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Optimizing Crop Nutrition

Editorial

Dear readers,

The COVID-19 pandemic has disrupted the global food supply chain, exacerbated the issue of food and nutritional insecurity, and focused attention on the critical importance of continued food production.

Agriculture has been strongly affected by the spread of the virus with movement restrictions, border closures and less rural labor, including migrant workers. Food processing facilities have been closed or reduced and the movement of imported food shipped by air has also been more difficult. Nevertheless, the current situation has driven new initiatives to strengthen local food production systems.

Prior to COVID-19, smart web-based geospatial decision-support systems, robots working in greenhouses, vertical farms and automated farming systems had been in various stages of development. These technologies could all help guarantee food supply in the future and thus will be further developed more quickly.

The COVID-19 pandemic has also been disruptive for agricultural research. Many research labs have closed and global conferences have been canceled. Strengthening communication between scientists and policymakers and improving distance learning techniques is therefore critical. The pandemic will also result in the resetting of research priorities to focus on making agriculture and food production more resilient and help us face the ongoing, long-term challenges of climate change, population growth, environmental degradation and food security.

In the current *e-ifc* edition, we present two papers on polyhalite experiments: one with pomegranate in China and another from Vietnam on black pepper. In addition, we have a short report on polyhalite on organically grown cabbage in Switzerland.

Finally, we are pleased to announce three new IPI coordinators: Dr. Cheng Cong Rong for Malaysia & Indonesia, Dr. Adi Perelman for India, and Dr. Heinrich Thoele for Germany. We warmly welcome them to the IPI family!

I wish you an enjoyable read and stay safe!

Dr. Patricia Imas
IPI Scientific and Communications Coordinator

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Photo cover page: Sesame experiment in Israel. Photo by N. Cohen Kadosh.

Research Findings

An open fruit of soft-seed pomegranate. Photo by the authors.

Testing Coherent Fertilizing Approaches in Soft-Seed Pomegranate Production at Heyin, Henan Province, China

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Abstract

The Heyin region of Henan Province is a traditional pomegranate (*Punica granatum* L.) production area in China. In recent decades, soft-seed cultivars have been introduced to the region, which have gained increasing popularity. A survey carried out among Heyin pomegranate growers revealed substantial variability of yields; about 65% of growers obtain yields lower than 22.5 Mg ha^{-1}, compared to 45 Mg ha^{-1} obtained by the top 3% of farmers. The common pomegranate fertilization practice is intuitively focused on nitrogen (N), phosphorus (P), potassium (K), and organic manure, and lacks scientific quantitative basis. Moreover, it ignores other macronutrients essential to crop production, such as calcium (Ca) and magnesium (Mg). The objectives of the present study were to investigate the current motivation of local pomegranate growers to adopt new fertilizer approaches; to examine the contribution of soil testing and formula fertilization (STFF) approach to soft-seed pomegranate fruit yield and quality; and, to examine the effect of polyhalite, a supplementary fertilizer

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(Ca, Mg, K, and S donor), applied in addition to the STFF practice, compared to farmers' common practice (FFP). An experiment was set in selected farmers' orchards, distinguishing between three groups of tree age: 10, 15, and 20 years. The experiment included three treatments: FFP, STFF, and STFF + supplementary polyhalite application. Fruit yield significantly increased by 24.6-59.4% in response to the STFF treatment. Supplementary polyhalite application in addition to STFF brought about a further yield increase, which ranged from 30-82% compared to FFP. The higher yields were obtained despite the drastic reduction in NPK application in the two STFF treatments, compared to FFP, but was dependent on tree age; the younger the tree, the greater the impact of fertilizer treatment. Fruit quality traits, such as fruit size, color, aril sugar and acid contents and ratio, and vitamin C content, were significantly improved under the STFF treatments, while polyhalite further enhanced fruit attractiveness in terms of size and color. Consequently, the STFF treatment plus supplementary polyhalite increased farmers' net income by 48-148%. Nevertheless, additional fine-tuning of the STFF approach, as well as the precise polyhalite dose required, is still needed.

Keywords: Calcium; fruit quality; fruit yield; polyhalite; Polysulphate; *Punica granatum* L.

Introduction

Pomegranate (*Punica granatum* L., Punicaceae) is a domesticated fruit tree; its fruit is highly appreciated due to its nutritional and economic values (Romano *et al*., 2016). The tree species also has significant cultural prestige. Pomegranates originated in Central Asia (Iran and Afghanistan) and spread to China, India, Mediterranean countries, and Africa (Janick, 2005; Stover and Mercure, 2007; Holland *et al*., 2009; Cao *et al*., 2015). Recent growing interest in the health benefits of pomegranate juice has led to growth in both global demand and production area. According to recent estimations, from 2014 to 2025, the area under pomegranate cultivation will increase ten-fold (Venkataramudu *et al*., 2018). China is among the leading countries in pomegranate production, with increasing consumption, output and cultivation area year by year (Wang *et al*., 2010). Heyin area of Henan Province has a long history of pomegranate cultivation. With a cultivated area of about 3,000 ha, Heyin is one of the leading pomegranate growing regions in China (Cao and Hou, 2013).

Until recently, pomegranate varieties cultivated in China belong to the common type, the seed coats of which are rigid and, therefore, are not easy to chew and swallow. Softness, or absence of seeds, is a desirable economic trait that improves the consumptive quality of fruits (Mars, 2000). The 'Tunisia' pomegranate is a soft-seed variety introduced to China in 1986 (Baike.so.com, 2016). After years of careful cultivation, 'Tunisia' has been adapted to China's environment, becoming the best soft-seed pomegranate variety currently available (Xue *et al*., 2017a). The market price of soft-seed pomegranate is 2-4 times that of the common variety, and soft-seed pomegranate growth has obviously increased the income of farmers (Xue *et al*., 2017b). With the increasing market demand for soft-seed pomegranate, planting of 'Tunisia' soft-seed pomegranate has extensively expanded; at present, 67% of pomegranates in Heyin region are soft-seed pomegranates (Chen *et al*., 2005).

Most studies on pomegranate have focused on fruit characteristics and the benefits to human nutrition and health. However, the scientifically-based agronomic perspective of pomegranate crop requirements is quite vague, and professional empirical recommendations are limited (Lazare *et al*., 2019). The lack of knowledge is even more significant with regard to the relatively new soft-seed cultivars. Consequently, fruit yield and quality vary greatly among local pomegranate growers in Heyin; inasmuch as the potential for increasing soft-seed pomegranate production in response to agronomic improvements is huge in this region.

The importance of fertilizer application in support of production and quality is very clear to most pomegranate growers. However, lacking concrete, scientifically-based recommendations, many pomegranate growers use fertilizers blindly, or over-use fertilization. This practice not only wastes fertilizer, but also adversely affects tree growth and development, and causes substantial damage to the soil environment (Zhang *et al*., 2012). Soil testing and formula fertilization (STFF) is a method to determine crop fertilizer requirements based on direct examination of the soil's nitrogen (N), phosphorus (P), and potassium (K) availability to plants at a specific time and location. Principal rules of NPK uptake by crops, and comprehensive monitoring of the relationships between crop growth and development and soil nutrient status, can give rise to the appropriate fertilizer dosage required to obtain certain yield levels and to efficient nutrient use, while improving produce quality and saving farmers' inputs (Zhang, 2006). STFF has already been successfully applied to fruit trees such as apples, citrus, pears, and peaches (He, 2009; Ye, 2017; Zhang *et al*., 2017).

Nevertheless, beyond NPK, other macronutrients such as calcium (Ca), magnesium (Mg), and sulfur (S) are essential, ensuring normal crop performance, productivity, and adequate produce quality. Calcium has well-documented roles in plant signaling, water relations and cell wall interactions. The broad influence of Ca on fruit development, physical traits, disease susceptibility, and ripening through facilitating developmental and stress response signaling, stabilizing membranes, influencing water relations and modifying cell wall properties through cross-linking of de-esterified pectin was recently reviewed by Hocking *et al*. (2016). Pomegranate was determined as a 'Ca loving species', which displayed a higher total amount of Ca than all other nutrients throughout the growing season (Maity *et al*.,

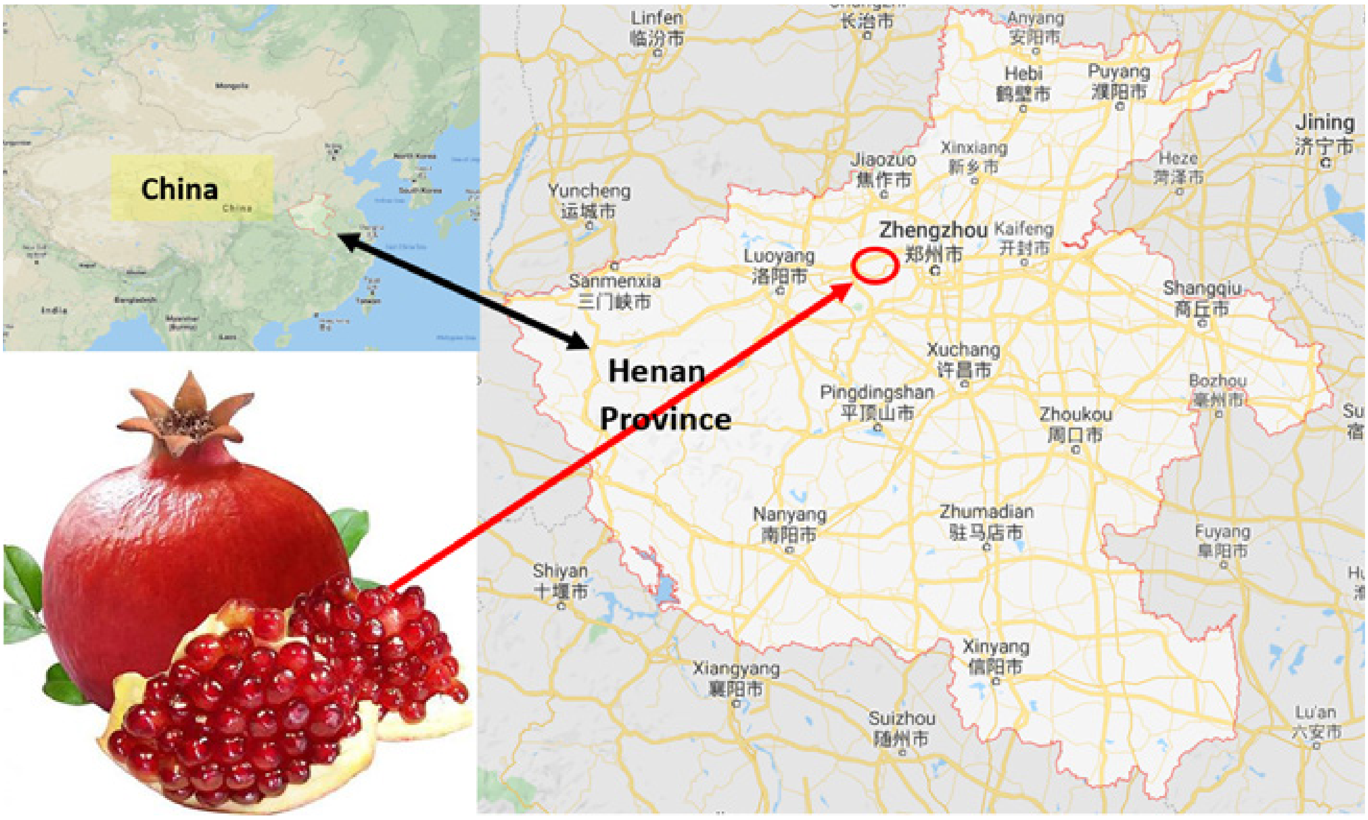

Fig. 1. Heyin pomegranate production area near Xingyang City in Henan Province, China (red circle). *Source:* Maps were extracted from Google Maps, and the image of soft-seed pomegranate was taken from http://eng.fruitkii.com/Product/details/281244.

2019). The authors demonstrated that the macronutrient uptake pattern in pomegranates followed the order of Ca>N>K>Mg>S>P, and that most of the uptake of N, K, Ca, Mg and S from the soil occurred between pre-pruning and bloom. Chater *et al.* (2020) have also recently highlighted the particular significance of Ca to pomegranate cultivation. Davarpanah *et al.* (2018) described the effects of foliar Ca application on reducing fruit cracking damage in pomegranates.

Unequivocally, Heyin fruit farmers have an urgent need for well-founded locally fitted pomegranate-specific fertilizer recommendations in order to achieve high yields from their fruit trees and improve the quality of soft-seed pomegranate. The desired practice should consider local soil properties, yearly precipitation pattern, and crop nutrient requirements during the growing season. A major question, however, is the extent of cognizance, and the consequent willingness to adopt new practices, among local farmers. There were therefore three objectives of the present study to: 1) investigate the current motivation of local pomegranate growers to adopt new fertilizer approaches; 2) examine the contribution of the STFF approach to soft-seed pomegranate fruit yield and quality, compared to the common practice; and, 3) examine the effect of polyhalite, a new supplementary fertilizer (Ca, Mg, K, and S donor), applied in addition to the STFF practice.

Materials and methods

Regional pomegranate cultivation survey

In order to characterize pomegranate production in the Heyin Pomegranate area, Henan Province, China (Fig. 1), a field study was carried out in six administrative villages, including Gaoxiang, Liugou, Guanyu, Zaoshugou, and Niukouyu in Fuyang City. Out of 157 households interviewed during May to December 2016, 112 valid questionnaires were obtained. The survey items included farmers' education, understanding of soil testing and formula fertilization techniques, pomegranate orchard area, planting density, yield, and fertilization practices.

Soil and climate

Subsequent to the survey, a field experiment was carried out in pomegranate orchards exhibiting similar soil fertility. Topsoil samples were taken from each field at five sampling points, at a depth of 0-20 cm. Samples were mixed and air-dried, and the soil pH (soil-water ratio was 1:2.5), total N content (half-micro-Kelvin method), available P_2O_5 ($NaHCO_3$ method), and available K_2O (NH_4OAc extraction method) were determined according

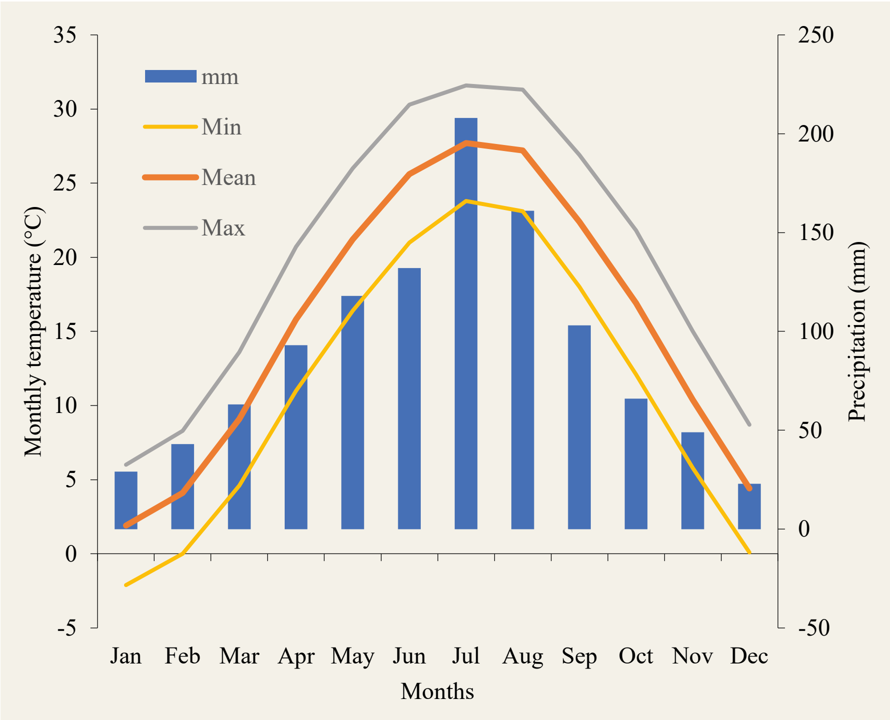

Fig. 2. Climatic profile of Xingyang City, China, including monthly precipitation, and minimum, mean, and maximum monthly temperature. *Source:* Data were taken from https://en.climate-data.org/asia/china/henan/xinyang-2679/.

Table 1. Basic chemical soil properties at the soft-seed pomegranate experiment at Heyin, Henan Province, China.

Tree age	pH	Total N	Available P	Available K
Years		*g k^{-1}*	--------------------*mg k^{-1}*--------------------	
10	7.56	0.91	15.74	151.3
15	7.54	0.87	14.76	152.5
20	7.54	1.03	16.25	162.2

Table 2. Seasonal doses of N, P_2O_5, K_2O, CaO, MgO, and SO_3, as applied according to the three fertilizer treatments included in the soft-seed pomegranate experiment in Heyin, Henan Province, China.

Treatment code	Organic fertilizer	N	P_2O_5	K_2O	Polyhalite			
					K_2O	CaO	MgO	SO_3
	-----------------------------			*kg ha^{-1}*	-----------------------------			
FFP	7,500	500	500	500	-	-	-	-
STFF	-	373.5	223.5	327	-	-	-	-
STFF+PH	-	373.5	223.5	327 +	52.5	63.75	2.25	180

to Bao (2005). The basic soil chemical properties of the experiment sites are shown in Table 1. The regional climate conditions (Fig. 2) are characterized by a warm wet summer, cold winter, and mild intermediate seasons. The main rainy season is during the summer, but precipitation, averaging 1,088 mm year^{-1}, may occur all year round.

Fertilization treatments

The experiment focused on Tunisian soft-seed pomegranate. Trees were categorized according to three age groups: 10, 15, and 20 years, the planting density of which was 1,482; 1,739; and 1,184 trees ha^{-1}, respectively. In the experiment, three fertilization approaches were tested within each tree-age group, as shown in Table 2.

The farmers' fertilization practice (FFP), which served as the control, included organic fertilizer application in the autumn, and NPK application at the spring bloom stage. In the second treatment, soil test and formula fertilization (STFF), NPK doses were reduced according to the predetermined soil chemical properties (Table 1) and divided into four applications in autumn (following harvest, November), early spring (before shoot burst, late March), late spring (bloom, late May), and summer (fruit expansion, late August). The third treatment, STFF+PH, polyhalite (Polysulphate®, ICL Fertilizers, Cleveland, UK) was added in addition to the NPK fertilization practice of STFF, contributing Ca, Mg, S, and some additional K (Table 2). Each treatment was repeated three times, and the test plot area was 200 m^2.

Yield and quality assessments

On September 25, 10 pomegranate trees were randomly selected for harvest in each plot. The number of fruits per tree was recorded and the total weight was determined. Ten representative pomegranate fruits from each plot were selected for quality determination. Juice total sugar concentration was determined using a DBR45 digital refractometer (Delta Acque, Italy). Total acid content was determined by NaOH titration. To determine levels of reduced vitamin C, the 2, 6-dichlorophenol method (Li, 2000) was employed.

