Research Findings

Photo 1. Observation of black pepper (*Piper nigrum* L.) development. Photo by the authors.

Polyhalite Effects on Black Pepper (*Piper nigrum* L.) Yield and Quality in the Central Highlands of Vietnam

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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 consequent reduction in yield and quality. While farmers already practice frequent fertilizer application, different types of fertilizers are required in order to further improve nutrient availability and to broaden nutrient range in the soil. Polyhalite is a natural mineral consisting of K_2O, SO_3, MgO, and CaO at 14, 48, 6, and 17%, respectively, and has potential as a slow-release multi-nutrient fertilizer. For this study, polyhalite was examined in combination with MOP (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 MOP.

The present study demonstrates the pivotal role of K application in black pepper production on acid soils. Splitting the K dose into bimonthly applications brought leaf K contents to the required range. Polyhalite application can partially replace MOP as the K source and, furthermore, polyhalite provides the crop with other essential nutrients such as Ca, Mg, and 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 MOP/polyhalite, respectively, gave rise to the best crop performance and to the highest yield, produce quality, and profit. However, the exact contribution of polyhalite to the soil nutrient status requires further research.

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 216,432 Mg yr^{-1}, followed by Indonesia, India, Brazil, and China, with 82,167; 55,000; 54,425; and 34,587 Mg yr^{-1}, respectively (FAOSTAT, 2016). In Vietnam, pepper production is concentrated on the red soils of Central Highlands and in Phu Quoc Island. 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° north to 20° south 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 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, and 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 3.1-3.40%; 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,

Photos 2. Fertilizer application and irrigation of black pepper. Photos by the authors.

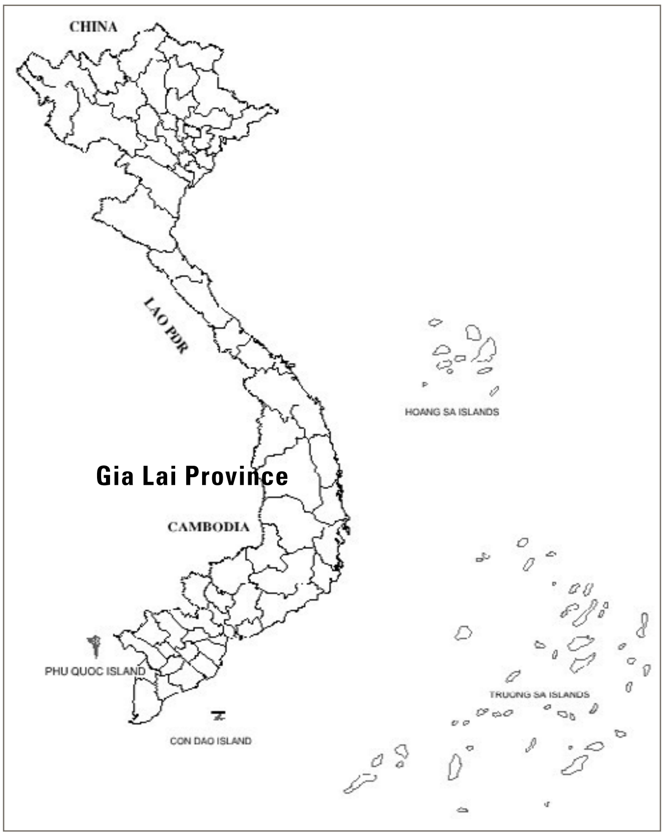
as well as coffee and tea plantations were established on virgin forests after clearing the vegetation (de Geus, 1973; Chiem and Nhan, 1974; D'haeze *et al.*, 2005). However, owing to heavy rains and unsustainable soil management practices, soils became poor in fertility and balanced manuring of crops became essential (de Waard, 1969). Over the course of time, sustainable traditional manuring practices were replaced with 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 nutrient availability throughout the year must be taken care of. In this respect, the microflora of black pepper rhizosphere has been recently explored (Xiong *et al.*, 2015; Li *et al.*, 2016), in order to influence beneficial chemical processes in the soil. 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 sources of Ca and Mg.

Polysulphate™ (produced by Cleveland Potash Ltd., 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 to crop nutrition. In addition, polyhalite releases the nutrients considerably slower than other K-containing fertilizers, which may also be significant for soil K availability. Once a proper application is established, polyhalite may not only provide a significant part of 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.



