Research Findings

Photo 1: Xu Xiang kiwifruit on the vine. Photo by the authors.

Impact of Alternative Polyhalite Fertilizers on 'Xu Xiang' Kiwifruit Yield and Quality in Shaanxi Province, China

Zhao, N.[(1)*], H. Guo[(1)], J. Suo[(1)], Y. Lei[(1)], G. Li[(2)], P. Imas[(2)], and H. Magen[(2)]

Abstract

China is the world-leading kiwifruit (*Actinidia deliciosa*) producer, however the mean fruit yield in China lags far behind other countries. This research examines possible reasons for this, and investigates the impact more balanced mineral nutrition could have on kiwifruit production. The polyhalite fertilizers Polysulphate® and MegaPoly™ were integrated into the common farmers' fertilization practice in Zhouzhi County, Xi'an City, Shaanxi Province – the main kiwifruit producing region in China. These fertilizers partly replaced the potassium (K) usually supplied through chemical fertilizers, and enriched the orchard with calcium (Ca), magnesium (Mg), and sulfur (S). Fertilizer application was split between two events: at budding and towards fruit enlargement. Total fruit yield was between 10.5 and 13.9 Mg ha^{-1}, with a tendency of yield enhancement in some of the polyhalite treatments. This tendency became highly significant within the yield of commercial-grade fruit, which ranged

[(1)]Rural Science and Technology Development Center of Shaanxi Province and Shaanxi Bailui Kiwi Fruit Research Institute Co. Ltd, Xi'an City, Zhouzhi County, Shaanxi Province, China
[(2)]International Potash Institute (IPI), Zug, Switzerland
[*]Corresponding author: sjt_9527@163.com

from 3.5 to 6.1 Mg ha^{-1}, compared to 2.0 Mg ha^{-1} for the control. Economic analysis showed that most of the polyhalite treatments gave rise to considerably higher profits for the farmer. However, the relatively low yields (approximately one third of the mean kiwifruit yield in New Zealand), and particularly the poor rates of commercial-grade yields (only 18-44% of the total yield), raise serious concerns about the consequences of excess nitrogen (N) fertilizer use in the experiment, a practice common in the region. The possibility that excess N has masked many of the benefits expected from the polyhalite fertilizers, including improved fruit size, yield, and fruit postharvest quality parameters, is discussed. Further investigation of the effects of polyhalite fertilizer on kiwifruit performance would be required under a more appropriate N fertilization regime.

Keywords: *Actinidia deliciosa*; balanced plant nutrition; MegaPoly; nitrogen; Polysulphate.

Introduction

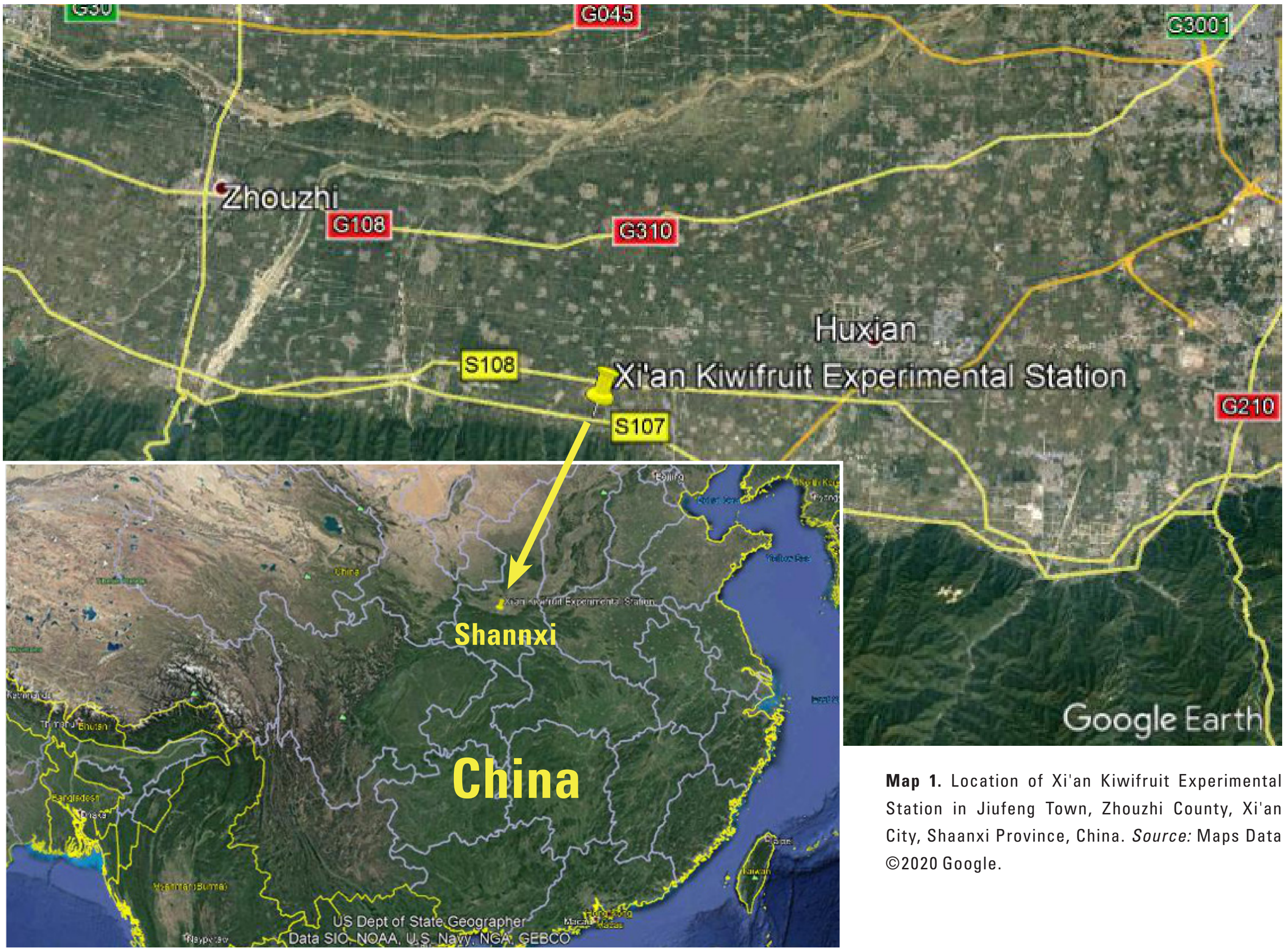
Kiwifruit or Chinese gooseberry is the edible berry of the woody vine *Actinidia deliciosa*, a species native to central and eastern China (Morton, 1987). In the early 20th century, cultivation of kiwifruit spread from China to New Zealand, where the first commercial plantings occurred. The fruit became popular during World War II, and has spread and been exported throughout the world (Morton, 1987) ever since. At present (2018), China is the world-leading annual kiwifruit producer, producing more than 2 million tonnes, about half the world's production, followed by Italy, New Zealand, Iran, Greece, and Chile (FAOstat, 2018). Nevertheless, the current mean kiwifruit yields in China, 12.1 Mg ha^{-1}, lag well behind that of New Zealand (36.8 Mg ha^{-1}) or those of other key kiwifruit producing countries (20.0-27.8 Mg ha^{-1}). There may be various reasons for this considerable yield gap. Assuming that no significant differences occur in the plant material between countries (similar cultivars and clones), that chilling requirements are fulfilled (Wang *et al.*, 2017), and that suitable climate conditions prevail during plant and fruit development, then improved agronomic practices may be the key to closing the yield gap.

