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)

Tien, T.M.[(1)*], T.T.M. Thu[(1)], H.C. Truc[(2)], and T.C. Tu[(2)]

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

[(1)]Soils and Fertilizers Research Institute, Duc Thang, Bac Tu Liem, Hanoi, Vietnam
[(2)]Central Highland Soils and Fertilizers Research Centre, Hoa Thang, Buon Ma Thuot, Dak Lak, Vietnam
*Corresponding author: tranminhtien74@yahoo.com

(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: $K_2Ca_2Mg(SO_4)_4·2(H_2O)$. 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.

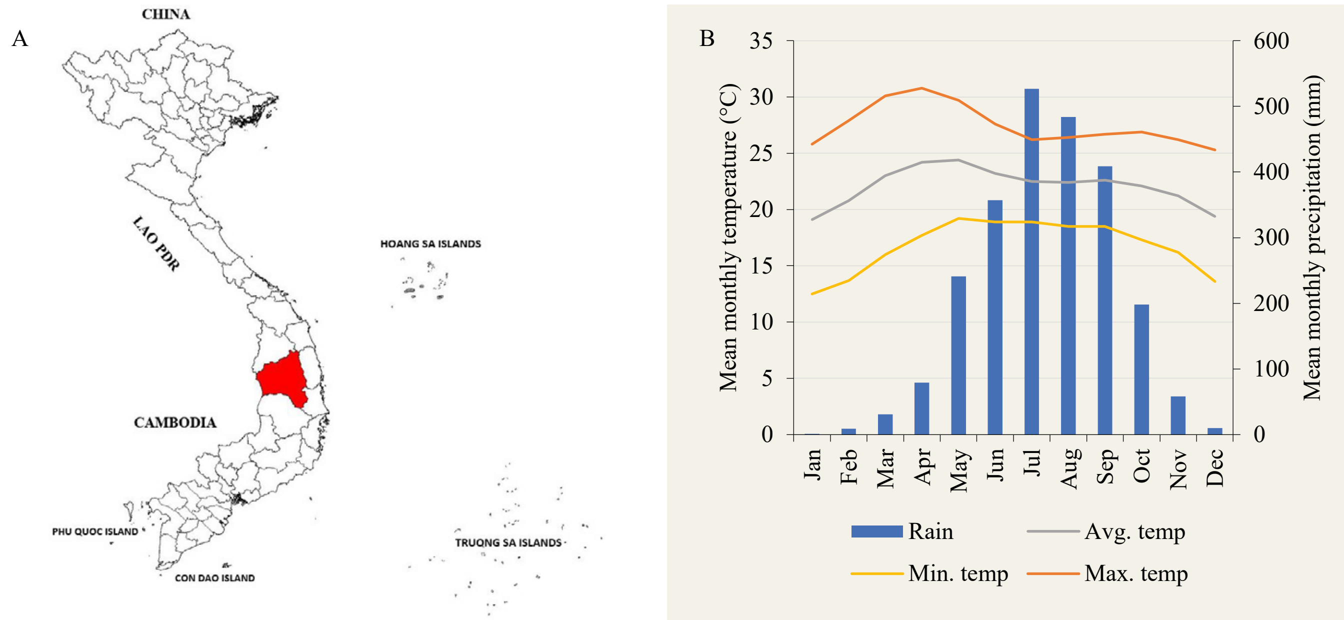

Fig. 1. Location of Gia Lai Province in the Central Highlands of Vietnam (A); and the typical climate profile (temperatures and precipitation) of the region (B). *Source:* https://en.climate-data.org/asia/vietnam/gia-lai-province/pleiku-4282/.

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 m^2 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^{o}C to exterminate yeasts, and then dried at 80^{o}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).