Map. 1. Location of the experiment in 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 (Map 1), and took place from January 2016 to December 2017, in a black pepper garden (cultivar Loc Ninh), planted in 2012.

The experiment was conducted on an acidic (pH_{KCl}: 4.5-4.6) reddish brown soil (Rhodic Ferralsols). Organic matter (OM) and total N contents were relatively high (OM: 3.50-3.62%; N: 0.18%). Total P was high, 0.21-0.23%, however, available P was poor (42.5 mg P_2O_5 kg^{-1}). Available K and S were moderate (102.6-103.1 and 21.9-22.5 mg kg^{-1} K_2O and SO_4, respectively). Alkaline cations, Ca^{2+} and Mg^{2+} were very low, 1.89 and 1.59 cmol kg^{-1}, respectively.

The experiment consisted of six treatments with four replications in a randomized complete block design (RCBD). Each plot included 30 pepper plants (180 m^2). 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 (T_1), and a second control (T_2), which received only the standard N and P fertilizers. Treatments T_3-T_6 were applied with the standard N and P fertilizers, but differed in the rate and combination of MOP and polyhalite, to provide a consistent rate of K_2O supply. Thus, T_3 and T_4 received a yearly dose of 120 kg K_2O ha^{-1}: T_3 - MOP, exclusively; and T_4 - MOP and polyhalite, 60 kg K_2O ha^{-1} each, but 100 and 429 kg fertilizer ha^{-1}, respectively. In treatments T_5 and T_6, 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, MOP, and polyhalite were applied every two months, as shown in Table 2.

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

Treatment	N		P		K			
	Urea	N	FMP	P_2O_5	MOP (KCl)	K_2O	Polyhalite	K_2O
	kg ha⁻¹							
T_1 (FP)	750	345	600	90	450	270	0	0
T_2 (control)	652	300	667	100	0	0	0	0
T_3	652	300	667	100	200	120	0	0
T_4	652	300	667	100	100	60	429	60
T_5	652	300	667	100	200	120	857	120
T_6	652	300	667	100	300	180	1,286	180

Note: FP = farmers' practice; 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.

Five plants per plot were monitored each 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 from each of three trees $plot^{-1}$, from four different directions around the tree) were collected from non-bearing internodes of fruit-bearing branches. Leaves were heated for an hour at 105-110°C 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 kept in desiccators until nutrient analyses were carried out. Leaf N content was determined using the Kjehldahl method. To determine leaf total P and K contents, the powder was extracted using H_2SO_4 + $HClO_4$, 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 abscission 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 acorns, 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; and, profit rate (%).

Results and discussion

Leaf nutrient concentrations were monitored during the year, prior to and 20 days after each fertilizer application. Nitrogen and P leaf contents prior to fertilizer application in July were

2.85-2.91% and 0.13-0.14%, respectively - under the minimum threshold. Twenty days after fertilization, leaf N and P contents increased significantly to 3.16-3.21% and 0.17-0.18%, respectively, within or above the optimum range, in all treatments. Thus, the N and P fertilizer levels and the application regime practiced in the present study (300 kg N, 100 kg P_2O_5), as well as the farmers' practice (345 kg N, 90 kg P_2O_5), are quite suitable for black pepper cropping on reddish brown soil in Chu Se district, Gia Lai province.

The annual K dose was split into six applications during the year (Table 2). The effects of fertilizer treatments on leaf K contents were very similar in both years (Fig. 1). Pre-application leaf K contents were significantly lower than the minimum threshold of 3.4%. Post-application measurements revealed an obvious recovery in leaf K content in all treatments but the control, which continued to decline.

The provision of 120 kg K_2O ha^{-1} in treatments 3 and 4 considerably increased leaf K content; nevertheless, values remained below the minimum threshold for pepper. At this low K dose, no significant advantage for the 1:1 combination of KCL and polyhalite was observed. The higher K doses applied in T_1, T_5, and T_6, ranging from 240-360 kg K_2O ha^{-1}, brought post-application leaf K contents into the optimum range. Yet, even with the significant positive response to the rising K dose, leaf K contents remained substantially lower than the upper threshold of 4.3%.

The fluctuations in leaf K content, and particularly its decline below the optimum range, suggests that under the environmental circumstances in the Central Highlands of Vietnam, plants' opportunities for K uptake are too short to refill the nutrient holding capacity. This may also indicate that the agronomic efficiency of the K application regime can be further improved.