Both viticulture and kiwifruit management are complex and require a high degree of precision to guarantee sufficient fruit set from pollination (Gianni and Vania, 2018; Mu *et al.*, 2018), and to maintain an appropriate ratio between vegetative and fruit growth (Minchin *et al.*, 2011). After considerate pruning and fruit thinning (Burge *et al.*, 1987; Boyd and Barnett, 2011), balanced crop mineral nutrition is an important tool for controlling vine growth and development, and providing timely nutrient supply for fruit development (Ferguson and Eiseman, 1983; Kotzé and de Villiers, 1989). After decades of surplus nitrogen (N) fertilization by the Chinese fruit industry in general, and by the kiwifruit industry in particular, significant attempts were made to reduce N application doses, thus minimizing its substantial environmental consequences (Tong *et al.*, 2004; Lu *et al.*, 2018) and increasing N use efficiency (Zhao *et al.*, 2013). With the growing awareness of the benefits of balanced mineral nutrition for kiwifruit (Pacheo *et al.*, 2008; Parent *et al.*, 2015), efforts have recently been made to promote a more balanced N, phosphorus (P), and potassium (K) nutrition in the kiwifruit orchards of China (Zhao *et al.*, 2017; Wang *et al.*, 2019).

The Chinese kiwifruit industry has paid little attention so far to the status of other essential macronutrients such as calcium (Ca), magnesium (Mg), and sulfur (S). Ferguson and Eiseman (1983) estimated the removal of Ca and Mg in a moderately productive kiwifruit orchard in New Zealand to be 100 and 25 kg ha^{-1}, respectively. In South Africa, Kotzé *et al.* (1989) described the distribution of the macronutrients N, P, K, Ca, and Mg among the organs of the kiwifruit vine during the growing season. Higher Ca concentration in several fleshy fruit, including kiwifruit, is a pre-requisite for lower incidence of Ca-related diseases and improved fruit nutritional value. Moreover, approximately 80% of the total Ca content of fruit is accumulated during the early weeks after fruit-set, suggesting that failure to deliver good fruit Ca nutrition at that time may lead to poor fruit Ca content at harvest (Montanaro *et al.*, 2014). An adequate Mg supply is essential for kiwifruit vine development and fruit yield (Smith *et al.*, 1987; Clark and Smith, 1988). This nutrient is pivotal to the photosynthesis apparatus and sugar metabolism, as demonstrated in analysis of kiwifruit leaves (Dimassi-Theriou and Bosabalidis, 1997). Sulfur interacts with N to significantly enhance protein metabolism (Jamal *et al.*, 2010) and has often been associated with high productivity (Dick *et al.*, 2008). With the increasing utilization of chemical NPK fertilizers in the Chinese orchards, other macro- and micronutrients were left behind (Zhao *et al.*, 2017). Recently, the growing motivation to explore and enhance kiwifruit nutritional values (Ma *et al.*, 2019), has encouraged the search for new sources of secondary macronutrients.

Polyhalite is a natural mineral which occurs in sedimentary marine evaporates and consists of a hydrated sulfate of K, Ca, and Mg with the formula: $K_2Ca_2Mg(SO_4)_4 \cdot 2(H_2O)$. The deposits found in Yorkshire, in the UK, typically consist of K_2O: 14%, SO_3: 48%, MgO: 6%, CaO: 17%. As a fertilizer providing four key plant nutrients – S, K, Mg, and Ca – polyhalite may offer attractive solutions to crop nutrition. In addition, polyhalite is less water soluble than more conventional sources (Yermiyahu *et al.*, 2017; Yermiyahu *et al.*, 2019) and is, therefore, a suitable fertilizer to supply these four nutrients during rainy growing seasons. Polyhalite is available in its natural form as Polysulphate®. Due to its relatively low K content, fortified polyhalite formulations are also available, among which is MegaPoly™, comprising of 32, 6.7, 24.3, and 8.6% K_2O, MgO, SO_3, and CaO, respectively.

The objectives of the present study were to evaluate the effects of Polysulphate and MegaPoly on kiwifruit fruit yield and quality, and to determine appropriate application doses and timing for these fertilizers for the kiwifruit production system at Zhouzhi County, Xi'an City, Shaanxi Province, China.



Map 1. Location of Xi'an Kiwifruit Experimental Station in Jiufeng Town, Zhouzhi County, Xi'an City, Shaanxi Province, China. *Source:* Maps Data ©2020 Google.

Materials and methods

The experiment was carried out in 2019 at Xi'an Kiwifruit Experimental Station (34°3'49.54"N, 108°26'41.44"E), which is in the main kiwifruit cultivation area in Jiufeng Town, Zhouzhi County, Xi'an City, Shaanxi Province (Map 1). The region is defined as having a warm temperate continental monsoon climate (Fig. 1). The annual average rainfall is 660 mm, annual mean temperature is 13.2°C, with 1,867.5 hours of sunshine annually. In 2019, July and August were the warmest months, with average maximum temperatures of 34°C, and average minimum night temperatures of 24 and 23°C, respectively. January was the coldest month, with average maximum and minimum temperatures of 7 and 0°C, respectively. The dry season occurred from December to March, and the wet season from April to November, with rainfall peaking in August and September with 110 and 161 mm, respectively (Fig. 1). The region's kiwifruit growing season begins with budding in early April and ends at harvest in November, corresponding with the wet season. The soil at the experiment location was sandy loam with a fertile nutrient status.

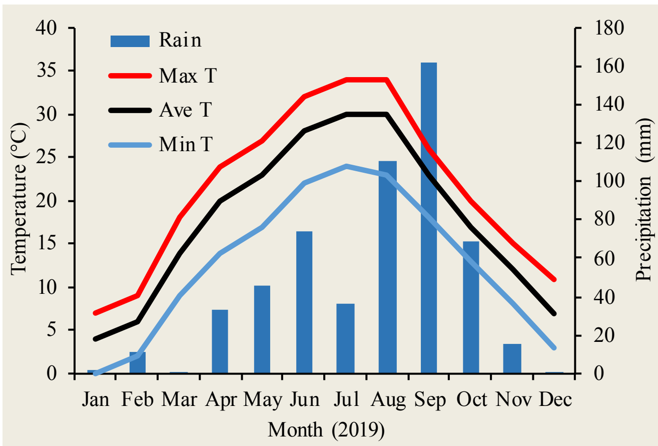


Fig. 1. Weather conditions during the experiment in 2019 at Zhouzhi, near the experiment location, including monthly mean maximum, average and minimum temperature, and monthly precipitation.
Source: www.worldweatheronline.com

Table 1. Detailed description of the fertilizer treatments. The amount of K_2O applied each time through each fertilizer is given in parentheses.

