, alone and together, in order to improve the crop nutrient status, increase nutrient use efficiency, enhance pepper yield and quality, and raise the economic benefits to farmers. The first step was an adjustment of the compound NPK fertilizer composition ratio from 15-15-15 to 16-8-18, as formerly suggested by Ma *et al.*, 2010a, Lu *et al.*, 2011, and Liu *et al.*, 2017. The second step was adding polyhalite as a supplementary fertilizer contributing Ca, Mg, K, and S, to the NPK application doses.

Compared to the common NPK fertilizer treatment (T1), the new NPK fertilizer designed especially for pepper requirements (T3) increased N and K_2O inputs by 12 and 36 kg ha^{-1}, respectively; however, it lessened the total nutrient input, mainly through the considerably reduced P input (-84 kg ha^{-1}). Since the fruit yield was unaffected or even slightly increased (Fig. 1B), this step significantly increased the agronomic P use efficiency (Fig. 4B), while no influence was observed on N use efficiency (Fig. 4A). Nevertheless, the impacts of the second step – adding polyhalite to the NPK fertilizers – were much greater. It significantly increased pepper crop performance and yield (Fig. 1). These results are consistent with previous studies (Ma *et al.*, 2010a; Zhang *et al.*, 2015) and indicate that soil Ca and Mg deficiency have been two of the main limiting factors for pepper production in the yellow soils of this region. In addition, this study also showed that the application of Ca and Mg nutrients significantly increased the dry

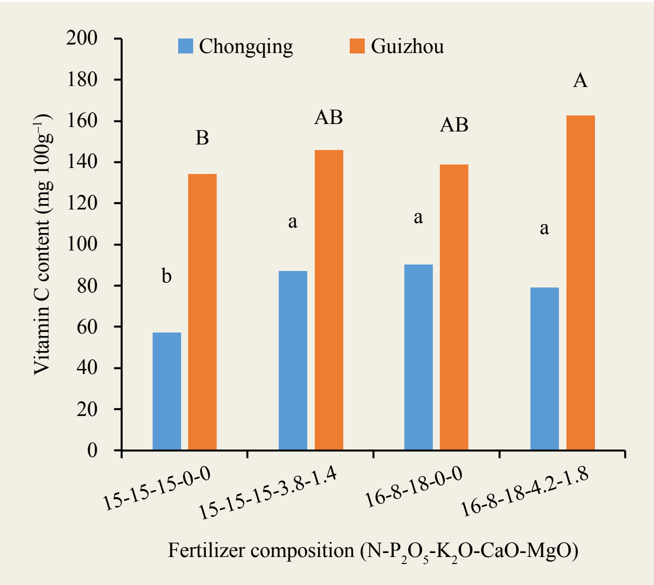

Fig. 5. Effects of fertilizer formulation on the concentration of vitamin C in pepper fruit at Chongqing and Guizhou experiment sites. Similar letters indicate no significant differences between treatments ($P<0.05$) at Chongqing (small letters) and at Guizhou (capital letters).

matter accumulation of all plant organs (Table 3), which is the basis for obtaining high yield (Ma *et al.*, 2010b). Furthermore, the added polyhalite significantly increased the nutrient use efficiency of both N and P (Fig. 4), suggesting positive interactive relationships between the four nutrients under the circumstances of the study. In areas with intense subtropical rainfall, Ca, Mg, and K are often substantially leached and lost (Oliveira *et al.*, 2002; Huang *et al.*, 2016; Li *et al.*, 2018). The inclusion of polyhalite in the fertilizer blend seemed to replenish the soil Ca and Mg reserves (Fig. 3) and simultaneously increase K and Mg crop uptake (Table 4). Nevertheless, more research is still needed to overcome the fertility problems of yellow soils. Polyhalite, which provides four essential nutrients over a prolonged period and in a slow-release manner (Yermiyahu *et al.*, 2017; 2019; Huang *et al.*, 2020), demonstrates the principles that should rule the required changes: balanced soil nutrition; adjustment to crop requirements; use of slow- or control-release fertilizers.

Previous studies have shown that the addition of Ca and Mg significantly increased the accumulation of mineral nutrients such as K, Ca and Mg in tomato, peppers, and Chinese cabbage (Xiao and Yang, 2000; Yao *et al.*, 2008). Recently, Mg was found to be particularly concentrated in pepper fruit and seeds (Ma *et al.*, 2019). In the present study, polyhalite application increased the accumulation of K and Mg in leaves and in fruit (Table 4), and in some cases, increased their concentrations in fruit (Fig. 2). Pepper has a high edible and medicinal value and tops the list of vegetables in terms of its vitamin C content (International Food Information Council, 2002). It has been found that in vegetable crops such as tomato, cucumber, and Chinese cabbage, the application of intermediate elements (Ca and Mg) effectively enhanced vitamin C content (Qin *et al.*, 2008; Luo *et al.*, 2015; Song *et al.*, 2015). In this experiment, added Ca and Mg (through polyhalite), and reduced P proportion (and dose) in the NPK fertilizer significantly increased vitamin C content in pepper fruit at the Chongqing experiment site. However, this approach failed to increase the Ca and Mg concentrations in the pepper fruit, possibly due to the dilution effect of the substantial increase in yield (7.3%-44.3% on average at the two test sites).

Photo 2. Pepper vines grown on the Chongqing experiment plot. Photo by the authors.

As one of the typical cash crops for the region, pepper is of great importance to the agricultural economy and development of southwest China. Compared with the common fertilization practices, the application of the enhanced fertilizer formula, and furthermore, the blend with polyhalite, demonstrated obvious advantages in all economic parameters (Table 5). Usually, a rise in the net income is considered significant when the output-input ratio (added-value/cost) is higher than 2.0 (Zou *et al.*, 2009). Applying polyhalite (treatments T2 and T4), the mean values of output-input ratio in the two test sites in this study were as high as 3.64, strongly indicating that using this fertilizer can significantly enhance the economic performance of pepper. Moreover, the calculated ROI for polyhalite application in the present study was very high, ranging from 15-27, clearly demonstrating the economic advantages of pepper production, and possibly of many other vegetable species, on the yellow soils of southwest China.

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