In addition to K, polyhalite is a source of S, Ca, and Mg. Prior to fertilizer application, leaf contents of these nutrients were below the minimum thresholds 0.09, 1.43, and 0.4% for S, Ca, and Mg, respectively, for all treatments (Fig. 2). Following the bimonthly fertilizer application in July, nutrient levels continued to decrease in treatments supplied solely with MOP and the unfertilized control (T_1-T_3). Whereas in plants supplied with combined MOP and polyhalite (T_4-T_6), leaf S, Ca, and Mg increased significantly, reaching but not exceeding the optimum range. Generally, the greater the polyhalite dose, the higher the corresponding nutrient content in the leaves. However, similar to the case of K, the effect seems transient and the plants possibly experience considerable fluctuations in leaf nutrient contents during the year.

Two major disorders quite often infest 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 fungi soil-borne opportunist pathogens such as *Fusarium* spp., *Phytophthora* spp., *Pythium* spp., etc. that cause root rot diseases. Once infected, the old leaves' veins turn yellow, a symptom which gradually expands to the whole pepper leaf. Consequently, infected plants shed leaves and stems, their canopy becomes scattered, and they die one to three years after infection. The disease has substantial effects on crop yield and quality as flowering, and fruit set and development, are significantly damaged. Mealybugs (*Pseudococcus citri*) attack

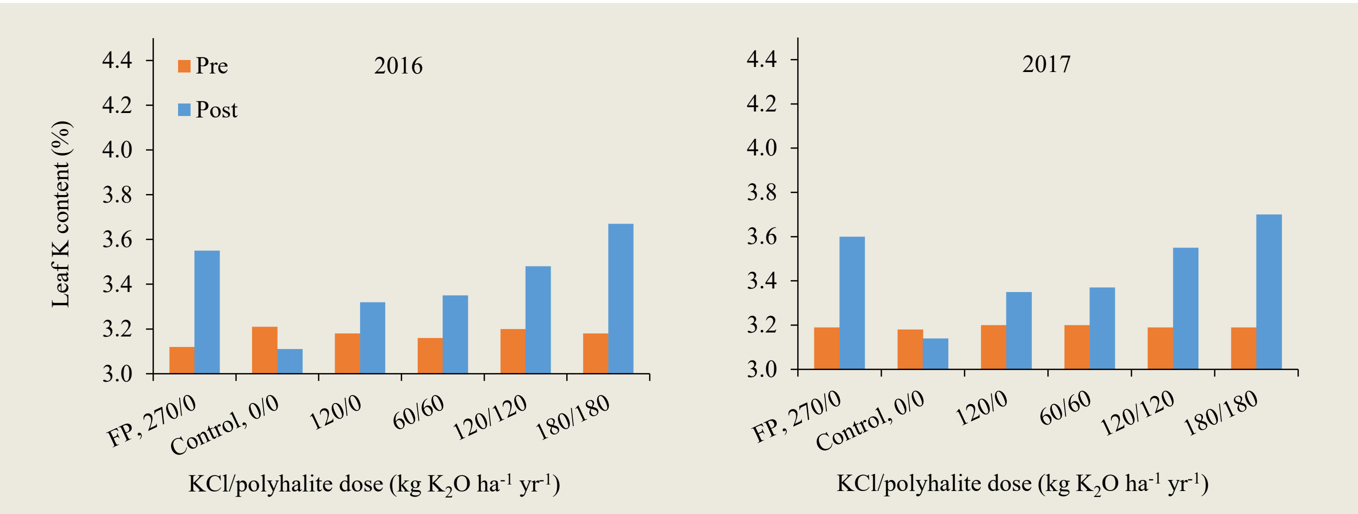


Fig. 1. Effect of KCl and polyhalite applications on pre- and post-application leaf K content in black pepper grown on acidic soil over two successive years, 2016 and 2017, in the Central Highlands of Vietnam. *Note:* FP = farmers' practice.