Treatment	Plant developmental stage upon fertilizer application					Total K_2O
	Budding		Fruit enlargement			
	Compound NPK 25:5:5	Polysulphate	Compound NPK 20:5:15	K_2SO_4	MegaPoly	
	kg ha⁻¹					
Control	750 (37.5)	-	750 (112.5)	300 (150)	-	300.0
T_1	750 (37.5)	375 (52.5)	750 (112.5)	300 (150)	-	352.5
T_2	750 (37.5)	375 (52.5)	750 (112.5)	-	300 (96)	298.5
T_3	750 (37.5)	375 (52.5)	750 (112.5)	-	600 (192)	394.5
T_4	750 (37.5)	375 (52.5)	450 (67.5)	-	300 (96)	253.5
T_5	750 (37.5)	750 (105)	450 (67.5)	-	300 (96)	306.0
T_6	750 (37.5)	750 (105)	750 (112.5)	-	300 (96)	351.0

The experiment was conducted using the region's main cultivar, 'Xu Xiang', on plants 8 years after grafting, with 4×2 m spacing and trellised on a greenhouse frame, common to the region. Crop management was consistent with the regional professional recommendations.

Fertilizers were delivered twice during the growing season: on budding in early April, and at the fruit enlargement in July. Upon budding, all treatments received compound NPK fertilizer (25:5:5 of $N:P_2O_5:K_2O$) at 750 kg ha^{-1}; Polysulphate was applied at 0, 375, and 750 kg ha^{-1} to the control, T_1-T_4, and T_5-T_6 treatments, respectively (Table 1). At fruit enlargement, a second application of compound NPK fertilizer with slightly reduced N and increased K_2O ratios (20:5:15) was carried out at 750 kg ha^{-1} to the control, T_1-T_3, and T_6 treatments, and 450 kg ha^{-1} to T_4-T_5; additionally, K_2SO_4 was applied to the control and T_1 (300 kg ha^{-1}); and MegaPoly was applied at 600 kg ha^{-1} to T_3 and 300 kg ha^{-1} to T_2 and T_4-T_6 (Table 1).

The experiment was designed in random blocks with 3 replicates. Each replicate covered 111 m^2 and consisted of 14 plants (333 m^2 and 42 vines per treatment). Statistical analysis was carried out using SPASS 17.0.

Soil samples were taken from each plot at early, mid, and late season stages on 12 April, 20 July, and 25 October 2019, respectively, from the upper (0-20 cm) and the deeper (20-40 cm) layers of the rhizosphere. Soil status measurements included pH, organic matter content, alkali-hydrolyzed N, available P, available K, exchangeable Ca, and exchangeable Mg.

At harvest, fruit were picked separately from each vine, weighed, and the number of fruit per plant and the total yield were determined. Fruit were sorted by size and shape to determine mean fruit size, and the absolute and rate of the commercial-grade yield. Representative commercial-grade fruit were selected from each treatment and photographed. Fruit quality parameters were determined at harvest using 10 fruit per treatment. Fruit firmness was determined using a penetrometer. Fruit were peeled and homogenized, and the total soluble solids (TSS) and titratable acids (TA) were determined, as well as the content of vitamin C (ascorbic acid). Twenty representative commercial-grade fruit were stored in ambient conditions to determine fruit firmness and TSS, as relevant fruit quality measures, after 5 and 10 days of shelf life.

Economic analysis was carried out, based on the commercial-grade yield, taking into account the total costs and the farmer's revenue to determine the farmer's profit per hectare.

Results

Significant changes were recorded in the soil properties of the experimental vineyard during the kiwifruit growing season of 2019. Soil pH was significantly higher in the upper layer (0-20 cm) compared to the deeper layer (20-40 cm), at 6.31 and 5.33, respectively. In the upper layer, the average pH was quite constant throughout the season, while it consistently decreased in the deeper layer from 5.69 at budding to 5.24 toward harvest. In contrast to the average pH across treatments, significant changes occurred within and between treatments (Table 2). At both early and mid-season measurements, control soil pH was significantly higher than in most of the other treatments. However, at the late stage, the control soil pH became the lowest among all treatments in both soil layers (Table 2).

Soil organic matter (OM) contents were very high, ranging from 8-41% (Table 2). The upper layer displayed much higher OM contents, with 26.9, 36.9, and 28.6% at the early, mid, and late season stages, respectively, compared to the decreasing average OM contents in the deeper layer, with 14.7, 11.3, and 8.7%, respectively. Soil OM content significantly differed between treatments at the early season measurements. The differences were significant also at the mid-season stage but

Table 2. Effects of fertilizer treatments on soil pH, organic matter, alkali-hydrolyzable N, and available P contents during the 2019 kiwifruit growing season at Xi'an Kiwifruit Experimental Station in Jiufeng Town, Zhouzhi County, Xi'an City, Shaanxi Province, China. Refer to Table 1 for detailed description of the fertilizer treatments.

Crop phase	Soil layer	Treatment	pH	Organic matter	Alkali-hydrolyzable N	Available P
				g kg⁻¹	*mg kg⁻¹*	*mg kg⁻¹*
Early (12 Apr)	0-20 cm	Control	6.88 a	29.4 ab	116.7 abc	200.9 a
		T_1	5.87 b	20.0 c	103.8 c	222.5 a
		T_2	5.96 b	24.5 bc	113.2 abc	235.3 a
		T_3	5.88 b	22.3 bc	102.7 c	222.2 a
		T_4	6.44 ab	26.0 abc	107.3 bc	220.5 a
		T_5	6.40 ab	33.3 a	133.0 a	286.1 a
		T_6	6.43 ab	32.5 a	131.8 ab	230.7 a
	20-40 cm	Control	7.00 a	15.1 bc	77.0 b	90.3 b
		T_1	5.21 c	9.1 d	49.0 c	84.7 b
		T_2	4.87 c	13.1 bcd	67.7 bc	141.5 ab
		T_3	5.20 c	11.4 cd	58.3 bc	112.7 ab
		T_4	5.22 c	15.0 bc	72.3 bc	182.0 a
		T_5	6.28 ab	16.3 b	73.5 b	132.1 ab
		T_6	6.06 b	22.8 a	113.2 a	184.7 a
Mid (20 Jul)	0-20 cm	Control	7.14 a	27.4 c	141.2 b	192.3 b
		T_1	5.89 c	39.1 a	180.8 a	315.1 a
		T_2	5.86 c	38.1 ab	185.5 a	308.5 a
		T_3	6.28 bc	34.0 b	173.8 a	319.5 a
		T_4	6.33 b	39.7 a	185.5 a	253.0 a
		T_5	6.55 b	40.6 a	184.3 a	268.7 a
		T_6	6.58 b	39.4 a	182.0 a	269.0 a
	20-40 cm	Control	6.90 a	14.7 a	78.1 a	52.1 d
		T_1	5.03 cd	10.0 b	71.2 ab	159.7 a
		T_2	4.41 d	10.3 b	78.2 a	149.7 ab
		T_3	5.27 bc	10.7 b	60.7 b	124.0 bc
		T_4	4.77 cd	10.9 b	67.7 ab	157.2 a
		T_5	5.94 b	11.9 ab	73.5 ab	114.1 c
		T_6	5.47 bc	10.8 b	63.0 ab	93.7 c
Late (25 Oct)	0-20 cm	Control	6.13 b	27.8 a	154.0 a	266.4 a
		T_1	6.26 b	26.0 a	157.5 a	274.8 a
		T_2	6.17 b	25.5 a	152.8 a	265.0 a
		T_3	5.94 b	27.4 a	166.8 a	294.9 a
		T_4	6.30 b	30.5 a	170.3 a	294.6 a
		T_5	6.20 b	30.7 a	162.2 a	311.9 a
		T_6	6.83 a	32.0 a	161.0 a	289.9 a
	20-40 cm	Control	4.98 b	7.8 b	63.0 ab	163.4 ab
		T_1	5.01 b	8.6 b	77.0 ab	137.3 b
		T_2	5.25 b	8.2 b	66.5 ab	185.9 ab
		T_3	4.91 b	8.7 ab	73.5 ab	153.5 ab
		T_4	5.08 b	9.2 ab	82.8 a	152.2 ab
		T_5	5.17 b	9.7 a	73.5 ab	217.1 a
		T_6	6.31 a	8.4 ab	57.2 b	132.6 b

Different letters indicate significant differences within a column at P<0.05.

were inconsistent with the former one, and almost disappeared at the late stage of crop development (Table 2).