Data processing and statistical analyses

Microsoft Excel 2010, SPSS 21.0, and Origin 8.1 programs were employed for data processing and analyses. The Duncan method was used to determine the significance of variance between the treatments.

Results

Survey of current production of soft-seed pomegranate in Heyin

A random survey, which included 112 fruit growers and about 71 ha in Heyin area, revealed that the yield levels of soft-seed pomegranate varied greatly, ranging from 7.5-45 Mg ha^{-1} (Table 3). Most farmers (about 65%), using about 52% of the planted area, obtained relatively low yield levels that ranged from 7.5-22.5 Mg ha^{-1} and were responsible for only 36% of production. In contrast, high-yield pomegranate orchards (37.5 Mg ha^{-1} or more) were associated with less than 12% of the growers, 11% of the surveyed area, and 19% of pomegranate production. The majority of pomegranate growers, more than 82%, were aware of the potential to improve yield and quality through modification of their fertilizer practice and showed willingness to adopt soil test-based formula fertilization, whenever it proved successful.

Table 3. Results of the orchard yield survey carried out among 112 pomegranate growers at Heyin region, Henan Province, China, in 2018.

Yield level	Growers		Area		Production	
Mg ha^{-1}	*number*	*%*	*ha*	*%*	*Mg*	*%*
7.5-15	4	2.9	4.00	5.7	48	2.8
15-22.5	68	61.8	32.53	46.0	586	33.7
22.5-30	20	17.7	15.73	22.3	409	23.6
30-37.5	8	5.9	10.67	15.1	363	20.9
37.5-45	8	8.8	6.40	9.1	269	15.5
>45	4	2.9	1.33	1.9	61	3.5
	112	100	70.66	100	1,735	100

Effects of fertilizer treatments on fruit yield parameters

The modified fertilizer treatments, STFF and STFF+PH, had significant positive influence on fruit size, number of fruits per tree, and consequently, on the yield of soft-seed pomegranate, compared to the common FFP control (Fig. 3). This was observed on top of a tendency of fruit weight to decline, and a significant increase in the number of fruits with aging trees. Compensating for these two opposite effects in tree age, the mean total yield was hardly affected, with 28.5, 31.6, and 27.2 Mg ha^{-1}, for 10, 15, and 20 years of tree age, respectively.

Fruit size significantly increased in young trees (10 years) in response to both STFF and STFF+PH treatments; however, this effect gradually declined with tree age, remaining significant for STFF+PH compared to FFP among 15-year-old trees, and almost completely diminished among older trees (Fig. 3A). The number of fruits per tree significantly increased in both STFF and STFF+PH compared to FFP throughout tree ages, with a slight but significant advantage for STFF+PH compared to STFF (Fig. 3B).

Consequently, when compared to FFP, total fruit yields significantly increased among younger trees by 59.4 and 82.4%

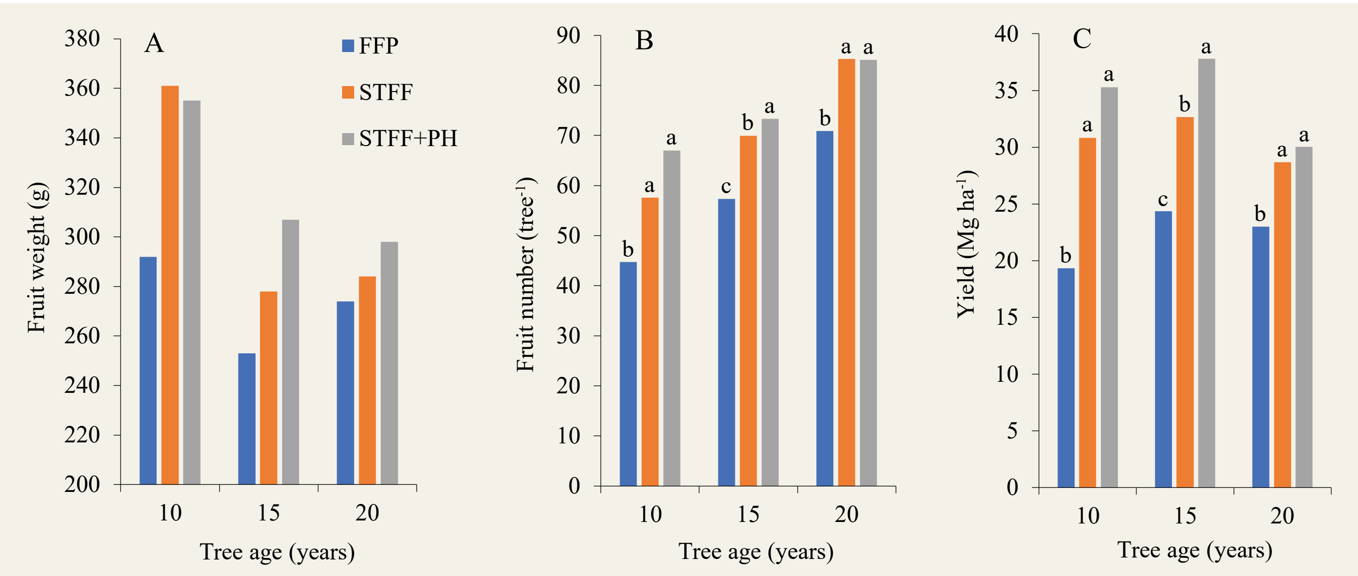

Fig. 3. Effects of fertilizer treatment on fruit weight (A), number of fruit (B), and fruit yield as a function of tree age in soft-seed pomegranate experiment in Heyin, Henan Province, China. Different letters indicate significant differences ($P < 0.05$) within each tree age.

Fig. 4. Effects of the modified fertilizer practices on appearance of soft-seed pomegranate fruit harvested from 15-year-old tree. Photo by the authors.

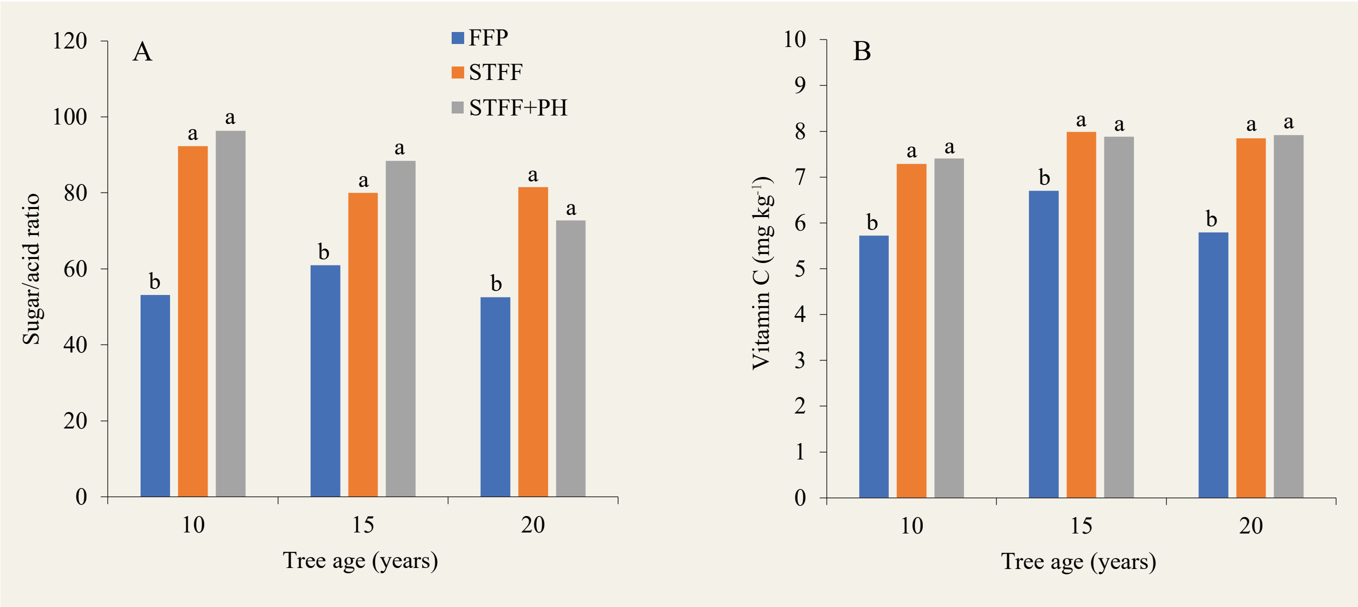

Fig. 5. Effects of tree age and fertilizer treatments on sugar/acid ratio (A) and vitamin C concentration (B) in the aril juice of soft-seed pomegranates. *Note*: different letters indicate significant differences ($P < 0.05$) within each tree-age group.

in response to STFF and STFF+PH, respectively. Among the 15-year-old trees, yield increase rates were smaller, 34.1 and 55.2% more than FFP, for STFF and STFF+PH, respectively. The increase in total fruit yield further declined in older trees but remained significant, with 24.6 and 30.5% more than FFP for STFF and STFF+PH, respectively, with no significant difference between the two modified fertilizer practices (Fig. 3C).

Effects of fertilizer treatments on fruit quality parameters

The modified fertilizer treatments had obvious positive effects on pomegranate fruit appearance and attractiveness (Fig. 4). Fruit were larger, well-shaped and colorful compared to the yellowish-green look of the FFP control fruit.

Pomegranate fruit diameter was significantly larger in response to STFF treatment, compared to the FFP control, without any influence of tree age. The supplementary polyhalite did not have any additive consistent effect on fruit diameter (Table 4). In contrast, the supplementary polyhalite brought about significant increase in the aril sugar concentration (Brix), while STFF alone showed a similar tendency, which was not significant. These effects on aril sugar concentration were limited, however, to the two younger tree groups, whereas the 20-year-old trees remained unaffected (Table 4). STFF, with and without supplementary polyhalite, significantly reduced aril juice acidity, compared to FFP, across tree-age groups (Table 4).

Both modified fertilizer treatments gave rise to significant and equal increases in the sugar/acid ratio and in vitamin C content of pomegranate aril juice, compared to FFP fruit across tree-age groups (Fig. 5).

Effects of fertilizer treatments on the economic benefit to pomegranate farmers

In spite of the significant reduction in amount of fertilizer applied, fertilizer

Table 4. Effects of fertilizer treatment and tree age on fruit diameter, and on aril Brix and acidity in the soft-seed pomegranate experiment at Heyin, Henan Province, China.

Tree age	Treatment code	Fruit diameter	Brix	Acidity
Years		*cm*	--------------------%--------------------	
	FFP	8.40 b	14.91 b	0.28 a
10	STFF	8.84 a	15.10 ab	0.16 b
	STFF+PH	8.70 a	15.77 a	0.16 b
	FFP	8.11 b	14.26 b	0.23 a
15	STFF	8.34 ab	14.97 ab	0.19 ab
	STFF+PH	8.57 a	15.03 a	0.17 b
	FFP	8.35 b	14.73	0.28 a
20	STFF	8.67 a	14.66	0.18 b
	STFF+PH	8.58 ab	15.09	0.21 b

Note: different letters indicate significant differences ($P < 0.05$) within each tree-age group.

Table 5. Effects of tree age and fertilizer treatment on farmers' revenue, fertilizer cost, and farmers' net income, calculated from the results of the soft-seed pomegranate experiment at Heyin, Henan Province, China.

Tree age	Treatment code	Revenue	Fertilizer cost	Net income	Net income rise
Years		-----------------*Yuan* 10^4 *ha*$^{-1}$		-----------------	*%*
	FFP	19.34	0.57	10.52	-
10	STFF	30.83	0.63	21.95	109
	STFF+PH	35.27	0.90	26.12	148
	FFP	24.35	0.57	15.53	-
15	STFF	32.65	0.63	23.77	53
	STFF+PH	37.79	0.90	28.64	84
	FFP	23.01	0.57	14.15	-
20	STFF	28.68	0.63	19.80	40
	STFF+PH	30.03	0.90	20.88	48

costs for the STFF treatment and for the STFF+PH treatment are higher than for the common FFP (Table 5). Nevertheless, the obvious rise in revenue and, subsequently, in the net income to the grower, more than compensates for the higher fertilizer cost. The rate of the net income rise varied between treatments and among tree-age groups; STFF gave rise to 109, 53, and 40% higher net income in 10, 15, and 20-year-old trees, respectively, while supplementary polyhalite in addition to STFF brought about even greater increases of 148, 84, and 48%, respectively (Table 5).

Discussion

Heyin pomegranates were already highly appreciated in ancient times and were mentioned in the "Farmers' Almanac" written by Wang Zhen of the Yuan Dynasty as "the best pomegranates in China" (Li, 2009). Today, Heyin pomegranates continue to exhibit numerous advantages including large size, thin skin, juiciness, sweetness, attractive appearance, soft seeds, and long postharvest storage life. Nevertheless, a huge gap exists between the rising demand for quality pomegranates and the growers' capacity to meet this demand. Therefore, increasing the yield and improving the quality of soft-seed pomegranate in Heyin is of great importance to the development of the pomegranate industry in China (Lu and La, 2015).

The present survey among Heyin pomegranate growers revealed a substantial variation in yields, ranging from 7.5-45 Mg ha^{-1}. Furthermore, about 65% of pomegranate growers produce less than 22.5 Mg ha^{-1}, which leaves a lot of room for yield enhancement (Table 3). So far, the STFF approach has demonstrated outstanding results in many crops and fruit trees (Jin, 2005). Subsequently, and thanks to government promotion, scientific research and the media, more than 70% of the region's fruit farmers have some understanding of the technology. Among the farmers that took part in the present survey, more than 80% were willing to adopt the STFF approach for pomegranate even before any practical assessments.

In the practical experiment, the application of the STFF approach brought about significant fruit yield increases that ranged from 24.6-59.4%, depending on the tree age; the younger the tree, the greater the yield increase (Fig. 3). In addition to yield, STFF significantly enhanced fruit quality traits such as fruit diameter, color, sugar/acid ratio, and vitamin C content (Table 4, and Fig. 5). These results clearly demonstrate that the common fertilization practice (FFP) is utterly wrong and that pomegranate performance can be drastically enhanced through significant reduction of NPK inputs. A recent study of young fruiting pomegranate trees grown on perlite under fertigation showed that net N requirement for obtaining a reasonable fruit yield was about 750 g tree^{-1}, which is equivalent to 110 kg N ha^{-1} at a planting density of 148 trees ha^{-1} (Lazare *et al*., 2020). Even with more conventional fertilizer application techniques, and when soil-water-nutrient interactions are considered, this study suggests that further decreasing fertilizer dosage should be considered and tested in order to reduce production costs and minimize environmental consequences.

The efforts of the Ministry of Agriculture to maintain soil fertility, reduce nutrient losses, and obtain high yield and quality simultaneously through examination and dissemination of STFF, included secondary macronutrients such as Ca, Mg, and S, in addition to organic and inorganic sources of NPK (Jin, 2005). Supplementary Ca and Mg fertilizers are not always accessible to farmers, while pomegranate requirements of these nutrients are high (Holland *et al*., 2009; Maity *et al*., 2019; Chater *et al*., 2020). Polyhalite, comprising 48% SO_3, 14% K_2O, 6% MgO, and 17% CaO, is less water soluble than more conventional sources (Barbarick, 1991; Yermiyahu *et al*., 2017; Yermiyahu *et al*., 2019) and is, therefore, a suitable fertilizer to supply these four nutrients during the rainy growing season at Heyin (Fig. 2). In the present study, the addition of polyhalite on top of the STFF treatment further increased soft-seed pomegranate fruit yields (Fig. 3). Still, the yield increase largely depended on tree age, with significant advantage in the younger trees. However, this phenomenon is probably associated with general aging symptoms, such as increasing number of thinner twigs and consequently a larger number of flowers and fruit (Fig. 3B) that lead to smaller fruit size, rather than to the tree's nutritional status. Aging problems in fruit trees can often be solved by implementing suitable pruning and fruit thinning practices (Wünsche and Ferguson, 2005). The contribution of polyhalite to various fruit quality traits was less significant (Table 4 and Fig. 5), but it certainly enhanced the red color of the fruit (Fig. 4) and, thereby, attractiveness to consumers. Consequently, this substantially enhanced the benefit for growers (Table 5).

Direct demonstrative experiments in growers' orchards are powerful tools for disseminating beneficial ideas and technologies. Since the STFF approach has *a priori* gained much cognizance among Heyin fruit growers, the remarkable enhancement of fruit yield and quality of soft-seed pomegranate has only helped to strengthen growers' positive opinion. However, the idea of supplementary application of Ca and Mg fertilizers was rather new. The contribution of polyhalite, supplementary to STFF, in enhancing fruit appearance and attractiveness and, thereby, increasing farmers' net income, was very significant in the present study and, presumably, will persuade more growers to further balance pomegranate fertilization. Additional fine-tuning of the STFF approach, as well as the precise polyhalite dose required, is still needed.

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Research Findings

Photo 1. Observation of black pepper plant growth. Photo by the authors.

Fertilizer Agronomic Efficiency of KCl and Polyhalite Combinations in Black Pepper Cultivation in Central Highlands, Vietnam (2016-2018)

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Abstract

Acid soils significantly challenge the rapidly growing production of black pepper (*Piper nigrum* L.) in Vietnam. The perennial vines suffer from malnutrition, which gradually leads to plant deterioration, susceptibility to various diseases, and a consequent reduction in yield and quality. While farmers already practice frequent fertilizer application, different types of fertilizers are required to further improve nutrient availability and to broaden nutrient range in the soil. Polyhalite is a natural mineral consisting of potassium oxide (K_2O), sulfur trioxide (SO_3), magnesium oxide (MgO), and calcium oxide (CaO) at 14, 48, 6, and 17%, respectively, and has potential as a prolonged-release multi-nutrient fertilizer. For this study, polyhalite was examined in combination with potassium chloride (KCl), in equal proportions, to provide doses of 120, 240, and 360 kg K_2O ha^{-1} yr^{-1}, split into six applications during the year. These treatments were compared to doses of zero

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(control), 120, and 270 (farmers' practice) kg K_2O ha^{-1} applied solely as KCl. The present study demonstrates the pivotal role of potassium (K) application in black pepper production on acid soils. Splitting the K dose into bimonthly applications brought leaf K contents to the optimal range. Polyhalite application can partially replace KCl as the K source and, furthermore, polyhalite provides the crop with other essential nutrients such as calcium (Ca), magnesium (Mg), and sulfur (S). The supplemental nutrients strengthened the black pepper vines against mealybug attacks, supported better crop performance, and significantly improved yield and produce quality, which resulted in higher profits. The combination of 120/120 kg K_2O ha^{-1} of KCl/polyhalite, respectively, gave rise to the best crop performance and to the highest yield, produce quality, and profit.

Keywords: Acid soil; calcium; magnesium; *Piper nigrum* L.; polyhalite; potassium; *Pseudococcus citri*; sulfur.