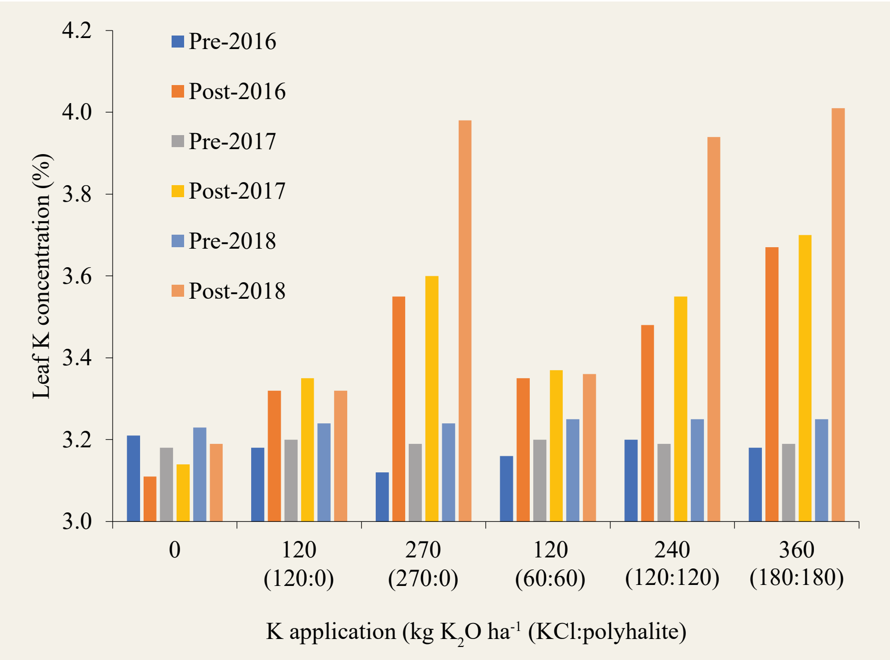

Fig. 2. Effects of KCl and polyhalite combinations on mean black pepper leaf K concentration (percent of dry matter) during a 3-year experiment in the Central Highlands, Vietnam. Leaves were sampled before, and 20 days after each fertilizer application.

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,

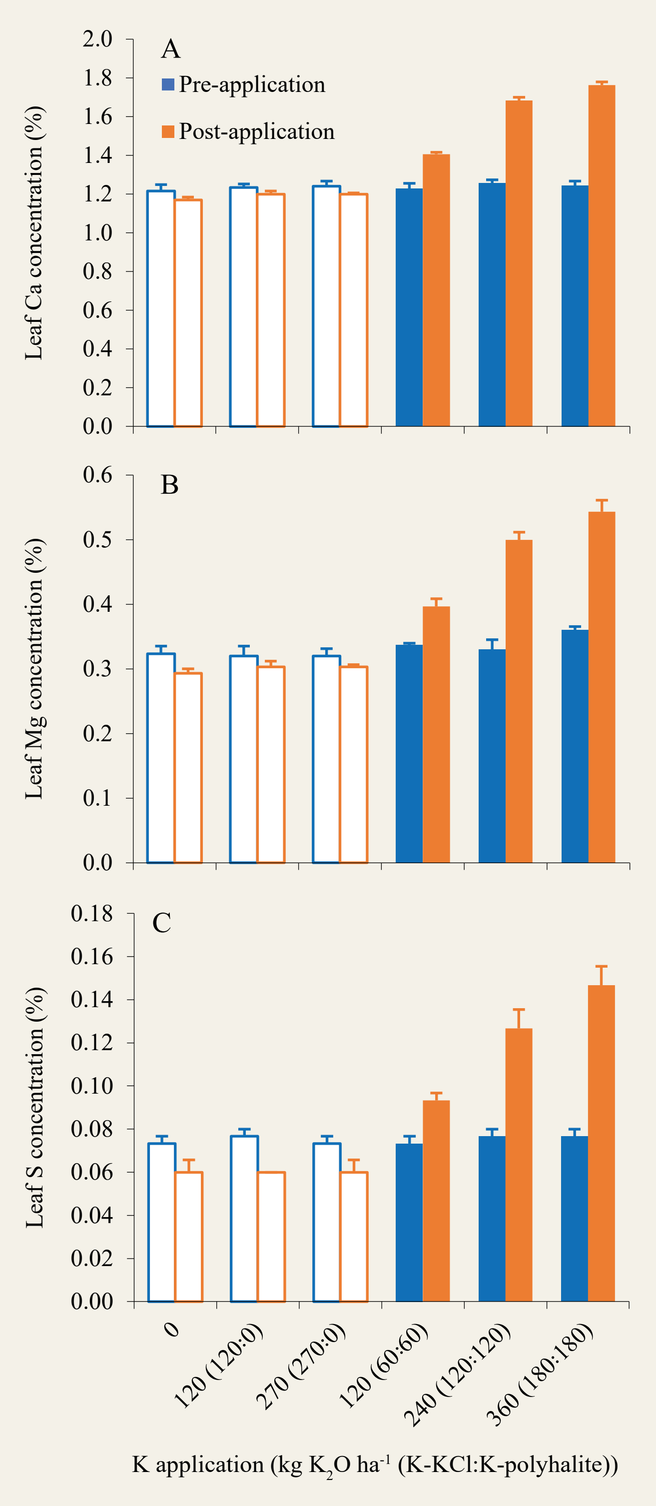

Fig. 3. Effects of KCl and polyhalite combinations on mean black pepper leaf Ca (A), Mg (B), and S (C) concentration (percent of dry matter) in the Central Highlands, Vietnam. Data are means of pre- and of 20-days post fertilizer application throughout the 3-year experiment. Blank bars indicate no polyhalite.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