Similar to soil pH and OM content, the average alkaline-hydrolyzable N content was substantially higher in the upper than in the deeper soil layer, 151 vs. 71 mg kg^{-1}, respectively. In the upper layer, the alkaline-hydrolyzable N content increased from 115 mg kg^{-1} at budding to 176 mg kg^{-1} at the mid-season check, and remained quite stable until the end of the season. In the deeper layer, this parameter was very stable at 70-73 mg kg^{-1} throughout the season. Although significant differences did occur in soil available N between treatments (Table 2), these were inconsistent and, furthermore, could

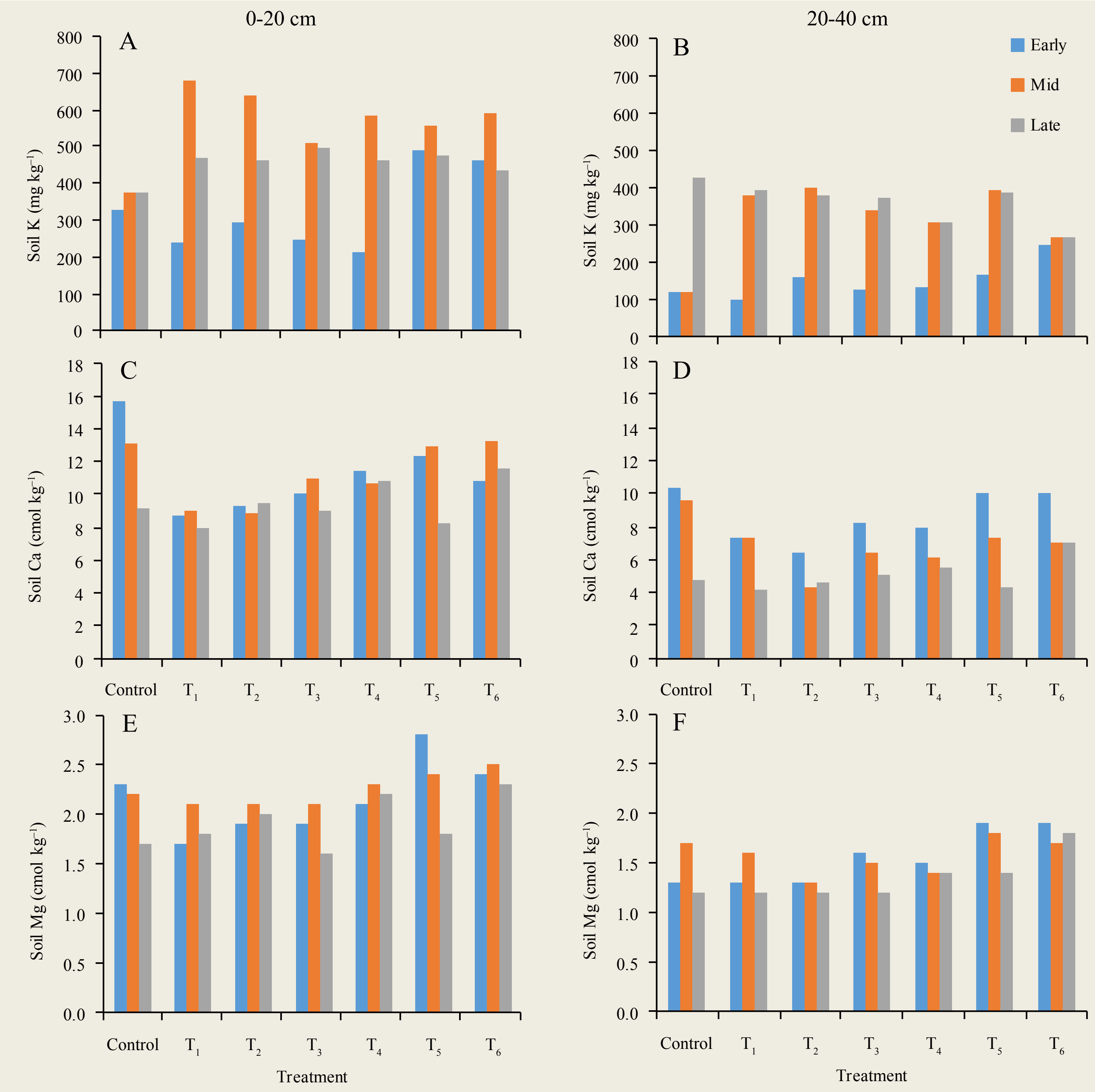


Fig. 2. Effects of fertilizer treatments on the soil available K (A, B), Ca (C, D), and Mg in the upper (0-20 cm; A, C, E) and deeper (20-40 cm; B, D, F) layers at the early, middle, and late stages (12 Apr, 20 Jul, and 25 Oct, respectively) of the kiwifruit growing season at Xi'an Kiwifruit Experimental Station in Jiufeng Town, Zhouzhi County, Xi'an City, Shaanxi Province, China. Refer to Table 1 for detailed description of the fertilizer treatments.

Table 3. Effects of fertilizer treatments on kiwifruit yield parameters. Values express means ± SE. Refer to Table 1 for detailed description of the fertilizer treatments.

Treatment	Mean fruit weight	Fruit number	Yield		Commercial yield	
	g fruit^{-1}	*Fruit plant^{-1}*	*kg plant^{-1}*	*Mg ha^{-1}*	*Mg ha^{-1}*	*%*
Control	61.42 ± 0.34	124 b	7.69 b	10.90 b	1.971 e	18.08
T_1	62.62 ± 2.73	125 b	7.90 b	11.21 b	3.258 d	29.06
T_2	67.88 ± 3.63	144 a	9.78 a	13.87 a	6.107 a	44.03
T_3	63.22 ± 3.58	116 c	7.43 c	10.54 c	3.476 c	32.98
T_4	66.01 ± 2.75	125 b	8.38 b	11.88 b	4.868 b	40.98
T_5	63.88 ± 0.40	144 a	9.32 ab	13.22 ab	3.877 d	29.33
T_6	67.57 ± 3.24	114 c	7.97 b	11.31 b	4.762 ab	42.10

Different letters indicate significant differences within a column at P<0.05.