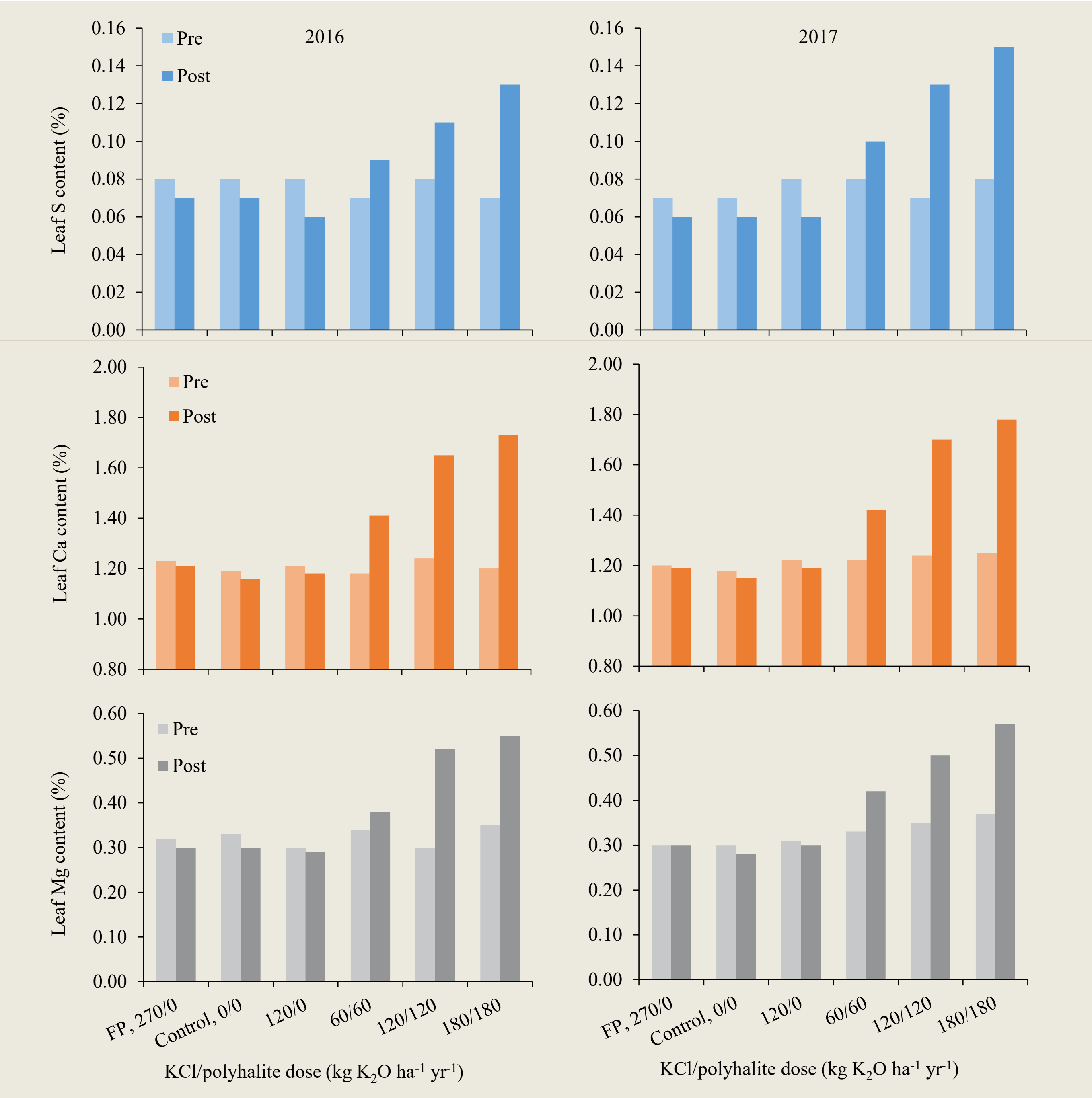


Fig. 2. Effect of KCl and polyhalite applications on pre- and post-application leaf S, Ca, and Mg contents of black pepper grown on an acidic soil over two successive years, 2016 and 2017, in the Central Highlands of Vietnam. *Note:* FP = farmers' practice.

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). A well-balanced crop nutrition is very efficient at preventing pests and diseases (Tang Ton and Buu, 2011).