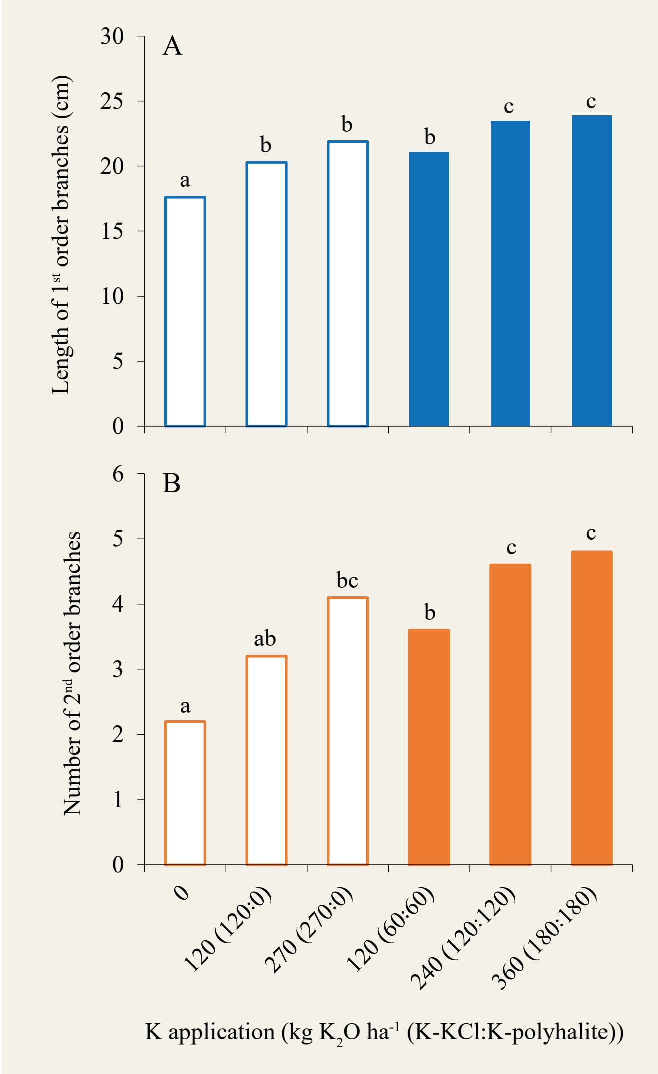

Fig. 4. Effects of KCl and polyhalite combinations on mean length of first order branches and the number of second order branches in a 3-year black pepper experiment carried out in the Central Highlands, Vietnam. Data are means of three seasons. Blank bars indicate no polyhalite. Different letters indicate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

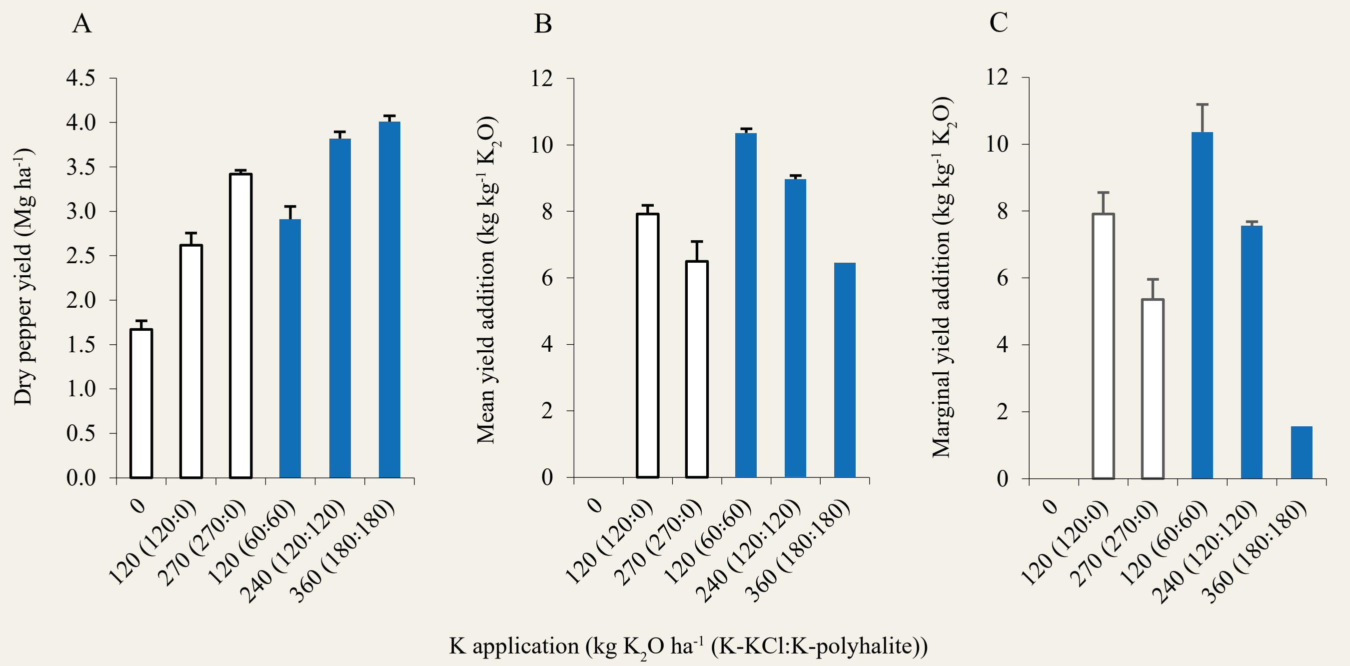

Fig. 5. Effects of KCl and polyhalite combinations on mean black pepper yield (A), mean yield addition (B), and marginal yield addition (C) in the Central Highlands, Vietnam. Data are means of three consecutive years of experiment. Bars indicate SE.

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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