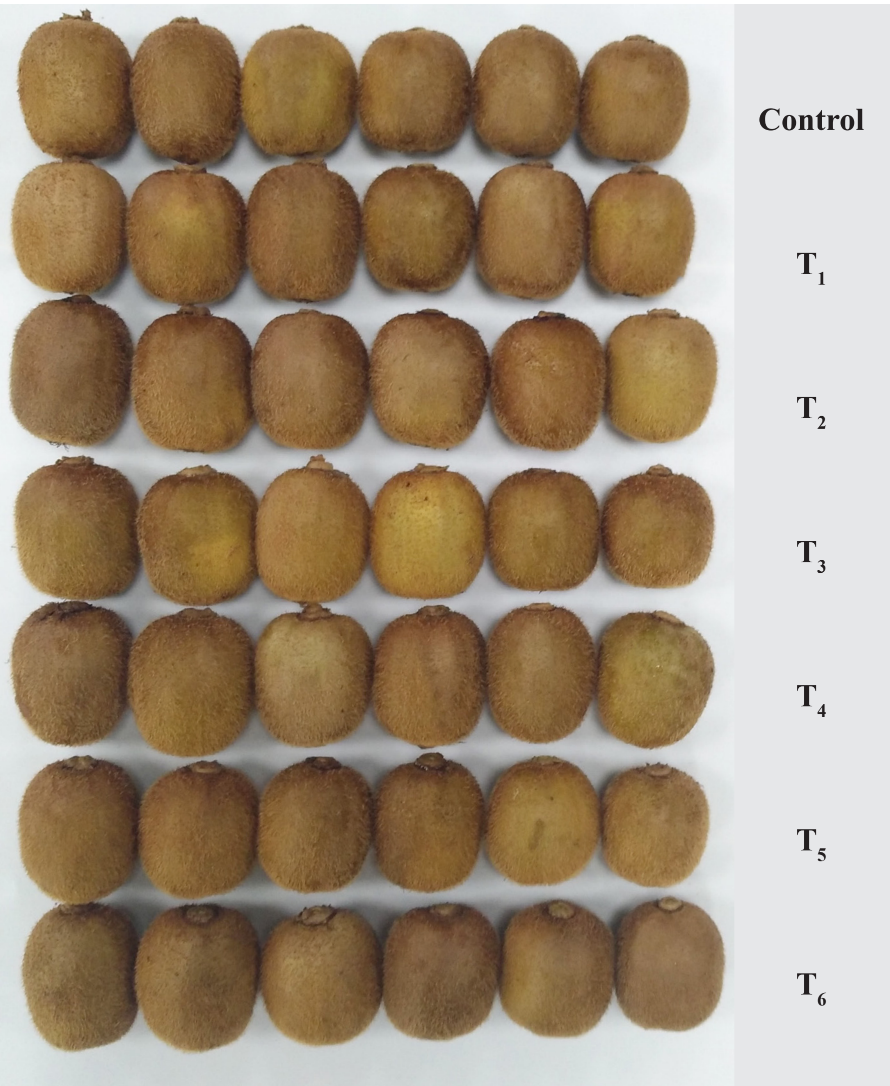


Fig. 3. Effects of fertilizer treatments on appearance of commercial-grade fruit at harvest. Refer to Table 1 for detailed description of the fertilizer treatments.

not be associated with the differences in N application rate between treatments. For example, T_3 and T_4, which received 337.5 and 277.5 kg N ha^{-1}, respectively, showed no significant differences in their soil alkaline-hydrolyzable N content (Table 2).

Soil available K was significantly higher at the earliest sampling date (12 Apr) in T_5 and T_6, probably due to the higher Polysulphate application rate during the early season. This effect was much clearer in the upper soil layer, but could be identified in the deeper one as well (Fig. 2A, B). Soil available K was greatly affected by the second K application of polyhalite fertilizers at the fruit enlargement stage, expressed as significantly higher values compared to the control, which received compound NPK and K_2SO_4. The effects of the second fertilizer application was very clear in the deeper soil layer, although the nutrient levels were generally higher in the upper layer. Interestingly, the strategy of an early high Polysulphate application strengthened by a later MegaPoly application, as practiced in T_5 and T_6, seemed to support high and stable levels of soil available K throughout the season (Fig. 2A, B).

Soil available Ca and Mg levels were significantly higher in the upper than in the deeper soil layer (Fig. 2C-F). Treatments T_5 and T_6 displayed significantly higher soil available Ca compared to T_1 and T_2, while T_3 and T_4 exhibited intermediate levels. Surprisingly, the control showed high soil available Ca levels, at least during the early stages of the growing season (Fig. 2C, D). Soil available Mg levels tended to be higher in treatments T_5 and T_6, particularly during the earlier stages (Fig. 2E, F).

While fertilizer treatments did not show any clear impact on the mean fruit weight, the number of fruit per plant was highest (144) in treatments T_2 and T_5, lowest at T_6 and T_3 (114 and 116, respectively), and intermediate (124-125) in the other treatments (Table 3). Consequently, the total yield was highest at T_2 (13.87 Mg ha^{-1}), lowest at T_3 (10.54 Mg ha^{-1}), and intermediate at the control, T_1, T_4, and T_6. Although T_5 exhibited a high yield, 13.22 Mg ha^{-1}, it did not statistically differ from the highest and the intermediate levels (Table 3).

The commercial yield, following fruit sorting according to size distribution and external appearance, was much smaller, ranging from 1.971-6.107 Mg ha^{-1}, or 18-44% of the total yield. Thus, T_2 displayed the highest commercial yield, T_4 and T_6 were second best, while T_1, T_3, and T_5 had low to intermediate levels, and the control exhibited the least commercial yield level (Table 3).

At harvest, fruit appearance (Fig. 3), as well as quality parameters of the commercial-grade fruit were very slightly affected by the fertilizer treatments (Table 4). Fruit firmness ranged from 48.7-52.7 N, with T_6 fruit significantly firmer than T_1 fruit, whereas fruit of all other treatments demonstrated intermediate firmness values that did not differ from the T_1 and T_6 treatments (Table 4). Fruit TSS varied from 8.4-9.13%, with no statistical differences between treatments. Titratable acidity (TA) ranged from 0.77-0.84%, and the TSS/TA ratio from 10-11.87, with no significant differences between treatments, at this stage. Fruit vitamin C content at harvest was 99.3 mg 100 g^{-1} in T_3 fruit, significantly higher than in the control, T_1, T_2, and T_6 fruit that ranged from 69.8-74.4 mg 100g^{-1}, while T_4 and T_5 exhibited intermediate vitamin C content of about 85 mg 100 g^{-1} that did not differ significantly from the other treatments (Table 4).