In the present study, in both years, the basic rates of yellow pepper leaf disease were very low, leaving no room for any improvement by the fertilizer treatments (data not shown). In contrast, mealybug infestation rate in the control was 8-10% (Fig. 3). Potassium applications significantly reduced mealybug infestation rates in a dose-dependent manner. Furthermore, the results of treatments

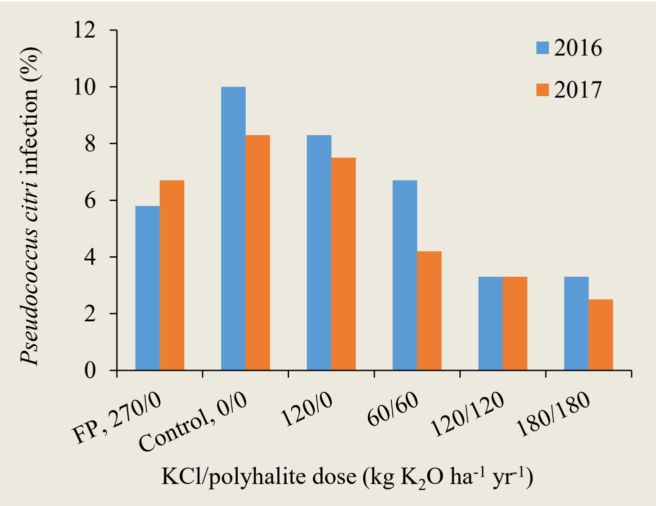


Fig. 3. Effect of KCl and polyhalite application on the rate of *P. citri* infection in black pepper plants. The experiment was conducted over two successive years, 2016 and 2017, in the Central Highlands of Vietnam. *Note:* FP = farmers' practice.

T_3 and T_4 may indicate that polyhalite application is more efficient than MOP in strengthening black pepper plants against mealybugs attack (Fig. 3). 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).

Potassium applications significantly enhanced the vegetative growth of black pepper plants (Fig. 4). While the elongation of primary branches at the high K dose increased by 30%, compared to the unfertilized control, the number of secondary branches more than doubled, providing a substantially larger and stronger platform for the reproductive phase and consequently, for higher yield and better quality. Premature fruit abscission was dramatically reduced from 35% at the unfertilized control to 20% at the farmers' practice, which received 270 kg K_2O ha^{-1} yr^{-1}. Treatments T_3 and T_4, with a significantly lower K dose (120 kg K_2O ha^{-1} yr^{-1}), displayed higher fruit abscission rates, while at the higher K doses (240 and 360 kg K_2O ha^{-1} yr^{-1}), fruit shedding rates were further reduced to 16.9 and 16.2%, respectively (Table 3).

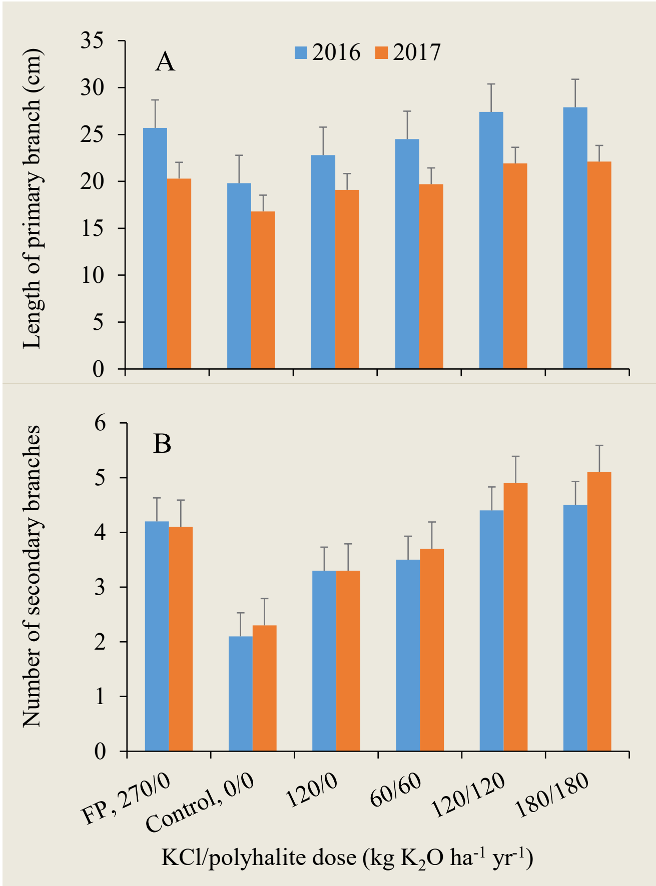


Fig. 4. Effect of KCl and polyhalite applications on the vegetative growth of black pepper plants. The experiment was conducted over two successive years, 2016 and 2017, in the Central Highlands of Vietnam. *Note:* FP = farmers' practice. Bars indicate $LSD_{0.05}$.