Introduction

Black pepper (*Piper nigrum* L., Piperaceae), the 'king of spices', originated in the tropical evergreen forests of the Western Ghats of India (Sivaraman *et al*., 1999), and is one of the oldest spices known to humankind. Global black pepper production is led by Vietnam, with 262,658 tonnes yr^{-1}, followed by Indonesia, India, Brazil, and China; however, average yield levels in Vietnam are low, 2.44 Mg ha^{-1}, considerably below the yield levels of some other producing countries (FAOSTAT, 2018). In Vietnam, pepper production is concentrated in Phu Quoc Island and on the red soils of the Central Highlands. The increasing prices in recent years have led to further expansion of pepper cultivation to other regions in Vietnam.

Black pepper grows successfully between 20° N to 20° S of the equator and from 0 to 1,500 m above sea level. It is a plant of the humid tropics, requiring 1,250-2,000 mm of rainfall, tropical temperatures and high relative humidity with little variation in day length throughout the year (Sivaraman *et al*., 1999). Black pepper grows well on soils ranging from heavy clay to light sandy clays rich in humus with a porous friable nature, well drained, but still with ample water retention. Soils with near neutral pH, high organic matter and high base saturation with calcium (Ca) and magnesium (Mg) were found to enhance black pepper productivity (Mathew *et al*., 1995).

Nutrient removal and composition of black pepper vines varies with variety, age, season, soil type and management. Sim (1971) estimated the macronutrient removal by black pepper as 233, 39, 207, 30, and 105 kg ha^{-1} of nitrogen (N), phosphorus pentoxide (P_2O_5), potassium oxide (K_2O), magnesium oxide (MgO), and calcium oxide (CaO), respectively; later estimates did not differ significantly (Sivaraman *et al*., 1999). The critical stages of nutrient requirement for black pepper are during initiation of flower primordia and flower emergence, and during berry formation and development (Raj, 1978). Nybe *et al*. (1989) reported that phosphorus (P) and potassium (K) had greater importance than N in enhancing black pepper yields. Leaf macronutrient concentration ranges required for normal pepper development were estimated to be 3.1-3.4%, 0.16-0.18%, and 3.4-4.3% for N, P, and K, respectively. The suitable leaf concentration ranges of sulfur (S), Ca, and Mg should be 0.09-0.29%, 1.42-3.33%, and 0.40-0.69%, respectively (de Waard, 1969; Phan Huu Trinh *et al*., 1988).

Black pepper is a surface feeder; feeding roots are concentrated in the top 50-60 cm layer of the soil. In the past, black pepper, as well as coffee and tea plantations, were established on virgin forests after clearing vegetation (de Geus, 1973; Chiem and Nhan, 1974; D'haeze *et al*., 2005). However, owing to heavy rains and unsustainable soil management practices, soils became poor in fertility and balanced manuring of crops became essential (de Waard, 1969). Over time, sustainable traditional manuring practices were replaced with unbalanced use of manufactured chemical fertilizers and, consequently, dieback of branches, foliar disorders, low yields and considerable reduction in life span of vines were observed (de Waard, 1969; Raj, 1978; Sivaraman *et al*., 1999; Zu *et al*., 2014).

Soil acidity is an acute problem in the humid tropics, where annual precipitation exceeds 2,000 mm or frequent heavy rainfall events take place. Under such environmental circumstances, soil acidification is a natural process; appreciable quantities of exchangeable bases (Ca^{2+}, Mg^{2+}, and K^+) are leached from the soil's surface layer. Subsequently, the rising relative concentrations of exchangeable hydrogen (H^+) and exchangeable aluminum (Al^{3+}) reduce soil pH, and hence, are responsible for soil acidification (Coulter, 1969; Pavan, 1983). The content of mobile Al in soils with pH below 5.5 is rather high, which leads to increased uptake of toxic Al by plants, root growth retardation and dysfunction (Ryan *et al*., 1993; Zu *et al*., 2014), and to consequent diminishing nutrient uptake (Duchanfour and Souchier, 1980). Where soil pH declines below 5.5, the availability of plant nutrients, particularly N, P, K, Ca, Mg, S, molybdenum (Mo), and boron (B), decrease significantly (Zu *et al*., 2014; Aloka, 2016).

Overcoming the direct and indirect effects of acid soils on crop performance requires complex simultaneous solutions. Repeated liming is useful in many cases as a practice aimed to reconstruct soil pH (Fageria and Baligar, 2008). However, liming has not always been successful due to its low solubility in water, very slow effect, unsuitable methods of application, and high cost (Liu and Hue, 2001). Gypsum ($CaSO_4{\cdot}2H_2O$) was proposed as an effective amendment for subsoil acidity (Shainberg *et al*., 1989) and, in a recent study, demonstrated significant enhancement of black pepper crop performance (Aloka, 2016). Nevertheless, along with efforts to reduce detrimental effects of acid soils, consistent

Photo 2. Magnesium deficiency symptoms in leaves of black pepper. Photo by the authors.

nutrient availability throughout the year must be taken care of. In this respect, the microflora of the black pepper rhizosphere has recently been explored (Xiong *et al*., 2015; Li *et al*., 2016) to influence beneficial chemical processes in the soil.

Two major disorders often affect black pepper crops: the yellow pepper leaf (de Waard, 1986), and mealybugs (Tang Ton and Buu, 2011). The yellow leaf disease – named after its most noticeable symptom – is a multi-pathogen disease, which begins with a nematode (*Meloidogyne incognita*) attack that injures the roots, and continues with various fungal soil-borne opportunistic pathogens such as *Fusarium spp*., *Phytophthora spp*., *Pythium spp*., etc. that cause root rot diseases. Once infected, the old leaves' veins turn yellow (Photo 2), a symptom which gradually expands to the whole pepper leaf. Consequently, infected plants shed leaves and stems, their canopy becomes scattered, and they die 1-3 years after infection. The disease has substantial effects on crop yield determinants such as flowering, fruit set, and fruit development. In addition, produce quality parameters are significantly damaged.

Mealybugs (*Pseudococcus citri*) attack weak plants and impact on their carbon and energy balance, and hence, reduce pepper fruit yield and quality. In addition, mealybugs are known as vectors of various plant virus diseases that negatively affect crop performance (Selvarajan *et al*., 2016). Well-balanced crop nutrition is very efficient at preventing pests and diseases (Tang Ton and Buu, 2011).

However, in the absence of adequate soil fertility, and under a frequent precipitation regime, any kind of external nutrient supply should address this point. Splitting the fertilizer dose, where practical, is one promising solution. Slow-release fertilizers provide another solution; fertilizer efficiency to supply N and P significantly improved when slow-release 'nimin' (nitrification inhibitor) coated urea (Sadanandan and Hamza, 1993) and mussoorie rock phosphate (Sadanandan 1986), respectively, were applied to black pepper. Still, more stable K fertilizers are needed, as well as long-lasting Ca and Mg sources.

Polysulphate® (produced by ICL Fertilizers, Cleveland, UK) is the trade mark of the natural mineral 'polyhalite', 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 for crop nutrition. In addition, polyhalite is less water soluble than the more conventional sources (Barbarick, 1991; Yermiyahu *et al*., 2017; Yermiyahu *et al*., 2019) and is, therefore, a suitable fertilizer to supply these four nutrients during the rainy growing season. Once a proper application is established, polyhalite may not only provide a significant part of the crop K requirements, but also supply secondary macronutrients that are essential under the present cropping environment of black pepper in Vietnam.

The objectives of the present study were to evaluate the effectiveness of polyhalite as a supplementary fertilizer on black pepper performance, yield, quality, and economic efficiency, and to offer new alternatives for black pepper fertilization under the conditions of the Central Highlands of Vietnam

Materials and methods

The experiment was located in the Nguyễn Văn Tứ household, H'Lốp commune, Chư Sê district, Gia Lai province of the Central Highlands of Vietnam (Fig. 1A), and took place from January 2016 to December 2018 in a black pepper garden (cultivar Loc Ninh) planted in 2012. The site has typical humid tropic climate with a relatively cool and dry season from November-April, and a warmer rainy season from May-October (Fig. 1B), with an average yearly precipitation of 2,400 mm.

The experiment was conducted on an acidic (pH_{KCl}: 4.5-4.6) reddish-brown soil (Rhodic Ferralsols). Soil samples were collected twice, before the first fertilization (Feb 2016) and at the end of the experiment (Nov 2018). Soil was sampled from 0-30 cm depth at five scattered locations in each experiment plot, mixed, and examined. Soil pH was measured using the KCl 1N solution method. Soil organic matter was determined using the method of Walkley and Black (1934). Nitrogen was determined using the Kjeldahl method (1884). Total P and K were determined by soil digestion in H_2SO_4 + $HClO_4$ and measurements using spectrophotometer and flame-photometer, respectively. Available P was determined using the Bray II method (Bray and Kurtz, 1945); available K was extracted in H_2SO_4 0.1N solution and measured using a flame-photometer. Calcium and Mg cation exchange was measured using an atomic absorption spectrophotometer.

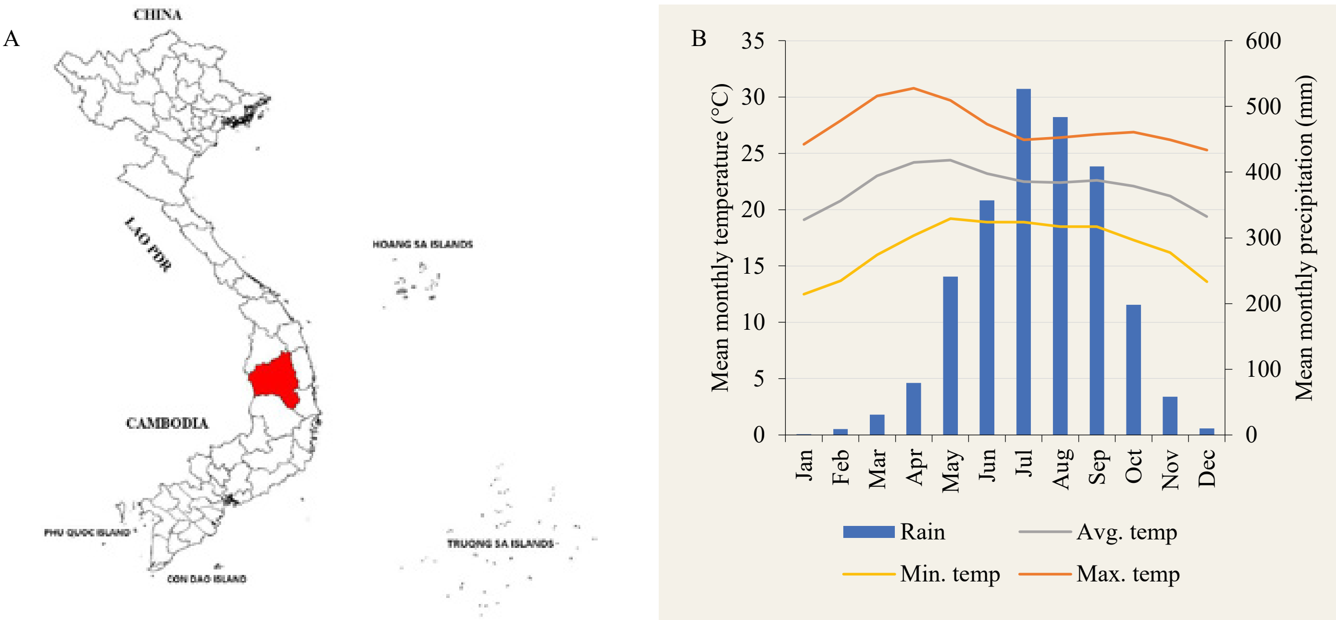

Fig. 1. Location of Gia Lai Province in the Central Highlands of Vietnam (A); and the typical climate profile (temperatures and precipitation) of the region (B). *Source:* https://en.climate-data.org/asia/vietnam/gia-lai-province/pleiku-4282/.

Table 1. Detailed description of fertilizer and available nutrients applied according to treatments.

Treatment	N		P		K			
	Urea	N	FMP	P_2O_5	KCl	K_2O	Polyhalite	K_2O
	kg ha⁻¹							
T1 (FP)	750	345	600	90	450	270	0	0
T2 (C)	652	300	667	100	0	0	0	0
T3	652	300	667	100	200	120	0	0
T4	652	300	667	100	100	60	429	60
T5	652	300	667	100	200	120	857	120
T6	652	300	667	100	300	180	1,286	180

Note: FP – farmers' practice; C – control; FMP – fused magnesium phosphate (15% P_2O_5).

Table 2. Timing of fertilizer application during the year (% of the yearly dose).

Fertilizer	Jan-Feb	Mar-Apr	May-Jun	Jul-Aug	Sep-Oct	Nov-Dec
Urea	10	10	25	20	20	15
FMP	-	-	50	-	50	-
MOP (KCl)	10	10	15	20	20	25
Polyhalite	10	10	15	20	20	25

Note: FMP – fused magnesium phosphate.

The experiment consisted of six treatments with four replications in a randomized complete block design (RCBD). Each 180 m² plot included 30 pepper plants. A detailed description of the fertilization regime and treatments is given in Tables 1 and 2. Treatments included farmers' practice (FP) as the first control (T1), and a second control (T2), which received only the standard N and P fertilizers. Treatments T3-T6 were applied with the standard N and P fertilizers, but differed in the rate and combination of KCl and polyhalite. Thus, T3 and T4 received a yearly dose of 120 kg K_2O ha^{-1}: T3 – KCl, exclusively; and T4 – KCl and polyhalite, 60 kg K_2O ha^{-1} each, but 100 and 429 kg fertilizer ha^{-1}, respectively. In treatments T5 and T6, K rates increased to 240 and 360 kg K_2O ha^{-1}, respectively, equally divided between MOP and polyhalite (Table 1). FMP (fused magnesium phosphate) was applied twice a year, during May-June and November-December. Urea, KCl, and polyhalite were applied every two months, as shown in Table 2.

Five plants per plot were monitored per year for vegetative growth at the beginning and end of the rainy season. In each plant, the length of four branches of the first order were measured and their elongation during the rainy season was calculated. Similarly, the number of lateral (second order) branches added during the rainy season to four tagged branches was counted.

Diagnostic leaves were sampled twice in July, before and 20 days after fertilizer application. The leaves (eight leaves each from three trees plot^{-1}, from four different directions around the tree) were collected from non-bearing internodes of fruit-bearing branches. Leaves were heated

Table 3. Effects of KCl and polyhalite combinations on soil chemical properties in black pepper cultivation at the end of a 3-year experiment in the Central Highlands, Vietnam. Soil was sampled before the experiment on February 2016 and at its end, on November 2018.

Treatment	K dose	KCl: polyhalite	pH		OM		P_2O_5		K_2O		S		Ca^{2+}		Mg^{2+}	
			Before	End	Before	End	Before	End	Before	End	Before	End	Before	End	Before	End
			-------*KCl*------		--------*%*-------		--------------------------*mg kg^-1^*--------------------------						---------------*cmol kg^-1^*--------------			
T1 (FP)	270	270:0	4.5	4.6	3.62	3.63	41.5	41.8	102.6	103.2	22.1	21.3	1.92	1.86	1.59	1.52
T2 (C)	0	0:0	4.5	4.5	3.59	3.60	41.8	41.9	102.8	97.2	22.2	21.2	1.90	1.87	1.59	1.54
T3	120	120:0	4.6	4.5	3.60	3.61	41.7	41.8	102.6	101.4	22.4	21.5	1.89	1.80	1.59	1.53
T4	120	60:60	4.5	4.5	3.61	3.63	42.6	43.0	102.9	101.5	21.9	22.4	1.89	1.98	1.61	1.65
T5	240	120:120	4.6	4.6	3.58	3.60	42.2	42.4	102.6	103.3	22.5	23.3	1.90	2.01	1.60	1.71
T6	360	180:180	4.6	4.7	3.50	3.53	42.6	42.9	103.1	105.6	22.2	24.1	1.90	2.05	1.57	1.76

Note: FP – farmers' practice; C – control.

for an hour at 105-110°C to exterminate yeasts, and then dried at 80°C for 8-12 hours, until a constant weight was achieved. The dry leaves were milled to fine powder, which was stored in desiccators until nutrient analyses were carried out. Leaf N content was determined using the Kjeldahl method. To determine leaf total P and K contents, the powder was extracted using sulfuric acid (H_2SO_4) + perchloric acid ($HClO_4$), and then measured using a spectrophotometer and a flame-photometer, respectively. Leaf Ca and Mg were determined using an atomic absorption spectrometer. Leaf S content was determined using the turbidity comparison method (Tabatabai and Bremner, 1970).

Pest examinations (yellow leaf disease and mealybugs) were carried out monthly and the rate of infested plants was determined. Additionally, young fruit were counted on first order branches before the rainy season, and again towards harvest, giving rise to the fruit drop rates. At harvest, the total yield was determined (Mg ha^{-1}). Black pepper quality traits, such as fresh/dry weight ratio, weight and volume of 1,000 corns, and fruit density were determined. Piperine content in fruit was extracted and determined following Raman and Gaikar (2002). The evaluation of the economic efficiency included: total income (calculated according to yield); quality; current produce price in million VND; total cost (including fertilizers); absolute profit; profit and return on investment (ROI) rates (%).

Statistical analyses were carried out between treatments within years, between different years, and over the whole 3-year experiment using ANOVA and IRRISTAT software.

Results

The experiment was conducted on an acidic reddish brown soil (Rhodic Ferralsols). Initial soil pH_{KCl} was 4.5-4.6, and did not change during the 3-year experiment (Table 3). Soil organic matter, as well as available P increased very slightly, with no differences between treatments. Available K, which initially varied from 102.6-103.1 mg K_2O kg^{-1}, decreased during the experiment in treatments T2 (unfertilized control), T3, and T4, but increased in T1 (FP), T5 and T6 (Table 3). Soil available S, Ca, and Mg consistently decreased in treatments T1-T3, and increased during the experiment in treatments T4-T6 proportionally to the polyhalite dose (Table 3).

Nutrient content of diagnostic leaves was extremely sensitive to fertilizer applications. Leaf N and P concentrations before application were 2.9 and 0.03%, respectively, consistently below the recommended range. However, 20 days after fertilizer application, N and P values dramatically increased to 3.3 and 0.17%, respectively, reaching the desired range (data not shown).

Similar response patterns were observed with leaf K concentrations; nevertheless, the differences in K application dose and in the K donor had substantial effects (Fig. 2). In the control, which did not receive any K fertilizer, leaf K concentration remained consistently lower than the minimum threshold of 3.4%, and even exhibited a slight decrease between each pair of measurements during the season. A positive response to K application was visible under K application dose of 120 kg ha^{-1}; however, that dose was inadequate to bring leaf K concentration to the optimum range of 3.4-4.3%. When K dose was doubled, post-application leaf K did reach this range, but further K dose increases did not result in higher leaf K concentrations. Interestingly, pre-application leaf K was always sub-optimal, no matter the K application dose or fertilizer composition (Fig. 2).

Mean pre-application leaf Ca, Mg, and S concentrations were consistently below the minimum thresholds of 1.43, 0.4, and 0.09%, respectively, regardless of the fertilizer treatment. Expectedly, treatments with no polyhalite application displayed no significant response to fertilizer application events, remaining at sub-optimal levels (Fig. 3). In contrast, polyhalite applications brought about significant increases in leaf Ca, Mg, and S, all of which reached the optimum range. Increase in leaf nutrient concentrations were proportional to the polyhalite application dose (Fig. 3).