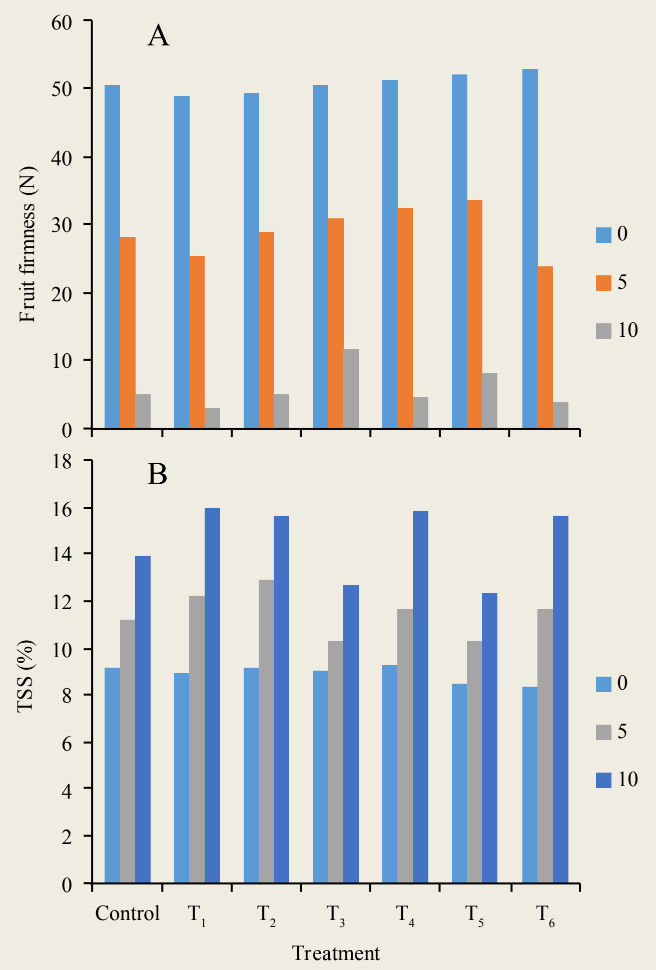


Fig. 4. Effects of fertilizer treatments on fruit firmness degradation (A), and on the rise of the total soluble solids (B) in Xu Xiang kiwifruit at harvest (day 0), and after 5 and 10 days of shelf-life at 20°C. Refer to Table 1 for detailed description of the fertilizer treatments.

Table 4. Effects of fertilizer treatments on fruit quality parameters (fruit firmness; total soluble solids [TSS]; titratable acids [TA]; and vitamin C content) of Xu Xiang kiwifruit at harvest. Refer to Table 1 for detailed description of the fertilizer treatments.

	Firmness	TSS	TA	TSS/TA	Vitamin C
	N	------------%	------------		*mg 100g⁻¹*
Control	50.6 ab	9.13	0.81	11.27	71.08 b
T_1	48.7 b	8.89	0.78	11.40	69.81 b
T_2	49.2 ab	9.12	0.77	11.84	72.53 b
T_3	50.5 ab	9.03	0.77	11.73	99.31 a
T_4	51.3 ab	9.32	0.8	11.65	85.7 ab
T_5	52.2 ab	8.48	0.78	10.87	84.37 ab
T_6	52.7 a	8.4	0.84	10.00	74.4 b

Different letters indicate significant differences within a column at P<0.05.

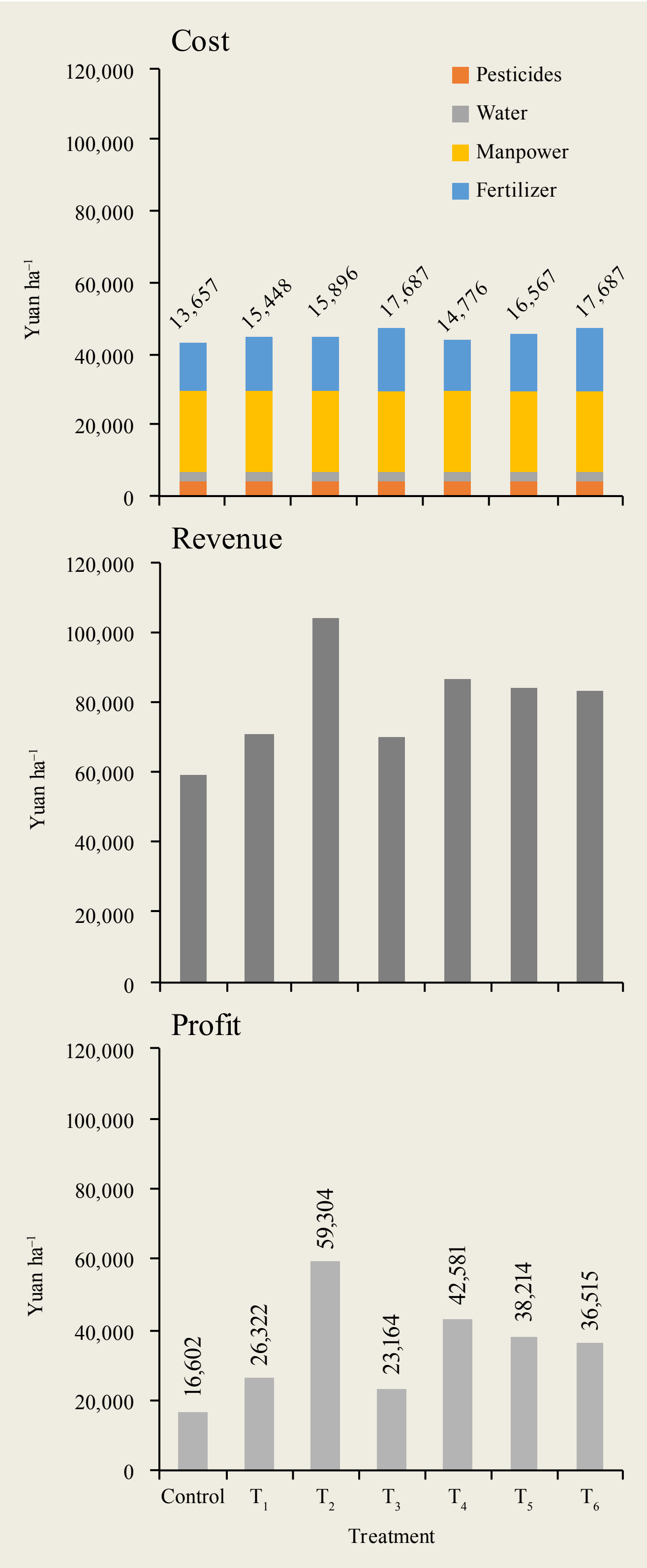


Fig. 5. Economic analysis of fertilizer treatments in kiwifruit production in China. Refer to Table 1 for detailed description of fertilizer treatments.

Fruit firmness declined rapidly under shelf-life conditions after harvest. This decline was slightly slower among T_3-T_5 fruit. After 10 days, fruit firmness was significantly higher in T_3 fruit (Fig. 4A). Fruit of treatments T_3 and T_5 also exhibited the lowest TSS rates among all treatments (Fig. 4B), indicating a slower ripening processes.

Economic analysis carried out using the experiment results showed that the effects of the fertilizer treatments on the total costs of kiwifruit production was very small, adding no more than 4K Yuan ha^{-1} (Fig. 5). The differences in the yield of commercial-grade fruit had consequent impacts on the farmer's revenue. Treatment T_2 obtained 104K Yuan ha^{-1}, while revenue from treatments T_4-T_6 varied from 83-86.5K Yuan ha^{-1}, T_1 and T_3 generated about 70K Yuan ha^{-1}, and the control returned the least, with just below 60K Yuan ha^{-1} (Fig. 5). Nevertheless, the differences in the farmer's profit were much more pronounced between treatments. T_2 obtained the highest profit, 59.6K Yuan ha^{-1}, 257% greater than the control, 57% of it's revenue, and 132% of it's total costs. The profits of treatments T_4-T_6 varied from 36.5-42.6K Yuan ha^{-1}, indicating intermediate performance levels, only 120-160% better than the control. Treatments T_1 and T_3 exhibited substantially inferior profits of 23-26.3K Yuan ha^{-1}, only 40-60% above control (Fig. 5).