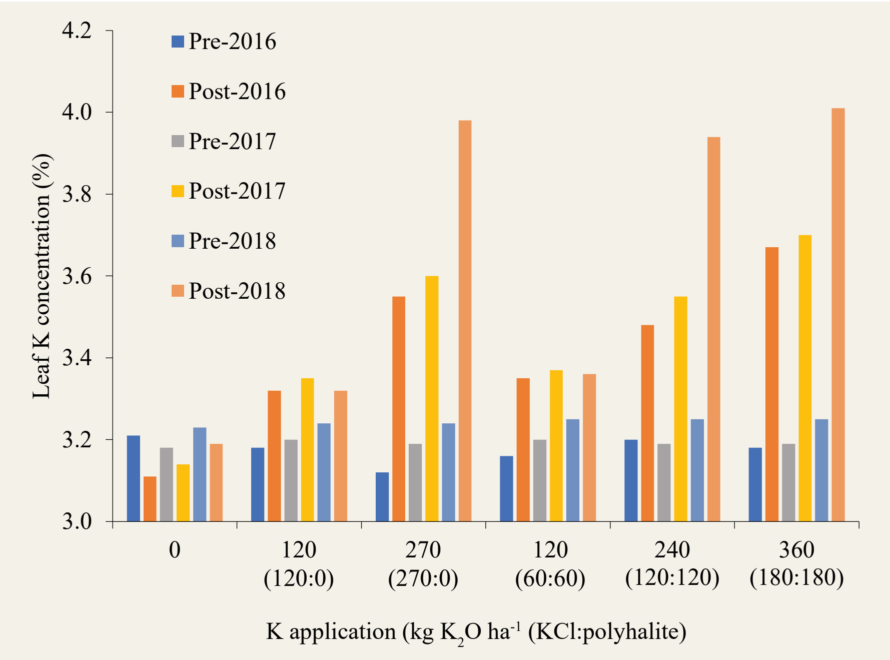

Fig. 2. Effects of KCl and polyhalite combinations on mean black pepper leaf K concentration (percent of dry matter) during a 3-year experiment in the Central Highlands, Vietnam. Leaves were sampled before, and 20 days after each fertilizer application.

Table 4. Effects of KCl and polyhalite combinations on mean rates of yellow-leaf disease and mealybug (*P. citri*) infestation, and fruit drop in a 3-year black pepper experiment in the Central Highlands, Vietnam.

Treatment	K dose	KCl:polyhalite	Rate of infested plants		Fruit drop rate
			Yellow leaf disease	Mealybugs (*P. citri*)	
	----*kg K_2O ha^{-1}*----		------------------------------%	------------------------------	
T1 (FP)	270	270:0	3.9	5.8 ab	20.7 b
T2 (C)	0	0:0	4.2	8.9 b	36.1 d
T3	120	120:0	3.3	7.2 b	26.9 c
T4	120	60:60	3.6	5.3 ab	24.5 c
T5	240	120:120	3.9	4.4 ab	17.7 a
T6	360	180:180	4.4	3.9 a	16.9 a

Note: Different letters indicate significant differences at $P < 0.05$. FP – farmers' practice; C – control.

Fertilizer treatments did not have any significant influence on the infestation rate of black pepper plants to yellow leaf disease (Table 4). Treatments did have significant effects on mealybug infestation rates; the higher the K application rate the lower the infestation rate. Nevertheless, a direct influence of polyhalite on the mealybug infestation rate could not be discerned under the circumstances of the present study (Table 4).

Fertilizer treatments had an obvious effect on young fruit drop rate (Table 4). Fruit drop rate was much greater, 36.1% of the initial fruit number, in the control treatment, which did not include any K fertilizer. Fruit drop rate declined significantly in direct correlation with K application dose. No clear influence on fruit drop was observed for polyhalite application (Table 4).

Plant vegetative growth and development were clearly affected by the fertilizer treatments (Fig. 4). Elongation of first order branches, which was significantly smaller in control plants (17.6 cm), gradually increased with the rising K application dose, reaching a maximum of 24 cm at 240 and 360 kg K_2O ha^{-1}, significantly greater than at 120 kg K_2O ha^{-1}. No advantage was observed for the combined KCl with polyhalite at 120 kg K_2O ha^{-1}; however, branches grew longer under 240 kg K_2O ha^{-1} with polyhalite (120:120 KCl:polyhalite) than under 270 kg K_2O ha^{-1} with KCl as the sole K donor (Fig. 4A).

The number of second order branches also increased with the rising K application dose (Fig. 4B). There were only 2.2 branches per first order branch in control plants, which more than doubled at the higher K dose levels. Under similar, or close, K doses, the combination of KCl and polyhalite tended to result in greater numbers of second order branches than with KCl alone.

Fertilizer treatments had significant effects on all black pepper fruit quality parameters tested (Table 5). Fruit fresh/dry weight ratio, which was very high (4.52) in control fruit, declined consistently with the increasing K application dose up to 240 kg K_2O ha^{-1}, obtaining values around 2.75 that did not change in response to a further rise in K dose. Fruit weight, which was significantly smaller at the control (42.4 g $1{,}000^{-1}$ corns), gradually increased to about 60 g $1{,}000^{-1}$ corns under 240 kg K_2O ha^{-1}, but not further. With regard to fresh/dry weight ratio and fruit weight, the combination of KCl and polyhalite did not show any significant advantage over KCl as the sole K donor (Table 5). Fruit volume, which was much smaller in control plants, increased significantly with each rise in K dose up to a maximum of 240 kg K_2O ha^{-1}. Under similar or close K doses,

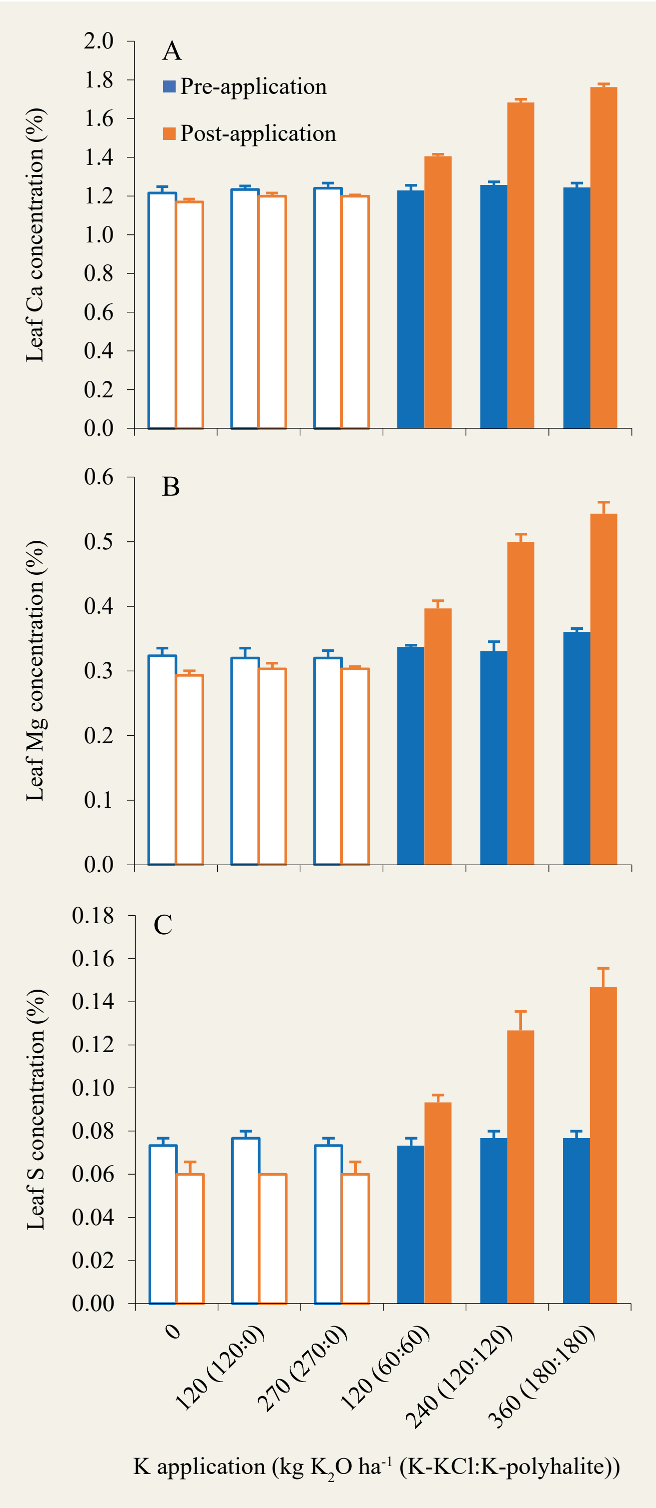

Fig. 3. Effects of KCl and polyhalite combinations on mean black pepper leaf Ca (A), Mg (B), and S (C) concentration (percent of dry matter) in the Central Highlands, Vietnam. Data are means of pre- and of 20-days post fertilizer application throughout the 3-year experiment. Blank bars indicate no polyhalite. Bars indicate SE.

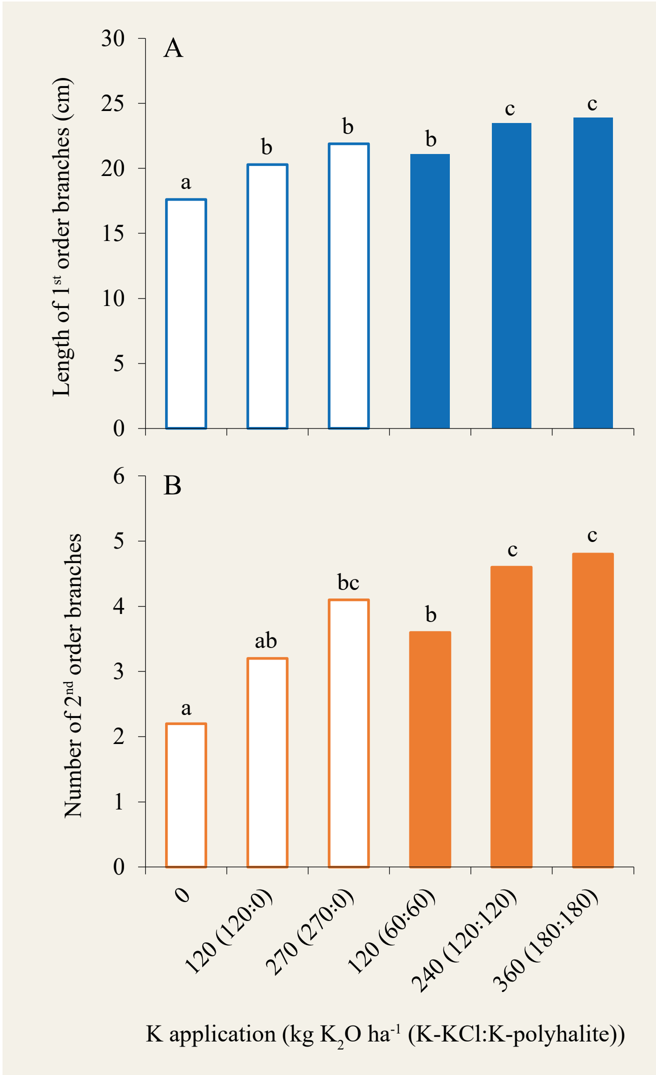

Fig. 4. Effects of KCl and polyhalite combinations on mean length of first order branches and the number of second order branches in a 3-year black pepper experiment carried out in the Central Highlands, Vietnam. Data are means of three seasons. Blank bars indicate no polyhalite. Different letters indicate significant differences at $P < 0.05$.

the combination of KCl with polyhalite resulted in significantly higher fruit volumes (Table 5). Similarly, fruit density gradually increased with the rising K dose but the tendency of polyhalite to enhance fruit density was not statistically significant. Fruit piperine concentration was hardly influenced by the fertilizer treatments, although it was significantly higher at 360 compared to 120 kg K_2O ha^{-1}, and did not show any special influence of polyhalite (Table 5).

Black pepper fruit yield increased significantly in response to the rising K application dose, from 1.67 up to 4.01 Mg ha^{-1}, under zero (control) and 360 kg K_2O ha^{-1}, respectively (Fig. 5A).

Table 5. Effects of KCl and polyhalite combinations on various standard fruit quality parameters of black pepper in a 3-year experiment carried out in the Central Highlands, Vietnam. Data are means of three seasons.

Treatment	K dose	KCl:polyhalite	Fruit fresh/dry ratio	Fruit wt.	Fruit volume	Density	Piperine
	--------*kg K_2O ha^{-1}*--------			*g 1,000^{-1} corns*	*cm^3 1,000^{-1} corns*	*g L^{-1}*	*%*
T1 (FP)	270	270:0	3.09 ab	56.8 bc	102.2 d	491.0 bc	3.99 ab
T2 (C)	0	0:0	4.52 c	42.4 a	73.8 a	437.0 a	3.63 a
T3	120	120:0	3.46 b	51.9 b	91.7 b	449.0 ab	3.75 a
T4	120	60:60	3.22 ab	53.9 bc	95.8 c	475.0 b	3.84 a
T5	240	120:120	2.75 a	59.6 c	107.9 e	530.7 c	3.97 ab
T6	360	180:180	2.68 a	60.4 c	109.0 e	543.7 c	4.10 b

Note: Different letters indicate significant differences at $P < 0.05$; FP – farmers' practice; C – control.

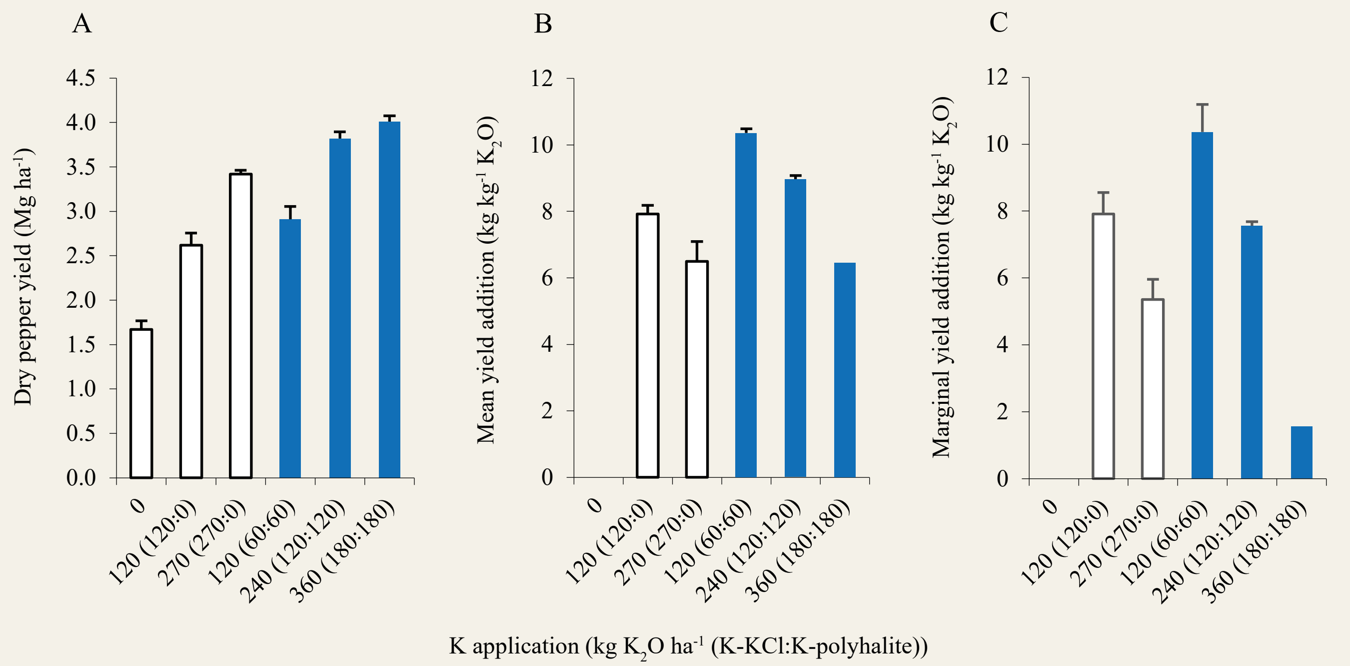

Fig. 5. Effects of KCl and polyhalite combinations on mean black pepper yield (A), mean yield addition (B), and marginal yield addition (C) in the Central Highlands, Vietnam. Data are means of three consecutive years of experiment. Bars indicate SE.

Under similar or close K application levels, the KCl:polyhalite combinations tended to result in higher yields, however, this trend was significant only under doses of 240-270 kg K_2O ha^{-1}. When K dose was raised from 240 to 360 kg K_2O ha^{-1}, yield increase was negligible (Fig. 5A).

The mean agronomic K efficiency (AKE) was highest at the lower dose of 120 kg K_2O ha^{-1}, and significantly declined with each rising step in K dose. Interestingly, mean AKE was significantly higher at the combined KCl and polyhalite applications, compared to KCl application alone: it was 10.4 vs. 7.9 kg kg^{-1} K_2O, and 9.0 vs. 6.5 kg kg^{-1} K_2O, under 120, and 240-270 kg K_2O ha^{-1}, respectively (Fig. 5B). The marginal AKE, which quantifies the contribution of each rising step in K application dose, ranged from 5.4-10.4 kg kg^{-1} K_2O at K doses from 120-240 K_2O ha^{-1}, but it dropped dramatically when K dose was raised to 360 kg K_2O ha^{-1} (Fig. 5C).

Cost analysis of the fertilizer treatments showed that the common farmer (FP) usually invests 142 million VND ha^{-1}, 30 million VND more than without any K fertilization. The use of combined KCl and polyhalite at 240 or 360 kg K_2O ha^{-1} would increase farmers' costs by 10-17 million VND, or 6.9-11.8%, respectively (Table 6). The common farmer's revenue was 297 million VND, twice as much as without any K fertilizer application. While K dose reduction from 270 to 120 kg K_2O ha^{-1} considerably cut farmer's revenue, irrespective of the fertilizer

Table 6. Economic analysis of KCl and polyhalite combinations in black pepper production in the Central Highlands, Vietnam. Calculations were based on average cost and revenue during three consecutive seasons (2016-2018).

Treatment	K dose	KCl: polyhalite	Total cost	Total revenue	Profit	Profit rate	Return on investment
	--kg K_2O ha^{-1}--		*------------VND 10^6 ha^{-1}--------*			*------------%------------*	
T1 (FP)	270	270:0	142.4	297.0	154.5	52.0	108.5
T2 (C)	0	0:0	112.0	145.0	33.0	22.8	29.5
T3	120	120:0	127.9	227.5	99.6	43.8	77.9
T4	120	60:60	134.6	252.7	118.1	46.7	87.7
T5	240	120:120	152.3	331.7	179.4	54.1	117.8
T6	360	180:180	159.2	348.2	189.0	54.3	118.8

Note: FP – farmers' practice; C – control.

composition, a slight decrease in K dose to 240 kg K_2O ha^{-1} of combined KCl and polyhalite increased farmer's revenue by 35 million VND ha^{-1}, or 11.7%. Increasing K dose to 360 kg K_2O ha^{-1} increased the total revenue by about 51 million VND, compared to the common farmer (Table 6). The common farmer's profit (net income) was 154.5 million VND ha^{-1} yr^{-1}, about five-fold higher than without K fertilizer. The reduction of K dose from the farmers' practice to 240 kg K_2O ha^{-1}, equally divided between KCl and polyhalite (T5), gave a profit increase of 25 million VND ha^{-1} yr^{-1}, or 16.1%. A further rise in K dose to 360 kg K_2O ha^{-1} added less than 10 million VND to the farmer's profit (Table 6). The ROI, which was 108% for the common farmer, reached 118% at T5, but did not increase further at T6 (Table 6).

Discussion

Accelerating soil acidity is among the most serious agricultural challenges in humid tropic regions (Pavan, 1983; Zu *et al.*, 2014). In acid soils, the high proton (H^+) concentration in the soil solution rapidly weathers the fine structure of the soil particles, releasing plant-toxic Al^{3+} ions (Coulter, 1969; Ryan *et al.*, 1993). Furthermore, the protons compete with essential nutrient ions such as K^+, Ca^{2+}, and Mg^{2+} on the cation exchange capacity of the soil particle surface, and consequently, nutrient availability for plants is significantly reduced (Fageria and Baligar, 2008; Aloka, 2016). In the present study, however, soil acidity remained very low (pH 4.5-4.7) but quite constant during the 3-year experiment and seemed unaffected by the various fertilizer treatments (Table 3).

Under the precipitation regime typical to the rainy season in the region (Fig. 1B), crop K nutrition might be severely challenged. Potassium is highly soluble and, therefore, very mobile in the soil profile (Zörb *et al.*, 2014). Any amount of K fertilizer applied in a given moment might be leached within a few days, carried by the large water quantities passing through the rhizosphere. Therefore, K application practices in the tropics have been undergoing principal changes, the first of which is splitting the seasonal dose into several consecutive applications, as demonstrated in Table 2. Under this practice, a seasonal dose of 240 kg K_2O ha^{-1} appears sufficient to maintain a stable soil K status over long periods. Higher doses slightly increased soil K availability, whereas smaller doses brought about K degradation (Table 3).

Supplementary polyhalite application gave rise to considerably higher soil Ca, Mg, and S concentrations at the end of the experiment, compared to a clear lessening of these nutrients where no supplementary fertilizer was applied (Table 3). Soil enrichment with Ca is pivotal to the buildup and maintenance of more suitable soil structure and texture, particularly on acid soils (Lie and Hue, 2001; Shainberg *et al.*, 1989).

The approach of splitting K fertilizer dose to several applications, together with K dose increase, had an immediate effect on K uptake by black pepper plants, as indicated by the significant upsurge in leaf K concentration soon after application, which was dose-proportional (Fig. 2). The central role of K nutrition in black pepper crop performance was demonstrated by the enhanced vegetative growth (Fig. 4), the substantial reduction in fruit drop rates (Table 4), the improvement of most fruit quality parameters (Table 5), and the significant yield rise (Fig. 5). Nevertheless, the rapid reduction of leaf K to sub-optimal levels prior to each fertilizer application during the season (Fig. 2) implies a transient impact of K fertilization. Further improvement of K application practices is required to achieve more reasonable nutrient use efficiency and additional enhancements of crop performance.

Beyond soil amendment, the supplementary application of Ca, Mg, and S through polyhalite tended to improve most crop performance parameters. Although not always significant compared to similar K treatments (Fig. 4; Tables 4 and 5), the contribution of polyhalite to each parameter was augmented and clearly manifested in significantly higher yields (Fig. 5). Interestingly, polyhalite application enhanced the significant positive effect of K nutrition, strengthening black pepper plants against mealybug attack (Table 4). This indication is supported by recent findings demonstrating that S fertilization increases glucosinolate production in plant leaves (Bohinc *et al.*, 2012; Santos *et al.*, 2018) and subsequently, the plants' effectiveness against generalist insect pathogens rises significantly (Kos *et al.*, 2012). Fortunately, throughout the present study, the basic rates of yellow pepper leaf disease were very low, leaving no room, however, for any improvement by the fertilizer treatments (Table 4).

Economic analyses unequivocally demonstrate the significance of adequate and timely K application and the benefits of supplementary polyhalite. This analysis also determines the upper fertilizer dose (240 kg K_2O ha^{-1}, 1:1 KCl:polyhalite), above which the profit parameters tend to diminish (Table 6). These results confirm recent results obtained with other crops grown on acid soils in Vietnam (PVFCCo, 2016a; PVFCCo, 2016b; Tam *et al*., 2016), and in Brazil (Vale and Sério, 2017; Bernardi *et al*., 2018) that have demonstrated the agricultural and economic advantages of using polyhalite as a source of K, Ca, Mg, and S.

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The paper "Fertilizer Agronomic Efficiency of KCl and Polyhalite Combinations in Black Pepper Cultivation in Central Highlands, Vietnam (2016-2018)" also appears on the IPI website.

Trial Focus

Photo 1. Organic cabbage field, nine weeks after planting. Photo by FiBL.

Testing Polyhalite as a Tool to Overcome Nutrient Deficiencies in Organic Cabbage Culture

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Abstract

In addition to regular nitrogen (N), phosphorus (P), and potassium (K) requirements, Brassica crops need significant amounts of calcium (Ca), magnesium (Mg), and sulfur (S). The organic farming approach restricts the use of chemical fertilizers, considerably challenging balanced mineral nutrition of cole crops such as cabbage (*Brassica oleracea* var. oleracea). Polyhalite, a natural mineral, is an authorized fertilizer (Polysulphate®) for producers of organic crops in many countries. Consisting of 14% K_2O, 48% SO_3, 6% MgO, and 17% CaO, polyhalite can be considered a useful supplementary fertilizer of four essential nutrients in organic farming. The objectives of the present study were to evaluate the effects of polyhalite application on cabbage performance and compare it with equivalent commercial organic fertilizers. When used on fertile soil, rich with K, Ca, and Mg, the effects of supplementary nutrition on crop performance were absent. Sulfur uptake tended to be greater with polyhalite than in the non-fertilized control (p = 0.071), driven by a combination of increased marketable yield as well as S concentration in

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leaves. Sulfur nutrition appeared key to enhancing cabbage crop performance. Polyhalite displayed a strong tendency to enhance and stabilize yields, compared to alternatives. It tended to be better as a Ca donor compared to foliar Ca application, and was at least equivalent to gypsum. Harbouring four essential nutrients, polyhalite may be a suitable fertilizer, particularly for the organic market. It is advantageous being natural and easy to spread. However, in order to fully demonstrate the advantages of polyhalite, it should also be tested at sites with much weaker soil fertility.

Keywords: Brassica oleracea var. oleracea; calcium; magnesium; potassium; Polysulphate; sulfur.

Introduction

The genus *Brassica* is known for its important agricultural crops, which include species and varieties of cole crops such as broccoli, cauliflower, and cabbage, root crops such as turnip and radish, herb crops like ruccola and choy sum, and oil and spicy seeds such as canola and mustard. World production of cole crops in 2017 was 71 million tonnes (FAO, 2020). Cabbage (*Brassica oleracea* var. oleracea) – a good source of vitamin K, vitamin C and dietary fiber (White and Broadley, 2005) – is consumed in many different ways: pickled, fermented, steamed, stewed, sautéed, braised, or raw.

Cabbage plants perform best when grown in well-drained soil in a location that receives full sun. Different varieties prefer different soil types, ranging from lighter sand to heavier clay, but all prefer fertile ground, with a pH from 6.0-6.8 (White and Broadley, 2005). For optimal growth, there must be adequate levels of nitrogen (N) in the soil, especially during the early head formation stage, and sufficient phosphorus (P) and potassium (K) during the early stages of expansion of the outer leaves (Wien and Wurr, 1997). In addition to NPK, brassica cole crops require significant amounts of calcium (Ca), magnesium (Mg), and sulfur (S). Calcium deficiency impedes cole development, which might induce physiological disorders and post-harvest damage, particularly following exposure to high temperature events during the growing period (Fig. 1).

Figure 1. Example of physiological disorders due to Ca deficiency. Photo by A. Vieweger (FiBL).

Crops in the Brassicaceae have been the focus of intense research based on their human health benefits (Björkman *et al*., 2011; Wang *et al*., 2020). Sulfur-containing secondary metabolites, such as glucosinolates, have been associated with some anti-cancer activities (Sarıkamış, 2009) and with a reduced risk of degenerative diseases, cardiovascular diseases and diabetes (Björkman *et al*., 2011, and references therein). Glucosinolates contents largely depend on S availability and significantly varies with S fertilization (Falk *et al*., 2007; Sung *et al*., 2018). Sulfur-deficient plants are typically small and spindly, characterized by interveinal chlorosis of young developing leaves that may become curved and brittle and eventually may fail to grow (Haneklaus *et al*., 2008). Additionally, N is known to positively interact with S; in many plant species, elevated availability of S promotes N uptake, and vice versa (Abdallah *et al*., 2010; Jamal *et al*., 2010).

The recent growing interest in organic farming has not skipped cabbage production (El-Shabrawy *et al*., 2005; Cordeiro *et al*., 2018; Farjana *et al*., 2019; Lee *et al*., 2019). Providing cabbage crops with an adequate, balanced, and timely supply of mineral nutrition is especially challenging under the tight restrictions of the organic approach, which prohibit chemical fertilizers and negates foliar mineral application. A promising solution may be found in polyhalite, a natural mineral which occurs in sedimentary marine evaporates, and consists of hydrated sulfates 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 14% K_2O, 48% SO_3, 6% MgO, and 17% CaO. The S content of gypsum, a common S and Ca supplement alternative, is only 18.6%. Polyhalite, available under the trade mark Polysulphate® (Cleveland Potash Ltd., UK), is approved as an input for organic farming systems in many countries.

The objectives of the present study were to evaluate the effects of polyhalite application on cabbage performance, comparing it with equivalent commercial fertilizers that have been approved and permitted to be used in the organic farming of high Ca and K demanding crops, such as potato, leek, and cabbage. We hypothesized that polyhalite would be at least as efficient as other commercial products commonly used in the market; polyhalite would bring a better long-term supply of S, K, and Ca; and that it would improve produce shelf life and prevent disorders through enhanced supply of K and Ca.

Materials and methods

The experiment took place at Müller Steimaur farm, Stegacher plot, Bachs (47°30′56.786″N 8°26′53.048″E), Switzerland. The trial was conducted 'on-farm' in order to be as close as possible to organic practices, improving applicability of the results obtained. The trial field had not been fertilized with compost nor lime for the last two seasons before the experiment and, therefore, the soil was expected to poorly deliver K and Ca during the crop cycle. Unfortunately, soil tests revealed quite high K, Ca and Mg availability (Table 1). In fact, organically managed soils with low K levels are very rare in Switzerland due to frequent compost and manure applications.

Fertilizer application took place on calendar week (CW) 22, a week before planting. Feather meal application provided 126 and 21 kg ha^{-1} of N and S, respectively, throughout the field. The experiment included four fertilizer treatments: unfertilized control; PatentKali + $CaCl_2$ sprays; PatentKali + gypsum; and, polyhalite (Polysulphate®). A detailed description of the fertilizer treatments is given in Table 2.

The experiment was designed in four blocks, with treatments randomly distributed within each block. The blocks were aligned along the slope of the field, in order to minimize variation within blocks and maximize the variation between blocks. The field size was 140 m^2 and plot dimensions were 3.6 × 10 m each.

Cabbage seedlings were planted on CW 23. Unfortunately, part of the cabbage trial, situated at the lower end of the field, was flooded due to two successively heavy rain events at the beginning of the season, during the middle of June. Thus, only three blocks were considered for analysis. The cabbage trial further suffered from heavy infestation of flea beetle, which retarded crop growth. Repeated application of organic insecticides minimized the damage, but harvest was delayed by two to three weeks.

All examinations were done in the core plots (4 middle rows, 2.4 m × 6 m), avoiding border effects. Root sampling took place on CW 31, eight weeks after planting. Four plants per plot were gently lifted with their roots using two spades. Roots were cleaned and washed, brought to the laboratory, weighed, oven-dried at 60°C for 48 hours, and weighed again. However, results might have been slightly biased as a result of considerable root loss due to the challenges of lifting plants and roots. Leaf sampling was done on CW 32, 35, and 38; from each plot, 20 leaves were collected, cutting the third fully developed one (counting from the base upwards). At harvest, 10 plants per plot were collected, washed, weighed, dried, and weighed again. All dry samples were sent to the lbu Labor für Boden und Umweltanalytik laboratory in Steffisburg, where they were digested using the Aqua Regia digestion method, followed by mineral analysis using ICP-AES.

Harvest was executed manually on CW 40 (30 Sep 2019, 17 weeks after planting), from each core plot (6 m length, four inner rows). The marketable heads were weighed and counted. All cabbage heads (excluding those sent for mineral analysis) were stored at 1.5°C for 64 days, after which a visual scoring for physiological disorders (Fig. 1) was carried out.

Statistical analysis was carried out using R (R version 3.6.1 (2019-07-05)). To check for normal and homogeneous distribution, Levene's and Shapiro's tests were carried out on the residuals of the results. Where the residuals of the results were distributed normally and homogeneously, a two-factorial ANOVA was run, estimating the effect of block and treatment. If ANOVA did not show any treatment effects, the Welch two sample T-test was carried out to test the polyhalite treatment against the control. If the distribution of the dataset did not allow for an ANOVA, the non-parametric test, Kruskal-Wallis, was used.

Table 1. Soil available and reserve nutrient status before the experiment.

Nutrient	Available (H_2O10)	Reserve (AAE10)
	---mg kg^{-1} soil---	
Nitrate	16.8	-
Phosphorus	5.6	130.2
Potassium	40.4	227.3
Calcium	55.3	2387
Magnesium	7.9	157.5

Table 2. A detailed description of the fertilizer treatments executed in the organic cabbage experiment in Switzerland.

Treatment	Fertilizers	Dose	Nutrient input			
			K_2O	Mg	Ca	S
		kg ha^{-1}	---*kg ha^{-1}*---			
Control	-	-	-	-	-	-
PatentKali + $CaCl_2$	PatentKali[a]	667	200	40	-	113
	$CaCl_2$	5[b]				
PatentKali + gypsum[c]	PatentKali	667	200	40	-	113
	Gypsum	900		17	174	131
Polyhalite	Polysulphate®	1429	200	51	174	274

Note: [a] PatentKali composition: K_2O (30%); Mg (6%); S (17%). [b] Foliar application of $CaCl_2$ took place 3 times, at CW 32, 35, and 38. [c] Gypsum composition: Mg (2%); Ca (20%); S (15%).

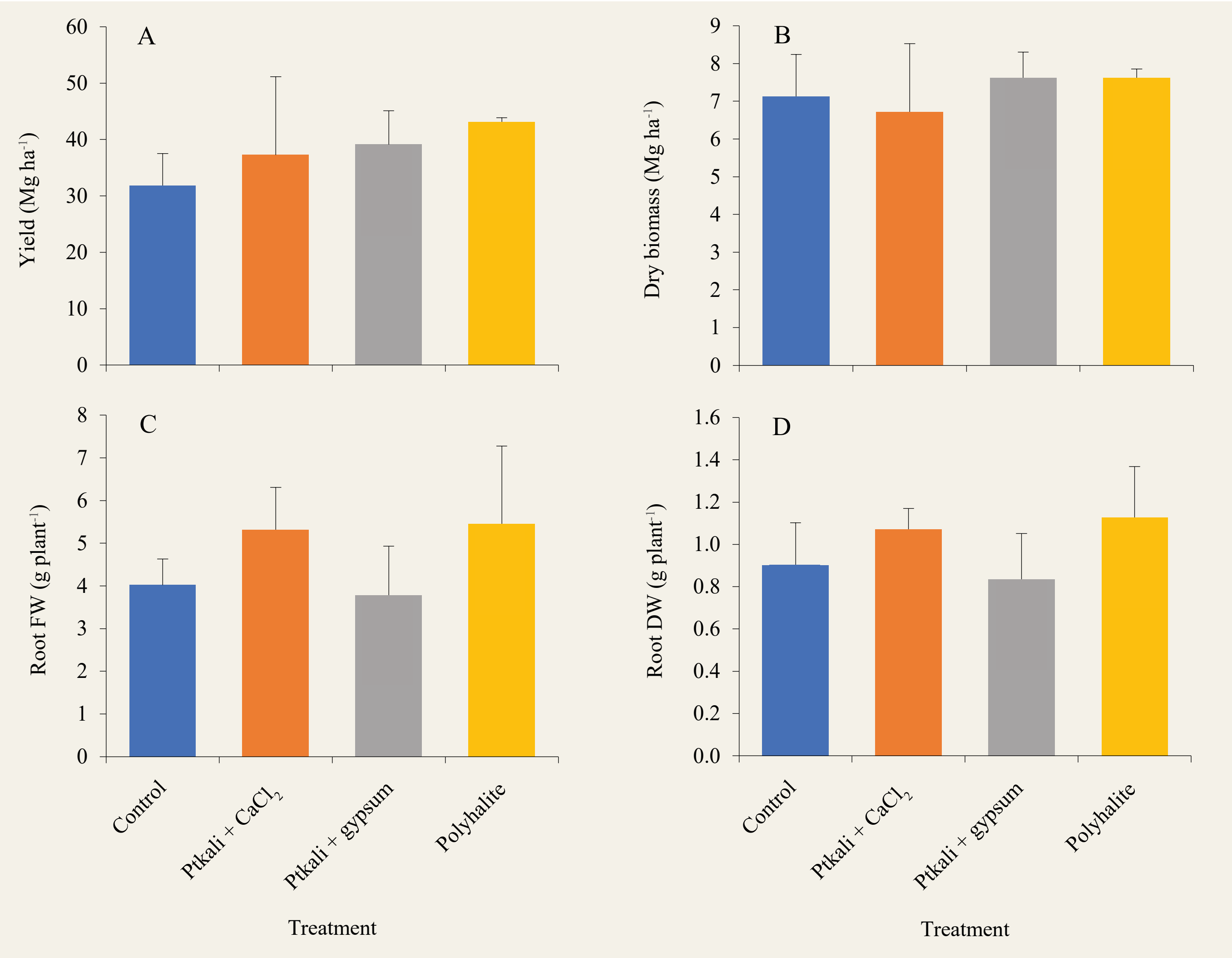

Fig. 2. Effects of the fertilizer treatments on cabbage commercial yield (A), total dry biomass (B), root fresh weight (C), and root dry weight (D). Bars indicate standard deviation.