Discussion

The present study was carried out in the heart of a major kiwifruit production region in China, on a very fertile soil, as indicated by the high OM contents (Table 2). On such soils, fertilizer application, and particularly N dose application, should be considered very carefully to maintain balanced crop nutrition. A recent study carried out in the same region (Lu *et al.*, 2018) concluded that the current level of N fertilization in kiwifruit orchards (900 kg N ha^{-1}) was very excessive, and reducing the N fertilizer rate by 25-45% could not only guarantee fruit yield, but also reduce N accumulation and loss. Zhao *et al.* (2017) suggested an annual N dose of 450 kg ha^{-1} as an optimum to obtain high kiwifruit yields, however these authors did not examine any lower N dose. In the present study, N application dose was reduced further and ranged from 277.5-337.7 kg N ha^{-1}. However, Pacheo *et al.* (2008) found that kiwifruit N requirements were much smaller, no more than 60 kg ha^{-1}. Ferguson and Eiseman (1983) showed that annual N removal by fruit and pruning was 78 kg ha^{-1} under kiwifruit yield of 16 Mg ha^{-1}. Assumingly, heavier yields would require greater N inputs, however, with considerably lower yield levels in the present study, an annual dose of about 300 kg N ha^{-1} appears substantially higher than required.

Excessive N application not only causes serious environmental consequences (Tong *et al.*, 2004; Lu *et al.*, 2018; Wang *et al.*, 2019), but also leads to imbalanced vine growth at the expense of the reproductive development (Minchin *et al.*, 2011). In addition, the temperature regime during the summer in Shaanxi seems considerably warmer (Fig. 1) than the optimum of 17°C for high kiwifruit yield and quality (Snelgar *et al.*, 2005), thus promoting further vegetative growth. These conditions may provide a partial explanation to the relatively low yield. Moreover, the average fruit size of all treatments ranged from 61-68 g (Table 3), far below the desired commercial range of 80-120 g fruit^{-1}. Although excess N application was not shown to directly cause decreased fruit size in kiwifruit (Morton, 2013), indirect effects of the surplus vegetative growth might have occurred. Excess foliage might have disrupted the pollination, leading to small numbers of seeds and consequently, to small fruit size and fruit developmental disorders (Gianni and Vania, 2018). In addition, overage shading is also known to restrict fruit size (Grant *et al.*, 1984; Blattmann *et al.*, 1988; Testoni *et al.*, 1990). So, excess N application alone can provide explanations for the poor rates of commercial-grade fruit, 18-44%, in the present study (Table 3).

In spite of the restrictions of excess N application, the polyhalite fertilizer treatments had significant influences on the yield (Table 3). Interestingly, T_3, with the highest seasonal K dose (Table 1), obtained the lowest fruit yield (Table 3). When K doses were reduced from about 400 to 350 kg ha^{-1}, yields were enhanced. A further reduction in K dose to 300 kg K_2O ha^{-1}, excluding the control, gave rise to the highest yields, and a further reduction to 250 kg K_2O ha^{-1} did not result in a great difference ot the yield (Table 3). In spite of the pivotal role of K in the remobilization and translocation of carbohydrate reserves and produced sugars to the developing fruit (Zörb *et al.*, 2014), this nutrient did not seem to be a yield-limiting factor in the present study. However, some advantage may be attributed to the increase in the available soil K content following polyhalite fertilizer application, particularly during the fruit development stage (Fig. 2), partially explaining the significantly higher commercial-grade yields of all treatments compared to the control (Table 3).

The polyhalite fertilizer treatments had much more significant effects on the rate of commercial-grade yield, with T_2, T_6, and T_4 obtaining 40-44%, compared to 18% in the control, and 29-33% in the other treatments (Table 3). The differences among treatments T_1-T_6 did not provide any adequate explanation for the differences in the commercial-grade yields between the two groups, neither did the soil analyses carried out during the experiment (Table 2; Fig. 2). It may be postulated, however, that the greater supply of Ca, Mg, and S to treatments T_2-T_6 (and S to T_1) enhanced fruit growth and development (Smith *et al.*, 1987; Clark and Smith, 1988).

The duration of fruit storage and shelf life, which are pivotal for the assessment of kiwifruit produce quality, are evaluated through the reduction of fruit firmness, and by the increase in TSS resulting from starch degradation; the slower the rate of change the better (Johnson *et al.*, 1995). While excess N accelerates postharvest fruit degradation (Johnson *et al.*, 1995; Vizzotto *et al.*, 1999; Morton, 2013), improved K, and moreover, Ca and Mg nutrition tend to extend kiwifruit shelf life (Clark and Smith, 1988). In the present study, treatments T_3 and T_5 exhibited a clear tendency to delay fruit firmness and starch degradation (Fig. 4). Unfortunately, fruit nutrient content at harvest was not examined and hence, the association of polyhalite application with postharvest kiwifruit performance, and especially, the direct mechanisms involved, awaits further research.

An economic analysis founded on the commercial-grade yields unequivocally showed that T_2, with moderate doses of Polysulphate and MegaPoly, at budding and at fruit enlargement, respectively, gave rise to the highest profit for the farmer (Fig. 5). However, understanding the reasons for the advantage of T_2 over T_4-T_6 would require further investigation. T_1 and the control, on the one hand, and T_3, on the other, all of which exhibited relatively low profits, might have represented the effect on profit from the deficient and or excess K, Ca, Mg, and S application rates, respectively.

In conclusion, application of polyhalite fertilizers, Polysulphate at budding and MegaPoly at fruit enlargement, demonstrated remarkable potential to enhance kiwifruit yield and quality. Nevertheless, the real contribution of these fertilizers should be revisited with a more balanced N fertilization approach.

Acknowledgements

We thank Guohua Li, Patricia Imas, and Hillel Magen for giving their advice and assistance for the study. This study was funded by the International Potash Institute.

References

Blattmann, P., B. Snelgar, P. Minchin. 2008. Hayward's First Priority: Shoot Growth. New Zealand Kiwifruit Journal (Jan/Feb):26-28.

Boyd, L.M., A.M. Barnett. 2011. Manipulation of Whole-Vine Carbon Allocation Using Girdling, Pruning, and Fruit Thinning Affects Fruit Numbers and Quality in Kiwifruit. HortScience 46(4):590-595.

Burge, G.K., C.B. Spence, R.R. Marshall. 1987. Kiwifruit: Effects of Thinning on Fruit Size, Vegetative Growth, and Return Bloom. New Zealand Journal of Experimental Agriculture 15(3):317-324.

Clark, C.J., G.S. Smith. 1988. Seasonal Accumulation of Mineral Nutrients by Kiwifruit 2. Fruit. New Phytologist 108(4):399-409.

Dick, W.A., D. Kost, L. Chen. 2008. Availability of Sulfur to Crops from Soil and Other Sources. *In:* Jez, J. (Ed.) Sulfur: A Missing Link between Soils, Crops and Nutrition. Madison. WI, USA: American Society of Agronomy p. 59-82.