Results and discussion

Marketable cabbage yields in the organic sector usually range from 30-80 Mg ha^{-1}, and the yields obtained in the present study were at the lower part of this range (Fig. 2A). Yield was highest at the polyhalite application treatment ($p = 0.071$), 35% more than the control, but was not significantly higher compared to the alternatives, PatentKali with $CaCl_2$ or with gypsum, which both failed to display significant effects on yield (Fig. 2). Nevertheless, there was a clear tendency of yield enhancement by the fertilizer treatments, which might have been statistically interrupted by the loss of one block due to prolonged flooding. The polyhalite plants exhibited the greatest stability among treatments, as indicated by the smaller standard deviations of yields and total dry biomass (Fig. 2A, 2B).

It was postulated that more balanced crop nutrition, enriching the soil with additional sources of Ca, Mg or S, and with prolonged K availability, would enhance root biomass development. Nevertheless, no significant effects on fresh or dry root biomass could be observed at the ninth week of crop development (Fig. 2C, 2D). Root biomass tended to be greater under the polyhalite and the PatentKali + $CaCl_2$ treatment compared to the two other treatments, but the general variability level did not allow any concrete conclusions to be made.

In general, K, Ca, and Mg leaf concentrations were higher at the beginning of the season, after which they gradually declined until harvest (Fig. 3A, 3B, 3C). The gradual decrease in leaf nutrient concentration is attributed to the principal difference between two phases of leaf growth: cell division, which is typified by dry matter accumulation, and cell expansion, during which most of the cell components are diluted. No differences were observed between treatments, which might indicate that these nutrients

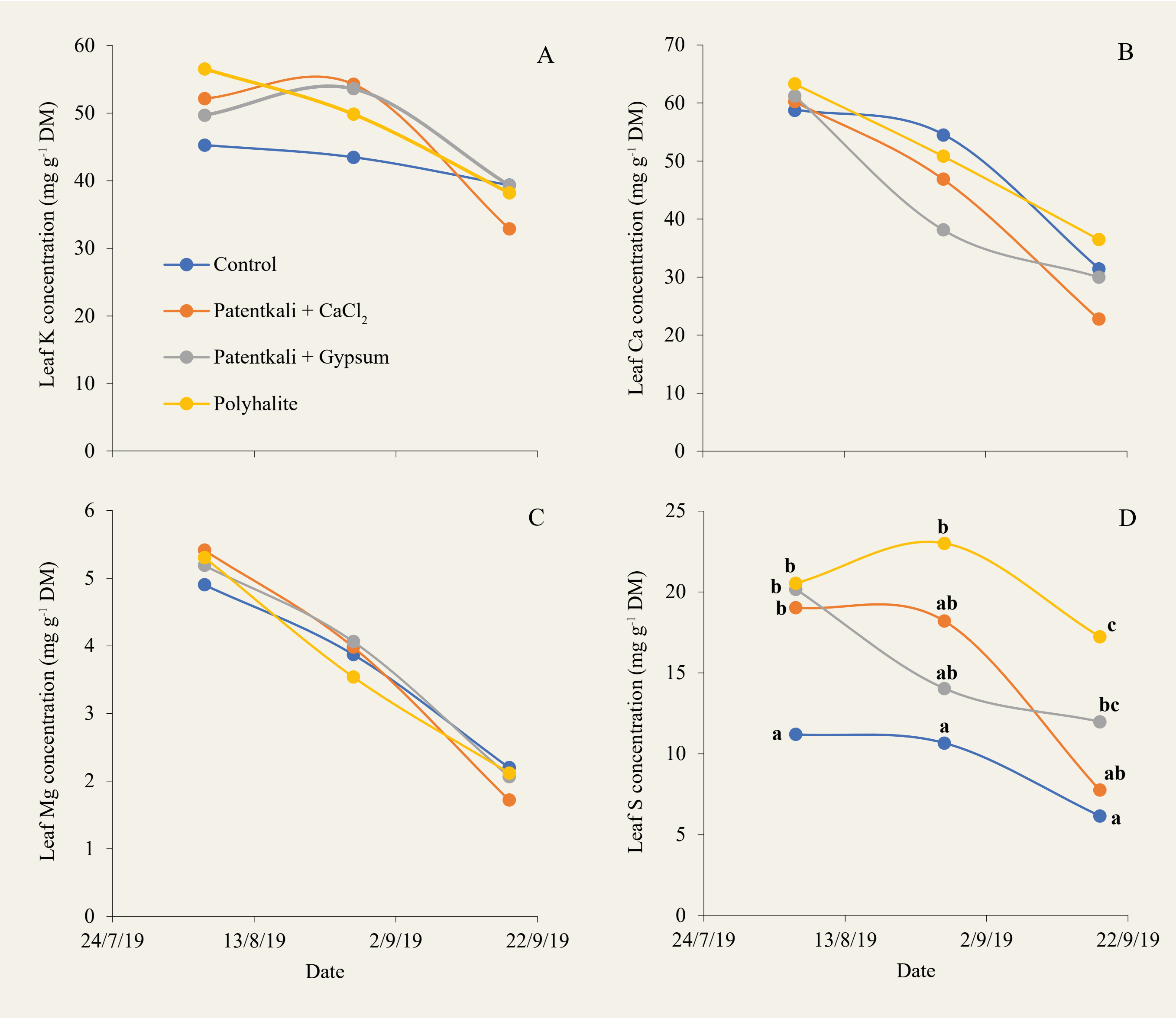

Fig. 3. Patterns of leaf K (A), Ca (B), Mg (C), and S (D) concentration changes during cabbage growth and development, as affected by fertilizer treatments. Different letters indicate significant differences between treatments within a date, at $P < 0.05$.

were not at risk of deficiency. Indeed, K, Ca, and Mg contents in the natural soil of the experiment site were quite high (Table 1). Alternatively, these results may indicate other factors that limit plant growth and yield and, consequently, reduce other nutrient requirements. Nitrogen, for instance, was applied at a seemingly adequate dose through feather meal. However, N is generally the most difficult nutrient to manage for organic crop production. While various organic N donor fertilizers can contribute substantial N for crops, it is challenging to synchronize N release from these materials with the plant demand. Careful management of organic N sources is required to meet crop requirements, while avoiding undesirable N losses to the environment (Mikkelsen and Hartz, 2008; Wild *et al.*, 2011; Möller, 2018). Unfortunately, crop N status was beyond the frame of the present study, so assumptions concerning N as a limiting factor require further investigation.

The pattern of leaf S concentration during the season was substantially different from those of the other nutrients (Fig. 3D). The gradual reduction was much less pronounced, and significant differences occurred between treatments. Cabbage is well-known as an S-demanding crop (Satisha *et al.*, 2016; Wang *et al.*, 2020); accordingly, leaf S concentration displayed a linear positive response to rising S dose. Thus, polyhalite application

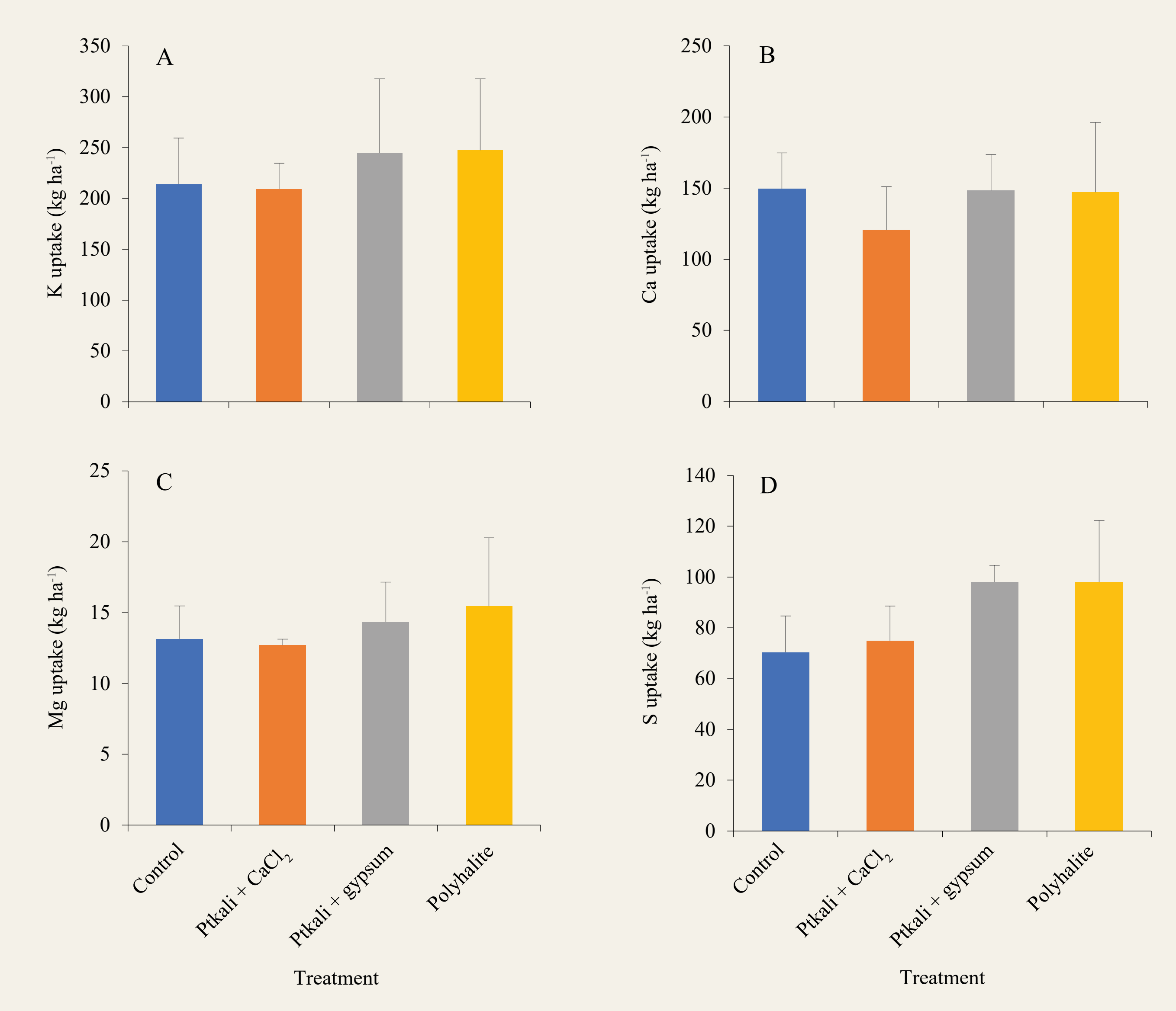

Fig. 4. Effects of fertilizer treatments on the total K (A), Ca (B), Mg (C), and S (D) uptake by organic cabbage plants. Bars indicate standard deviation.

brought about the highest leaf S concentration throughout most of the growing season, followed by PatentKali + gypsum, and PatentKali + $CaCl_2$ spray. Sulfur seems key to enhanced cabbage crop performance in the present study. Under N shortage, the synergy between N and S may improve N uptake and metabolism, and vice versa (Abdallah *et al.*, 2010; Jamal *et al.*, 2010). Alleviated S availability tended to increase the uptake of the other nutrients (Fig. 4), despite no significant differences occurring in crop biomass (Fig. 2B). Interestingly, $CaCl_2$ spray had no significant effect on leaf Ca concentration or Ca uptake. The slight advantage of polyhalite may well be an outcome of the higher S dose in this treatment; presumably, increasing the gypsum dose of the PatentKali + gypsum treatment to match the S level with the polyhalite treatment could have had a similar response.

No symptoms of S deficiency were observed. Sulfur deficiency is likely to occur in soils that have low levels of organic matter, light-textured sandy soils that have been leached by heavy rainfall or excessive irrigation, soils exhausted by intensive cropping, and soils derived from parent material that is inherently low in S (Jordan and Reisenauer, 1957). None of these conditions took place in the present study. Furthermore, soil tests carried out soon before planting indicate a relatively fertile soil, with adequate K, Ca, and Mg. Under such conditions, any significant advantages of supplementary fertilizers would be very difficult to show. This was also the case with the produce post-harvest quality parameters examined. No physiological disorders indicating a Ca deficiency were observed, on either the unfertilized control treatment or on the fertilized treatments, in spite of two extraordinary heat events that occurred at the end of June and end of July 2019.

Conclusions

Using a fertile soil, rich with K, Ca, and Mg, the absent effects of supplementary nutrition on crop performance is expected. Sulfur uptake tended to be greater with polyhalite than in the non-fertilized control ($p = 0.071$), reflected by a corresponding increase in marketable yield as well as higher S concentration in leaves. Sulfur nutrition appeared key to enhancing cabbage crop performance. Polyhalite displayed a strong tendency to enhance and stabilize yields, compared to the alternative fertilizers. It tended to be better as a Ca donor compared to foliar application of $CaCl_2$, and was at least equivalent to gypsum. Harbouring four essential nutrients, the natural mineral polyhalite may be a suitable fertilizer, particularly for the organic market, as it is natural and easy to spread. In order to demonstrate polyhalite's advantages of enhancing crop performance and post-harvest produce quality, sites with much weaker soil nutrient status should be employed, providing enough room for statistical differences.

Acknowledgements

We would like to thank the farmer for allowing us to conduct this on-farm trial on his land. This study was funded by the International Potash Institute.

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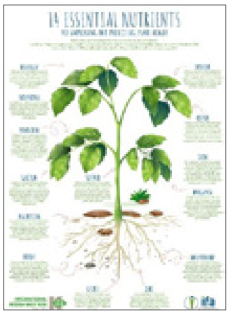
The paper "Testing Polyhalite as a Tool to Overcome Nutrient Deficiencies in Organic Cabbage Culture" also appears on the IPI website.

Photo 2. Photo by iStock.

Publications



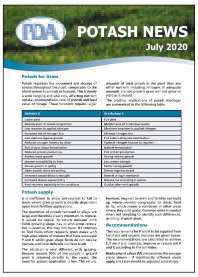
14 Essential Nutrients for Improving and Protecting Plant Health

A prerequisite for good crop yield is good plant health. However, capturing the complexity and the contribution of good nutrition for good health can seem a challenge. Nevertheless, explaining the range and function of essential plant nutrients is an important step towards understanding why and how to supply K and other key nutrients to crops.

To coincide with the International Year of Plant Health 2020, the IFA (International Fertilizer Association) has produced this clear and colorful infographic, 14 Essential Nutrients for Improving and Protecting Plant Health.

The poster is available to download from the IPI website. It is a very useful tool to explain how each of all fourteen essential plant nutrients benefit plant health in addition to improving yields.

Publications by the PDA



Potash for Grass

POTASH News, June 2020

Potash regulates the movement and storage of solutes throughout the plant, comparable to the blood system in animals or humans. This is clearly a wide ranging and vital role, affecting nutrient uptake, photosynthesis, rate of growth and feed value of forage. These functions require larger amounts of total potash in the plant than any other nutrient including nitrogen. If adequate amounts are not present, grass will not grow or yield as it should. Read more on the PDA website.

Potash Development Association (PDA) is an independent organisation formed in 1984 to provide technical information and advice in the UK on soil fertility, plant nutrition and fertilizer use with particular emphasis on potash. See also www.pda.org.uk.

Scientific Abstracts

K in the Literature

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Links Between Potassium of Soil Aggregates and pH Levels in Acidic Soils under Long-Term Fertilization Regimes

Liu Kai-lou, Han Tian-fu, Huang Jing, Asad Shah, Li Da-ming, Yu Xi-chu, Huang Qing-hai, Ye Hui-cai, Hu Hui-wen, Hu Zhi-hu, and Zhang Hui-min. 2020. Soil and Tillage Research 197:104480. https://doi.org/10.1016/j.still.2019.104480.

Abstract: Soil pH adjusted by the application of lime can improve soil potassium (K) availability to meet crop K uptake in acidic red soil. However, the response of aggregated K to pH changes is poorly understood. Objectives of this study was to quantify the relationships between aggregate K content and pH levels in soil with different fertilization patterns from a long-term field experiment Then, an incubation experiment of pH adjustment was conducted over 90 days at different pH levels where HCl and $Ca(OH)_2$ were added to nitrogen and phosphorus fertilizers (NP); NP and K fertilizers (NPK); and NPK with manure (NPKM) soils. Our results showed that double linear equations can fit the relationships between aggregate exchangeable K (EK) with pH levels. However, the slopes and other parameters of fitted equations varied among different fertilization soils. Linear equations indicated that increasing pH value could improve non-exchangeable K (NEK) contents of soil aggregates, especially in NP soil with lower initial pH. However, the proportions of EK and NEK stocks in soil aggregates were significantly changed by soil pH adjustment only in NPKM soil. Additionally, redundancy analysis and partial least squares path mode also suggested that soil pH only affected the NEK contents in soil aggregates, although fertilization had direct effects on the EK and NEK contents in soil aggregates. Therefore, this study demonstrated that the aggregate K distribution of adjusting pH varied among soils with different fertilization regimes, then, improved soil pH could maintain high EK and NEK content of soil aggregates in red soil.

Influence of Potassium Fertilization on Certain Homopterous Insects Infestation and Relationship with Chemical Constituents and Cell Thickness of Maize Plants

Ola I.M. Hegab, and M.A.M. Hagab. 2020. Journal of Plant Protection and Pathology 11(1):19-23. DOI: 10.21608/JPPP.2020.68917.

Abstract: The present work was conducted during 2017 and 2018 seasons in Diarb-Nigm district at Sharhia Governorate,

Egypt to study the effect of four rates of potassium fertilization (0, 24 , 48 , 72 kg K_2O / fed.) on maize infestation with certain piercing-sucking insects such as aphids, *Rhopalosiphum maidis* and *R. padi*, leafhoppers and planthoppers , *Empoasca decipiens*, *E.decedens*, *Balclutha hortensis*, *Cicadulina chinai*, *C. bipunctella* , *Sogatella vibix* and *S. furicefera* and relationship with the chemical components and epidermal cells thickness of maize plant leaves. The results showed significant differences in the population density of the aforementioned insects of the tested rates of potassium fertilization, whereas, the highest mean numbers of their insects were recorded at the rate of F1(zero kg K_2O /fed.), while the least mean numbers of the aforementioned insects occurred at the rate of F4 (72 kg K_2O / fed.). In addition, the results of some chemical analyses revealed that a positive relationship between total protein, carbohydrates contents, k values and the epidermal cell thickness and aforementioned rates of potassium fertilization. While, a reverse relationship was recorded between pH values and potassium fertilization. Also, the fertilization influenced significantly on six amino acids; aspartic, glutamic, glycine, alanine, isoleucine and leucine, which affected the attractive of these insect species, which may explain the decreasing in numbers of the insects by increasing the rates of fertilization. According to these results, the potassium fertilization should be recommended as effective factor in the integrated pests control program.

Effects of Long-Term K Fertilization on Soil Available Potassium in East China

Xiao-Dong Song, Feng Liu, Hua-Yong Wua, Qi Cao, Chen Zhong, Jin-Ling Yang, De-Cheng Li, Yu-Guo Zhao, and Gan-Lin Zhang. 2020. CATENA 188:104412. DOI: https://doi.org/10.1016/j.catena.2019.104412.

Abstract: Over the last three decades, both the crop yields and population in China have steadily increased due to continued agricultural investments. K fertilizer and the return of straw have played vital roles in the yield and quality of crops. However, the effects of long-term fertilization on soil K to a soil depth of 1 m have received little focus, and unbalanced K fertilization frequently occurs because local farmers lack sufficient information about soil K. In this study, the spatial distribution of available potassium (AK) in East China was predicted using kriging with external drift (KED) and random forest (RF) techniques. A comparison of the trends in the 1980s and 2010s showed that the mean AK values in East China generally increased. The mean AK values at soil depths of 0-20 cm, 20-50 cm and 50-100 cm increased by 17%, 12% and 23%, respectively, and the AK stocks increased from 0.14 Pg to 0.17 Pg. However, the spatial patterns of AK at the regional scale suggested that approximately 68.12% of the study area lacked AK. AK deficiency was found in Northeast and South China. The ratios of AK concentrations in the subsoil to those in the topsoil suggested that less K was stored in the subsoil than in the topsoil. Relatively more AK was found in the subsoil (20-50 cm) of paddy fields in the middle of East China than in the other areas. The maps produced in this study could be used to support the decisions of regional agriculture management, and our study demonstrates that effective K fertilizer application in East China should be taken into consideration.

Genome-Wide Association Study and QTL Meta-Analysis Identified Novel Genomic Loci Controlling Potassium Use Efficiency and Agronomic Traits in Bread Wheat

Luqman Bin Safdar, Tayyaba Andleeb, Sadia Latif, Muhammad Jawad Umer, Minqiang Tang, Xiang Li, Shengyi Liu, and Umar Masood Quraishi. 2020. Front. Plant Sci. DOI: https://doi.org/10.3389/fpls.2020.00070.

Abstract: Potassium use efficiency, a complex trait, directly impacts the yield potential of crop plants. Low potassium efficiency leads to a high use of fertilizers, which is not only farmer unfriendly but also deteriorates the environment. Genome-wide association studies (GWAS) are widely used to dissect complex traits. However, most studies use single-locus one-dimensional GWAS models which do not provide true information about complex traits that are controlled by multiple loci. Here, both single-locus GWAS (MLM) and multi-locus GWAS (pLARmEB, FASTmrMLM, mrMLM, FASTmrEMMA) models were used with genotyping from 90 K Infinium SNP array and phenotype derived from four normal and potassium-stress environments, which identified 534 significant marker-trait associations (MTA) for agronomic and potassium related traits: pLARmEB = 279, FASTmrMLM = 213, mrMLM = 35, MLM = 6, FASTmrEMMA = 1. Further screening of these MTA led to the detection of eleven stable loci: *q1A*, *q1D*, *q2B-1*, *q2B-2*, *q2D*, *q4D*, *q5B-1*, *q5B-2*, *q5B-3*, *q6D*, and *q7A*. Moreover, Meta-QTL (MQTL) analysis of four independent QTL studies for potassium deficiency in bread wheat located 16 MQTL on 13 chromosomes. One locus identified in this study (*q5B-1*) colocalized with an MQTL (*MQTL_11*), while the other ten loci were novel associations. Gene ontology of these loci identified 20 putative candidate genes encoding functional proteins involved in key pathways related to stress tolerance, sugar metabolism, and nutrient transport. These findings provide potential targets for breeding potassium stress resistant wheat cultivars and advocate the advantages of multi-locus GWAS models for studying complex traits.

Diagnosis of Nitrogen Nutrition in Rice Leaves Influenced by Potassium Levels

Wenfeng Hou, Merle Tränkner, Jianwei Lu, Jinyao Yan, Siyuan Huang, Tao Ren, Rihuan Cong, and Xiaokun Li . 2020. Front. Plant Sci. DOI: https://doi.org/10.3389/fpls.2020.00165.

Abstract: Evaluation of nitrogen (N) status by leaf color is a kind of classic nutritional diagnostic method. However, the color of leaves is influenced not only by N, but also by other nutrients such as potassium (K). Two-year field trials with a factorial combination of N and K were conducted to investigate the effects of different N and K rates on soil plant analysis development (SPAD) readings and leaf N, K, magnesium (Mg), and chlorophyll concentrations. Visual inspections in leaf greenness revealed darker green leaves with increasing N rates, while paler green leaves with increasing K rates. Data showed that SPAD readings, chlorophyll, N and Mg concentrations, and the chloroplast area increased significantly with raising N rates, while declined sharply with the increase in K rates due to the antagonistic relationships between K^+ and NH_4^+ as well as Mg^{2+}. It was also probable that the increase in K promoted the growth of leaves and diluted their N and Mg concentrations. The paler leaf appearance resulting from the application of K may overestimate the actual demand for N in the diagnosis of rice N status. The strong antagonistic relationships between K^+, NH_4^+, and Mg^{2+} should be considered in rice production and fertilization.

Growth Response of Cassava to Deficit Irrigation and Potassium Fertigation during the Early Growth Phase

Daniel O. Wasonga, Jouko Kleemola, Laura Alakukku, and Pirjo S.A. Mäkelä. 2020. Agronomy 10(3):321. DOI: https://doi.org/10.3390/agronomy10030321.

Abstract: Cassava (*Manihot esculenta Crantz*) experiences intermittent water deficit and suffers from potassium (K) deficiency that seriously constrains its yield in the tropics. Currently, the interaction effect between deficit irrigation and K fertigation on growth and yield of cassava is unknown, especially during the early growth phase. Therefore, pot experiments were conducted under controlled greenhouse conditions using cassava cuttings. Treatments initiated at 30 days after planting included three irrigation doses (30%, 60%, 100% pot capacity) and five K (0.01, 1, 4, 16, and 32 mM) concentrations. The plants were harvested 90 days after planting. Decreasing irrigation dose to 30% together with 16 mM K lowered the leaf water potential by 69%, leaf osmotic potential by 41%, photosynthesis by 35%, stomatal conductance by 41%, water usage by 50%, leaf area by 17%, and whole-plant dry mass by 41%, compared with full-irrigated plants. Lowering the K concentration below 16 mM reduced the values further. Notably, growth and yield were decreased the least compared with optimal, when irrigation dose was decreased to 60% together with 16 mM K. The results demonstrate that deficit irrigation strategies could be utilized to develop management practices to improve cassava productivity by means of K fertigation under low moisture conditions.

Chloride and Amino Acids are Associated with K^+-alleviated Drought Stress in Tea (*Camellia sinesis*)

Xianchen Zhang, Honghong Wu, Jingguang Chen, Linmu Chen, and Xiaochun Wan. 2020. Functional Plant Biology 47(5):398-408. DOI: https://doi.org/10.1071/FP19221.

Abstract: Drought is one of the main limiting factors affecting tea plant yield and quality. Previous studies have reported that K^+ (potassium) application significantly alleviated drought-induced damage in tea plants. However, the intrinsic mechanisms underlying K^+-alleviated drought stress are still obscure. In our study, two contrasting varieties, Taicha12 (drought tolerant) and Fuyun6 (drought sensitive), were used to investigate the intrinsic mechanisms behind K^+-alleviated drought stress in tea plants. In the present study, we compared with the case of tea plants under drought: higher water and chlorophyll contents were found in drought-stressed tea plants with an external K^+ supply, confirming the role of externally supplied K^+ in mitigating drought stress. We also found that an adequate K^+ supply promoted Cl^- accumulation in the mesophyll of Taicha12 (drought tolerant) over that of in Fuyun6 (drought sensitive). Moreover, Gly, Cys, Lys and Arg were not detected in Fuyun6 under 'Drought' or 'Drought + K^+' conditions. Results showed that an exogenous supply of Arg and Val significantly alleviated drought-induced damage in Fuyun6, suggesting their role in K^+-alleviated drought stress in tea plants. Collectively, our results show that chloride and amino acids are important components associated with K^+-alleviated drought stress in tea plants.

Mitigating Nitrate Accumulation in Potato Tubers Under Optimum Nitrogen Fertilization with K-Humate and Calcium Chloride

Ahmed I. Abdo, Ahmed S. Elrys, Mohamed K. Abdel-Fattah, El-Sayed M. Desoky, Li Huitong, and Linquan Wang. 2020. Journal of Cleaner Production 259:121108. DOI: https://doi.org/10.1016/j.jclepro.2020.121108.

Abstract: Producing safe food under excessive fertilization strategies is a serious issue; thus, this study introduced a novel approach combining K-humate and calcium chloride under nitrogen (N) fertilization for maximizing potato (*Solanum tuberosum* L.) yield and improving quality by reducing nitrate (NO_3^-) accumulation in tubers. A two-season field experiment during the 2017 and 2018 growing seasons was conducted in a farm field with a sandy loam texture. The experiment followed a modified Box-Behnken design with 13 treatments, which combined ammonium sulfate (N-AS), K-humate (KH) and calcium chloride (CC) alternately using their maximum rates (370 kg N ha^{-1} for Z, 8.0 kg kH ha^{-1} for X, and 1.20 kg Ca ha^{-1} for Y) and subdividing. A three-level, three-variable central composite model (TCCM), integrated with regression modeling, was interpreted to illustrate the combined effects of AS, KH and CC on all the variables under

investigation. The results indicated a remarkable increment in tuber yield and nitrate accumulation with the N-AS inputs, while KH and CC had minor impacts; however, the later decreased the nitrate concentration to some extent. The maximum soil N content (25 mg kg^{-1}), tuber N content (18 g kg^{-1}) and nitrate accumulation (450.5 mg kg^{-1}), which exceeds the acceptable limit (200 mg kg^{-1}) for human consumption, was recorded under the application of 370 kg N ha^{-1} as the ammonium sulfate fertilizer with the conventional farming practices used. The response surface combined with regression models showed that the N rate (246 kg N ha^{-1}), when combined with KH (1.33 kg ha^{-1}) and CC (0.2 kg ha^{-1}) representing T8 (66.6% N-AS + 16.6% KH + 16.6% CC), could reduce the NO_3^- content in tubers to an acceptable level (170 mg kg^{-1}) and at the same time resulted in the highest tuber yield (58.8 Mg ha^{-1}). The regression models accurately predicted the changes in nitrate accumulation in tubers, soil N and plant attributes under different N rates as related to KH and CC. Generally, when using these models under similar soil conditions worldwide, it can be concluded that using 222, 2.5, and 0.2 kg ha^{-1} of ammonium sulfate, potassium humate, and calcium chloride, respectively, would achieve a proximal yield (56 Mg ha^{-1}) while simultaneously decreasing nitrate accumulation in tubers to a very safe level (160 mg kg^{-1}).

Overexpression of V-type H^+ Pyrophosphatase Gene *EdVP1* from *Elymus dahuricus* Increases Yield and Potassium Uptake of Transgenic Wheat Under Low Potassium Conditions

Zhou, Y., Y. Li, X. Qi, R. Liu, J. Dong. W. Jing, M. Guo, Q. Si, Z. Xu, L. Li, C. Wang, X. Cheng, Y. Ma, and M. Chen. 2020. Nature Sci. Rep. 10:5020. DOI: https://doi.org/10.1038/s41598-020-62052-5.

Abstract: Lack of potassium in soil limits crop yield. Increasing yield and conserving potassium ore requires improving K use efficiency (KUE). Many genes influence KUE in plants, but it is not clear how these genes function in the field. We identified the V-type H^+-pyrophosphatase gene EdVP1 from *Elymus dahurica*. Gene expression analysis showed that EdVP1 was induced by low potassium stress. Protein subcellular localization analysis demonstrated that EdVP1 localized on the plasma membrane. We overexpressed EdVP1 in two wheat varieties and conducted K tolerance experiments across years. Yield per plant, grain number per spike, plant height, and K uptake of four transgenic wheat lines increased significantly compared with WT; results from two consecutive years showed that EdVP1 significantly increased yield and KUE of transgenic wheat. Pot experiments showed that transgenic plants had significantly longer shoots and roots, and higher K accumulation in shoots and roots and H^+-PPase activity in shoots than WT under low K. A fluidity assay of potassium ion in EdVP1 transgenic plant roots showed that potassium ion influx and H^+ outflow in transgenic plants were higher than WT. Overexpressing EdVP1 significantly improved yield and KUE of transgenic wheat and was related to higher K uptake capacity in root.

Effect of Rice Residue Retention and Foliar Application of K on Water Productivity and Profitability of Wheat in North West India

Meena, R.P., K. Venkatesh, R. Khobra, S.C. Tripathi, K. Prajapat, R.K. Sharma, and G.P. Singh. 2020. Agronomy 10(3):434. DOI: https://doi.org/10.3390/agronomy10030434.

Abstract: The rice-wheat cropping system being the backbone of food security in South-Asia has resulted in soil health deterioration, declining water table, and air pollution affecting livability index of the region. The effect of rice residue retention (RRR), irrigation levels and foliar application of K on wheat grain yield (GY), water use efficiency (WUE) and profitability was tested over three years. RRR increased wheat GY (5,224 kg ha^{-1}), above-ground biomass (AGBM = 11.9 t ha^{-1}), tillers per square meter (TPM = 469) and grains per meter square (GrPMS = 13,917) significantly. Relative water content (RWC = 93.8) and WUE (2.45 k gm^{-3}) were also increased significantly by RRR. Consequently, profitability (Net return = 624.4 $ and Benefit to cost (B:C) ratio) was enhanced. Foliar application of K enhanced GY (5,151 kg ha^{-1}), AGBM (12 t ha^{-1}), RWC (94.1), SPAD (52.2), WUE (2.40 kg m^{-3}), net returns (625.2 $) and BC ratio (1.62) significantly. RRR increased GY (15.66%) and WUE (17.39%) with additional revenue of 151 $ with only one irrigation at the CRI stage (ICS). RRR adopted over 10% of the area can earn 187 million-US$ annually. RRR if adopted over existing practice on a large area would reduce environmental degradation with an enhanced income to small and marginal farmers.

Normalized Difference Vegetation Index, N-NO_3^- and K^+ in Stem Sap of Potato Plants (Group Andigenum) as Affected by Fertilization

Gómez, M., A. Barragán, S. Magnitskiy, and L. Rodríguez. 2019. Experimental Agriculture 55(6):945-955. DOI: 10.1017/S001447971900005X.

Abstract: Remote sensors permit forecasting the nutrient status and yields in crops of economic importance in Colombia. The objective of this study was to determine the relationships between normalized difference vegetation index (NDVI) and yield as well as concentrations of N-NO_3^- and K^+ in stem sap of potato cultivars Diacol Capiro and Pastusa Suprema (*Solanum tuberosum* L., Group Andigenum) in relation to different fertilizer rates. Increasing doses (0, 1,450, 1,900 and 2,375 kg ha^{-1}) of macro- and micronutrient fertilizers were applied to determine NDVI behavior at 55, 75, 100, 125 and 150 days after planting. For Capiro, significant differences in NDVI readings (0.84-0.88) were found between phenological stages. In both cultivars,

NDVI correlated positively with yield and K^+ concentrations in stem sap during tuber filling and maturation, while in Capiro no correlation was established between NDVI values and N-NO_3^- concentrations in stem sap. The NDVI readings could be used to forecast productivity and K status in potato Group Andigenum.

Tuber Yield and Allocation of Nutrients and Carbohydrates in Potato Plants as Affected by Limestone Type and Magnesium Supply

Natália S. Assunção, Nathalia P. Ribeiro, Rudieli M. da Silva, Rogério P. Soratto, and Adalton M. Fernandes. 2020. J. Plant Nutr. 43(1):51-63. DOI: 10.1080/01904167.2019.1659345.

Abstract: Magnesium (Mg) is a nutrient that affects the development of plants and is mainly supplied through liming performed to correct soil acidity. By acting on photosynthesis and influencing carbohydrate partitioning in the plant, supplementary Mg supplied through soil or foliar application can increase the yield and quality of potato (*Solanum tuberosum* L.) tubers. The aim of this study was to evaluate the effect of supplemental Mg fertilization by soil or foliar application on plant nutritional status, tuber yield, and carbohydrate partitioning in potato crops in soil corrected with calcitic and dolomitic limestones. The experiment was carried out in pots under greenhouse conditions with a randomized block design in a 2 × 3 factorial scheme with four replications. Dolomitic limestone application and supplemental Mg fertilization via soil increased the concentrations of this nutrient in potato leaves. Liming with dolomitic limestone reduced the uptake of Ca and K by plants, but supplemental Mg fertilization did not alter the uptake of Ca, Mg or K. Supplemental Mg fertilization did not increase plant growth and tuber yield, even when calcitic limestone was used to elevate the base saturation to 60%; the exchangeable Mg concentration in soil was 9 mmolc dm^{-3}, and the Ca:Mg relationship was 3.7. Liming with dolomitic limestone or providing supplemental Mg fertilization did not increase sugar and starch partitioning to the tubers.

Supplementary Potassium and Calcium Improves Salt Tolerance in Olive Plants

Ajmi Larbi, Haifa Kchaou, Badii Gaaliche, Kamel Gargouri, Hakim Boulal, and Fermín Morales. 2020. Scientia Horticulturae 260:108912. DOI: https://doi.org/10.1016/j.scienta.2019.108912.

Abstract: Soil salinization increase, aggravated by the foreseen low precipitation related to climate change, is a worldwide problem causing crop yield reductions, affecting population and environmental issues due to the salt-containing low-quality water. Enhancing the salt tolerance of plants, especially crops, is an interesting and effective solution to minimize salt-related crop problems. Toward this goal, we evaluated in this study the effect of potassium (K) and calcium (Ca) application on plant growth, nutrient uptake, water status and electrolyte and potassium leakage of two-year-old potted olive plants grown under saline conditions (100 and 200 mM NaCl). Results showed that all measured parameters were affected by salinity. However, the application of K and Ca enhanced the growth parameters, improved the water status and reduced the electrolyte and K leakage, the latter reflecting a positive effect in membrane integrity. The nutritional balance was moderately improved in salt-stressed plants treated with K and Ca. The significant reduction in sodium (Na) concentration in both leaves and roots, and the enhancement of K and Ca concentration in the different plant tissues indicated that the K and Ca supply raised the Na exclusion mechanism. The largest positive effect of K was observed with 40 mM KNO_3 dose at both salinity levels. Furthermore, the beneficial effect of Ca was achieved with 40 and 10 mM $CaCl_2$ in plants grown at 100 and 200 mM NaCl, respectively. Thus, for this relatively salt-tolerant and economically important crop, K and Ca are recommended to supply in order to mitigate the harmful effects of salinity and to develop saline agriculture in, for instance, coastal saline land.

Coordinated Transport of Nitrate, Potassium, and Sodium

Natalia Raddatz, Laura Morales de los Ríos, Marika Lindahl, Francisco J. Quintero, and José M. Pardo. 2020. Front. Plant Sci. DOI: https://doi.org/10.3389/fpls.2020.00247.