Dimassi-Theriou, K., A.M. Bosabalidis. 1997. Effects of Light, Magnesium and Sucrose on Leaf Anatomy, Photosynthesis, Starch and Total Sugar Accumulation, in Kiwifruit Cultured in Vitro. Plant Cell, Tissue and Organ Culture 47(2):127-134.

FAOstat. 2018. http://www.fao.org/faostat/en/#data/QC.

Ferguson A.R., J.A. Eiseman. 1983. Estimated Annual Removal of Macronutrients in Fruit and Prunings from a Kiwifruit Orchard. New Zealand Journal of Agricultural Research 26(1):115-117.

Gianni, T., M. Vania. 2018. Artificial Pollination in Kiwifruit and Olive trees. Pollination in Plants. DOI: 10.5772/intechopen.74831

Grant, J.A., K. Ryugo. 1984. Influence of Within-Canopy Shading on Fruit Size, Shoot Growth, and Return Bloom in Kiwifruit. Journal of the American Society for Horticultural Science 109:799-802.

Jamal, A., Y-S. Moon, and M.Z. Abdin. 2010. Sulphur - A General Overview and Interaction with Nitrogen. Australian J. Crop Sci. 4:523-529.

Johnson, R.S., F.G. Mitchell, C.H. Crisosto, W.H. Olson, G. Costa. 1995. Nitrogen Influences Kiwifruit Storage Life. *In:* III International Symposium on Kiwifruit. Acta Hort. 444:285-290.

Kotzé W.A.G., J. de Villiers. 1989. Seasonal Uptake and Distribution of Nutrient Elements by Kiwifruit Vines 1. Macronutrients. South African Journal of Plant and Soil 6(4):256-264.

Lu, Y.L., T.T. Kang, J.B. Gao, Z.J. Chen, J.B. Zhou. 2018. Reducing Nitrogen Fertilization of Intensive Kiwifruit Orchards Decreases Nitrate Accumulation in Soil without Compromising Crop Production. Journal of Integrative Agriculture 17(6):1421-1431.

Ma, T., T. Lan, Y. Ju, G. Cheng, Z. Que, T. Geng, X. Sun. 2019. Comparison of the Nutritional Properties and Biological Activities of Kiwifruit (*Actinidia*) and their Different Forms of Products: Towards Making Kiwifruit More Nutritious and Functional. Food & Function 10(3):1317-1329.

Minchin, P.E.H., W.P. Snelgar, P. Blattmann, A.J. Hall. 2010. Competition between Fruit and Vegetative Growth in Hayward Kiwifruit. New Zealand Journal of Crop and Horticultural Science 38(2):101-112.

Montanaro, G., B. Dichio, A. Lang, A.N. Mininni, V. Nuzzo, M.J. Clearwater, C. Xiloyannis. 2014. Internal versus External Control of Calcium Nutrition in Kiwifruit. Journal of Plant Nutrition and Soil Science 177(6):819-830.

Morton, J. 1987. Kiwifruit. pp. 293-300. *In:* Fruits of Warm Climates. Julia F. Morton, Miami, FL.

Morton, A.R. 2013. Kiwifruit (*Actinidia spp.*) Vine and Fruit Responses to Nitrogen Fertilizer Applied to the Soil or Leaves (Doctoral dissertation, Thesis. Massey University. Palmerston North, New Zealand).

Mu, L., H. Liu, Y. Cui, L. Fu, Y. Gejima. 2018. Mechanized Technologies for Scaffolding Cultivation in the Kiwifruit Industry: A Review. Information Processing in Agriculture 5(4):401-410.

Pacheco, C., F. Calouro, S. Vieira, F. Santos, N. Neves, F. Curado, D. Antunes. 2008. Influence of Nitrogen and Potassium on Yield, Fruit Quality and Mineral Composition of Kiwifruit. Energy and Environment 2:517-521.

Parent, S.É., P. Barlow, L.E. Parent. 2015. Nutrient Balances of New Zealand Kiwifruit (*Actinidia deliciosa* cv. Hayward) at High Yield Level. Communications in Soil Science and Plant Analysis 46(sup1):256-271.

Smith, G.S., C.J. Clark, H.V. Henderson. 1987. Seasonal Accumulation of Mineral Nutrients by Kiwifruit I. Leaves. New Phytologist 106(1):81-100.

Snelgar, W.P., A.J. Hall, A.R. Ferguson, P. Blattmann. 2005. Temperature Influences Growth and Maturation of Fruit on 'Hayward' Kiwifruit Vines. Functional Plant Biology 32(7):631-642.

Testoni, A., G. Granelli, A. Pagano. 1990. Mineral Nutrition Influence on the Yield and the Quality of Kiwifruit. Acta Hort. 594:595-600.

Tong, Y.A., O. Emteryd, S.L. Zhang, D.L. Liang. 2004. Evaluation of Over-application of Nitrogen Fertilizer in China's Shaanxi Province. Scientia Agricultura Sinica 37:1239-1244.

Vizzotto, G., O. Lain, G. Costa. 1999. Relationship between Nitrogen and Fruit Quality in Kiwifruit. *In:* IV International Symposium on Kiwifruit. Acta Hort. 498:165-172.

Wang, N., H. He, C. Lacroix, C. Morris, Z. Liu, F. Ma. 2019. Soil Fertility, Leaf Nutrients and their Relationship in Kiwifruit Orchards of China's Central Shaanxi Province. Soil Science and Plant Nutrition 65(4):369-376.

Wang, S., C. Huang, J. Tao, M. Zhong, X. Qu, H. Wu, X. Xu. 2017. Evaluation of Chilling Requirement of Kiwifruit (*Actinidia spp.*) in South China. New Zealand Journal of Crop and Horticultural Science 45(4):289-298.

Yermiyahu, U., I. Zipori, I. Faingold, L. Yusopov, N. Faust, A. Bar-Tal. 2017. Polyhalite as a Multi Nutrient Fertilizer – Potassium, Magnesium, Calcium and Sulfate. Israel Journal of Plant Sciences 64:145-157.

Yermiyahu, U., I. Zipori, C. Omer, Y. Beer, 2019. Solubility of Granular Polyhalite under Laboratory and Field Conditions. International Potash Institute (IPI) *e-ifc* 58:3-9.

Zhao, Z.P., Y.M. Gao, F. Liu, X.Y. Wang, Y.A. Tong. 2013. Effects of Organic Manure Application Combined with Chemical Fertilizers on the Leaf Nutrition, Quality and Yield of Fuji Apple. Acta Horticulturae Sinica 40:2229-2236.

Zhao, Z.P., M. Duan, S. Yan, Z.F. Liu, Q. Wang, J. Fu. 2017. Effects of Different Fertilizations on Fruit Quality, Yield and Soil Fertility in Field-Grown Kiwifruit Orchard. Int. J. Agric. & Biol. Eng. 10(2):162-171.

Zörb, C., M. Senbayram, E. Peiter. 2014. Potassium in Agriculture – Status and Perspectives. Journal of Plant Physiology 171(9):656-669.

The paper "Impact of Alternative Polyhalite Fertilizers on 'Xu Xiang' Kiwifruit Yield and Quality in Shaanxi Province, China" also appears on the IPI website.