Abstract: Potassium (K^+) and nitrogen (N) are essential nutrients, and their absorption and distribution within the plant must be coordinated for optimal growth and development. Potassium is involved in charge balance of inorganic and organic anions and macromolecules, control of membrane electrical potential, pH homeostasis and the regulation of cell osmotic pressure, whereas nitrogen is an essential component of amino acids, proteins, and nucleic acids. Nitrate (NO_3^-) is often the primary nitrogen source, but it also serves as a signaling molecule to the plant. Nitrate regulates root architecture, stimulates shoot growth, delays flowering, regulates abscisic acid-independent stomata opening, and relieves seed dormancy. Plants can sense K^+/NO_3^- levels in soils and adjust accordingly the uptake and root-to-shoot transport to balance the distribution of these ions between organs. On the other hand, in small amounts sodium (Na^+) is categorized as a "beneficial element" for plants, mainly as a "cheap" osmolyte. However, at high concentrations in the soil, Na^+ can inhibit various physiological processes impairing plant growth. Hence, plants have developed specific mechanisms to transport, sense, and respond to a variety of Na^+ conditions. Sodium is taken up by many K^+ transporters, and a large proportion of Na^+ ions accumulated in shoots appear to be loaded into the xylem by systems that show nitrate dependence. Thus, an adequate supply of mineral nutrients is paramount to reduce the noxious effects of salts and to sustain crop productivity under salt stress. In this review, we will focus

on recent research unraveling the mechanisms that coordinate the K^+-NO_3^-; Na^+-NO_3^-, and K^+-Na^+ transports, and the regulators controlling their uptake and allocation.

Agronomic Practices Affect Rice Yield and Nitrogen, Phosphorus, and Potassium Accumulation, Allocation and Translocation

Yandong Lv, Yue Hu, Hongfang Jiang, Yuchen Lan, Heying Wang, Lingqi Xu, Dawei Yin, Guiping Zheng, and Xiaohong Guo. 2020. Agron. J. 112(2):1238-1249. DOI: https://doi.org/10.1002/agj2.20060.

Abstract: Applying appropriate agronomic practices instead of conventional farming practices might improve rice yield. However, few studies have focused on how integrated agronomic practices affect N, P, and K accumulation and allocation in rice (*Oryza sativa* L.). Therefore, this study was conducted to investigate grain yield, N, P, and K accumulation, and allocation under different agronomic practices. A japonica rice cultivar was grown in the field, with four agronomic practice treatments: no N application (N0), local farmers' practice (FP), high-yield practice (HYP), and super-high-yield (SHY) practice. The results showed that the latter two practices significantly increased grain yield by 11.0% and 26.4%, respectively, compared with that under FP, mainly as a result of an increase in mean number of panicles m^{-2} and spikelets $panicle^{-1}$. Mean aboveground N, P, and K accumulation significantly increased by 24.9, 15.3, and 79.1%, in HYP and 42.0, 38.8, and 219.7% in SHY, respectively, compared with that under FP. In particular, K accumulation was higher than N and P accumulation in HYP and SHY plants than those in FP plants. However, N, P, and K grain productivity was lower by 7.5, 9.5, and 20.3% under HYP, and 20.3, 17.2 and 62.7% under SHY treatments than that of FP, respectively, and N, P, and K grain productivity were negatively correlated with yield. Our results suggest that an increase in N, P, and K accumulation from the full-heading stage (FH) to the maturity stage (MS) may assist with improving rice yields under HYP and SHY treatments.

Potassium Fertilization Increases Hydraulic Redistribution and Water Use Efficiency for Stemwood Production in *Eucalyptus grandis* Plantations

Verónica Asensio, Jean-Christophe Domec, Yann Nouvellon, Jean-Paul Laclau, Jean-Pierre Bouillet, Lionel Jordan-Meille, José Lavres, Juan Delgado Rojas, Joannès Guillemot, and Cassio H.Abreu-Junior. 2020. Environmental and Experimental Botany 176:104085. DOI: https://doi.org/10.1016/j.envexpbot.2020.104085.

Abstract: Climate change is expected to increase the frequency of droughts in most tropical regions in the coming decades. A passive phenomenon called hydraulic redistribution (HR) allows some plant species to take up water from deep and wet soil layers and redistribute it in the upper dry layers where other plants and soil biota can benefit from it. In addition, soil fertilization, particularly potassium (K), may also affect drought-adaptive mechanisms and increase water use efficiency (WUE) on poor and acidic tropical soils. The present study aimed at quantifying the role of HR and K fertilization on both wood productivity and WUE for stemwood production (WUE_p) of *Eucalyptus grandis* plantations in Brazil under ambient and reduced (-37%) throughfall conditions.

Tree transpiration was measured using trunk sap flow sensors over 21 months, and HR was estimated from the reverse sap flow (RF) observed in shallow roots over 18 months. Tree biomass, hydraulic conductance, soil water storage from surface to the water table (down to 17 m), and leaf photosynthetic capacity were also assessed.

Significant HR was detected over the whole year, even during the rainy seasons. Neither potassium fertilization nor throughfall exclusion affected the velocity of water transported by HR, probably because most trees reached water table. Nonetheless, some photosynthetic capacity parameters, including the maximum photosynthetic rate (A_{max}), increased in treatments with K addition. This higher A_{max} combined with an increased sapwood area index, was associated with an increase in water uptake by 30%-50% and WUE_p by 300% relative to K-deficient trees. We postulate that the increase in WUE_p promoted by potassium fertilization was partly driven by an increase in biomass allocation to wood, at the expense of foraging organs (leaves and roots), because K addition alleviated constraints on light and water use. Our results indicate that fertilizing *E. grandis* plantations with K is beneficial to both wood biomass production and WUE_p.

Release Kinetics of Potassium from Silica-Rich Fern-Derived Biochars

Anh T.Q. Nguyen, Tu A. Bui, Nga T. Mai, Hien T. Tran, Son V. Tran, Nam H. Nguyen, Toshiki Tsubota, Yoshiyuki Shinogi, Stefan Dultz, and Minh N. Nguyen. 2020. Agron. J. 112(3):1713-1725. DOI: https://doi.org/10.1002/agj2.20209

Abstract: Recently, low input agriculture has been encouraged because of its sustainability and environmentally friendly vision. Conversion of biomass into control-released materials is one of the approaches to upcycle biomass and nutrients. This study aims at examining the dynamics of K release from Si-rich biochars formed from various pyrolysis strategies with the findings expected to be applicable to develop new refinery strategies for biomass nutrients. A Si-rich fern species [*Dicranopteris linearis* (Burm.f.) Underw.] was selected to prepare biochars under various pyrolysis conditions (e.g., temperature, N_2 supported). It

was found that K was re-located during pyrolysis and occurred as free K^+ ions, associated with organic matter and occluded in silica structure. Pyrolysis can be strategically applied to alter either the organic phase or the silica phase in the biochars in term of porosity and chemical reactivities, whereby controlling K release kinetics. The maximum level of released K was at 600 °C (5.4 g kg^{-1}) which was about one order of magnitude higher than the minimum level of released K at 200 °C (0.55 g kg^{-1}). This discrepancy in the release rates of K suggests that adjusting pyrolysis temperature can be a strategical practice to control K release and to develop biochar-based K fertilizers.

Estimation of Rice Plant Potassium Accumulation Based on Non-Negative Matrix Factorization Using Hyperspectral Reflectance

Jingshan Lu, Wanyu Li, Minglei Yu, Xiangbin Zhang, Yong Ma, Xi Su, Xia Yao, Tao Cheng, Yan Zhu, Weixing Cao, and Yongchao Tian. 2020. Precision Agriculture. DOI: https://doi.org/10.1007/s11119-020-09729-z.

Abstract: Rapid and accurate estimation of plant potassium accumulation (PKA) using hyperspectral remote sensing is of significance for the precise management of crop K fertilizer. This study focused on the separation of non-negative matrix factorization (NMF) for hyperspectral reflectance from the ground and unmanned aerial vehicle (UAV) platforms and its mitigation effect on the water and soil background. Pure vegetation spectra were extracted from the canopy mixed spectra using NMF, and then a partial least-squares regression (PLSR) model was established based on the extracted vegetation spectra and rice PKA to construct an estimation model of rice PKA. The results showed that the green light and red edge bands contributed significantly to the rice PKA estimation. NMF could effectively extract pure vegetation and water and soil spectra from mixed spectra, and enhance the green peak, red valley, and red edge information of the extracted vegetation spectra. Compared with spectral indices, the PLSR performed best for ground and UAV data. Besides, the R2 of the PLSR model based on NMF-extracted vegetation spectra increased by 15.15% to 0.76%, and the verified RMSE and RE decreased by 16.93% and 16.77% to 3.19 g m^{-2} and 45.07%, respectively. Hyperspectral dataset testing from different years, growth stages and varieties, and UAV platforms showed that NMF could improve the estimation accuracy of rice PKA. This study showed that NMF could be applied to both ground and UAV hyperspectral platforms to improve the estimation accuracy of rice K nutrition.

Nutritional Value of Savory Herb (*Satureja hortensis* L.) and Plant Response to Variable Mineral Nutrition Conditions in Various Phases of Development

Skubij, N., K. Dzida, Z. Jarosz, K. Pitura, and M. Jaroszuk-Sierocińska. 2020. Plants 2020(9):706. DOI: https://doi.org/10.3390/plants9060706.

Abstract: Mineral nutrition and plant ontogeny influence both the physiological balance between nutrients in a plant and determine the proper nutritional status of a plant, which is necessary to realize the yielding potential of a cultivated species. The aim of the present study was to assess the effect of nitrogen doses (0, 4, 8, 12, 16 g N·m^{-2}) and plant development phases (the beginning and full flowering) on the content of macroelements and changes in ionic ratios occurring in the herb of the summer savory cv. ‘Saturn’. The two-factor experiment was carried out in a random-block design with five replications. The mineral nitrogen nutrition applied increased the concentration of total nitrogen and its mineral forms in the plants. There was a change in ion homeostasis in the individual stages of the ontogenesis process, i.e., a higher content of P, K, Ca, and S in the initial flowering phase as well as Mg and Cl in the full flowering phase. The increase in the availability of mineral nitrogen in the soil solution caused a decrease in total sorption capacity, reducing the potential of the soil for saturation with alkaline cations.

Growth and Biomass Yield of Hydroponically Grown Thyme (*Thymus vulgaris* L.) in Response to Brackish Water-Induced Stress

Jalal Al-Tabbal, Moawiya Haddad, Nabeel Bani-Hani, Issam Qrunfleh, Khaled AL-Bashabsheha, and Suha Abu Al-Einein. 2020. Irrigation and Drainage. DOI: https://doi.org/10.1002/ird.2479.

Abstract: Reuse of non-traditional water (brackish water) in agriculture will reduce the cost of disposal. On the other hand, the use of brackish water may cause environmental pollution to the soil, groundwater and plants after being discharged to the soil. The purpose of the current study was to assess the effect of reusing filter station water on the growth and yield of thyme plants during three growing seasons, 2014–2016. Three types of irrigation water were used in the current study: fresh tap water (T1), mixed water (T2) and brackish water (T3), with total dissolved solids (TDS) of 500, 1,500 and 2,500 ppm, respectively. Number of lateral leaves, plant height (cm) and fresh and dry weights (g m^{-2}) were recorded. In addition, the percentage of nitrogen (N), phosphorus (P), potassium (K) and calcium (Ca) in the leaves was determined. Results showed that plant parameters as well as yield were affected by mixed and brackish water. In addition, the chemical composition of leaves was affected significantly by the treatments.

Interactive Effect of Variety and Potassium Fertilizer on the Yield of Salt-Tolerant Boro Rice

Kawsar Hossen, Sadia Sultana, Md. Mahfuzar Rahman, Ruhul Amin Rana, Tahmina Ferdous, Akhinur Shila and Rayhan Ahmed. 2020. Asian Australas. J. Biosci. Biotechnol. 5(1):21-26.

Abstract: Performance of salt-tolerant Boro rice was investigated under the interaction effect of variety and different doses of potassium fertilizer, which is a part of the research for developing agriculture in coastal areas of Bangladesh. A field experiment was conducted at the research field of Agriculture department, Noakhali Science and Technology University (NSTU), Noakhali-3814. The experiment was carried out in a Randomized Complete Block Design (RCBD) with three replications where two varieties viz. BINA dhan-8, BRRI dhan-28 and three doses of potassium viz. 120 kg/ha, 84 kg/ha and 36 kg/ha were used as treatments. Plant height (cm), tillers/hill, grain/panicle, 1000 grain weight (g), grain yield (t/ha), straw yield (t/ha) and harvest index (%) were compared among varieties and treatments. Results revealed that only variety and only potassium fertilizer had non-significant influence but the interaction of variety and potassium fertilizer had a significant effect on the performance of salt-tolerant Boro rice. Therefore, the present study suggests that salt-tolerant BINA dhan-8 variety may be cultivated with 120 kg potassium/ha for obtaining higher yield in the southern coastal area of Bangladesh.

Effect of Planting Date and Potassium Fertilization Rates on Yam Yield (*Dioscorea* sp) and Tubers Storability

Eman Abd El-Aty Boraeiy Abd El-Karem. 2019. Department of Vegetable Crops, Faculty of Agriculture, Cairo University, Egypt. http://erepository.cu.edu.eg/index.php/cutheses/article/view/8678.

Abstract: The experiments in this study were conducted at the Experimental farm of Vegetable Crops, Medicinal and Aromatic plants Research Institute. Agriculture Research Center. Dokki, Giza, during two successful seasons 2016/2017 and 2017/2018. This study aimed to investigate sequences of yam plant to identify the correct specie, the effects of application of gibberellic acid (GA3) and benzyladinine (BA) on yam tuber dormancy, to determinate the most appropriate dates for planting in Egypt, the best level of potassium for the highest productivity and the interaction between planting dates and potassium fertilizer on plant growth, yield and its components. The experimental design was split plot design with three replicates. The main plot was three different planting dates (1st of May, 1st of June and 1st of July). The sub plot was three levels of potassium fertilizer (96, 144, 192 kg/fed K_2O) in the form of potassium sulphate (48% K_2O) and control treatment (without adding potassium fertilizer). as well as storability of yam tubers, sp *Dioscorea abyssinica* grown in clay soil. Results show that highest sprouting percent (100%) was obtained with 1.0 mg/l BA. The combination between K_2O at 144 kg/fed with 1st June sowing date gave the highest vine length, leaf area, total chlorophyll, No/lateral branch/plant, tuber length, tuber diameter, fresh weight of tuber/plant, total yield/plot, total yield/fed, dry matter, starch, Ca, K, P, N, and total nitrogen in both seasons. Shelf life of yam tubers at room temperature was about two months.

Potassium Fertilization Effects on Quality, Economics, and Yield in a Pear Orchard

Paula Beatriz Sete, Marlise Nara Ciotta, Gilberto Nava, Lincon de Oliveira Stefanello, Auri Brackmann, Magno Roberto Pasquetti Berghetti, Eliana Aparecida Cadoná, and Gustavo Brunetto. 2020. Department of Vegetable Crops, Faculty of Agriculture, Cairo University, Egypt. Agron. J. 112(4):3065-3075. DOI: https://doi.org/10.1002/agj2.20235.

Abstract: Potassium (K) nutrient existent in the soil does not always supply pear tree (*Pyrus communis* L.) demand, which makes the use of potassium-based fertilizer necessary. The objective of this study was to evaluate the impact of potassium fertilization on yield and pears quality in order to establish critical K levels in soil and leaves. The treatments consisted of K application rates of control, 40, 80, 120 and 160 kg K_2O ha^{-1} yr^{-1} during four crops (2013 to 2017). The fruit quantity, mass and yield were evaluated, and leaves were collected for nutrient analysis. Stratified soil samples were collected, prepared and subjected to exchangeable K extraction by Mehlich^{-1}. In the last two crops, peel color, ethylene production, and respiratory rate were also evaluated after 90 days inside a controlled atmosphere storage chamber. After storage, pears were submitted to a shelf life of 7 days to evaluate the epidermis color, ethylene production, respiratory rate, total titratable acidity (TTA), soluble solids (SS), and pulp firmness. Potassium fertilization increased the exchangeable K contents in the soil, but it was not always correlated with an increase of K concentration in the leaves and fruit. The most economical dose was 45.40 kg K_2O ha^{-1} in the 2016/2017 crop season. It was not possible to estimate K critical levels in the soil and leaves. The fruits submitted to higher doses of K showed the lowest values of ethylene production and respiration rate, which resulted in an increase in storage life in cold rooms and on the shelves.

Read on

Potassium – An Integral Part for Sustainable Crop Production

Imas, P. Australian Resources & Investment 14(1).

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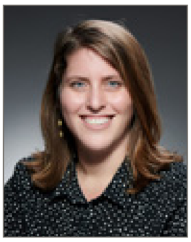
We are pleased to announce three new Coordinators

IPI Coordinator for India: Dr. Adi Perelman



Dr. Adi Perelman received both her BSc and MSc from the Hebrew University of Jerusalem (HUJI), before graduating with her PhD from the Institute of Agriculture and Biotechnology of Arid Areas, Ben Gurion University, in 2018. As well as conducting her formal studies, which focused on "Plant water uptake and its effect sodium accumulation at the root-soil interface". Dr. Perelman has instructed plant physiology at the International Center of Agricultural Training in Ramat Negev, "Plant Science" at HUJI, and served as a breeder assistant both on the Faculty of Agriculture, Rehovot, and at Tomatech R&D.

Dr. Adi Perelman started as the Coordinator for IPI activities in India in December 2019, and is based in Israel.

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IPI Coordinator for Malaysia and Indonesia: Dr. Cong Rong Cheng

Dr. Cong Rong Cheng graduated from the School of Agriculture, Food and Wine, at the University of Adelaide. He started his career in agricultural research in 2010 and has been active in the oil palm industry since 2014. Cheng has visited oil palm plantations in Malaysia and Indonesia, and he is active in the area of agronomy, research and plantation technologies. He has also been working on deploying Internet-of-Things sensors and using machine learning to improve agronomic input for the cultivation of oil palm. Recent involvement with polyhalite has given him the opportunity to study the importance of balanced nutrition on crop health and the improvement of fruit quality.

Dr. Cong Rong Chen started as the Coordinator for IPI activities in Malaysia and Indonesia from June 2020, and is based in Malaysia.

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IPI Coordinator for Germany: Dr. Heinrich Thoele

Dr. Heinrich Thoele has focused on agronomy of a variety of crops since he studied crop production at Humboldt University of Berlin. Key areas of interest have included studies in on-farm trials in cereals with sensor-based, variable-rate N fertilization and genetic impacts on GM canola volunteer occurrence. His PhD thesis concentrated on statistical software use to analyze on-farm trials to provide spatially correlated yield data.

Before joining ICL, Heinrich worked as a sales representative for cereal, corn and soybean seeds since 2012. From February 2020, he has been the lead agronomist for the development of ICL's FertilizerpluS products in Germany with regards to the development of S, NPK and PK, as well as K fertilizers for German crops.

Dr. Heinrich Thoele will start as the Coordinator for IPI activities in Germany in July 2020, and is based in Germany.

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