Black pepper yields of the unfertilized control in 2016 and 2017 were poor, 1.84 and 1.55 Mg ha^{-1}, respectively, significantly lower than in the other treatments (Fig. 5). MOP application at 120 kg

Table 3. Effects of K fertilizer type and dose on black pepper yield and quality traits.

Treatment	K-KCl	K-polyhalite	Fruit shed	Fresh/dry pepper	Fruit weight	Fruit volume	Fruit density	Piperine
	-----------kg K_2O ha^{-1}	*-----------*	*%*		*g 1,000^{-1} acorns*	*cm^3 1,000^{-1} acorns*	*g L^{-1}*	*%*
T_1	270	0	19.9	3.10	56.8	102.1	490	3.98
T_2	0	0	35.4	4.50	42.1	73.4	435	3.60
T_3	120	0	25.5	3.46	52.0	91.3	450	3.71
T_4	60	60	23.3	3.23	53.8	96.1	473	3.87
T_5	120	120	16.9	2.75	59.5	108.0	530	4.01
T_6	180	180	16.1	2.69	60.0	109.1	544	4.12
$LSD_{0.05}$			1.5	0.252	0.85	1.54	5.2	

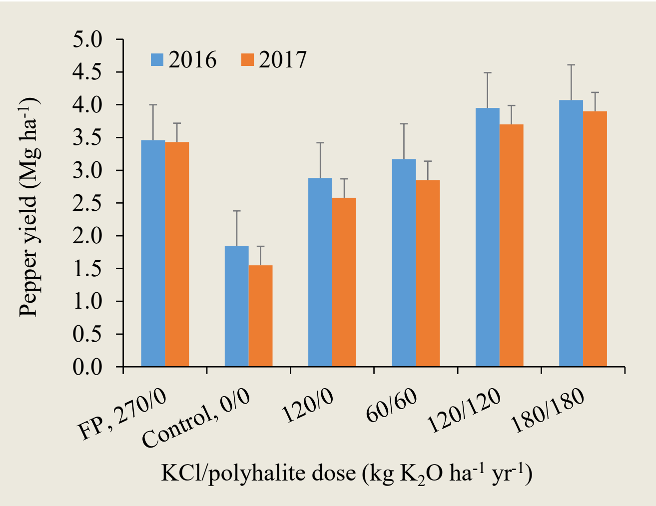


Fig. 5. Effect of KCl and polyhalite applications on black pepper yield. The experiment was conducted over two successive years, 2016 and 2017, in the Central Highlands of Vietnam. *Note:* FP = farmers' practice. Bars indicate $LSD_{0.05}$.

K_2O ha^{-1} yr^{-1} gave rise to significant yield increases of 56 and 66% more than the control, respectively. A similar dose, equally divided between MOP and polyhalite, had no further significant effects on yields. Farmers' practice, with a higher K dose of 270 kg K_2O ha^{-1} yr^{-1} applied as MOP, produced a much higher yield, averaging 3.45 Mg ha^{-1}. The greatest yields, ranging from 3.7 to 4.1 Mg ha^{-1}, were obtained at K doses of 240 and 360 kg K_2O ha^{-1} yr^{-1}, which were equally split between MOP and polyhalite (Fig. 5). There was no significant difference in yields between these two doses, suggesting that, at least under the circumstances of the present study, a yearly dose of 240 kg K_2O ha^{-1} would be sufficient. When compared to the farmers' practice, the advantage of polyhalite becomes obvious: a smaller K input of 240 kg K_2O ha^{-1}, 50% of which originated from polyhalite, resulted in 8-14% more yield than obtained at 270 kg K_2O ha^{-1} applied with MOP.

Economic analyses, based on the current costs, yield and produce quality and the consequent estimated income, showed that K application doses above 240 kg K_2O ha^{-1} provide maximum absolute and relative profits (Fig. 6). Lower K doses yielded significantly poor profits, while lack of K supply led to loss of money. A comparison between MOP alone, and in combination with polyhalite, at a relatively low K dose (120 kg K_2O ha^{-1}) indicate an advantage for combined fertilization. Furthermore, the combined MOP and polyhalite at the doubled dose (240 kg K_2O ha^{-1}) was more profitable than the farmers' practice, at 270 kg K_2O ha^{-1} (Fig. 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

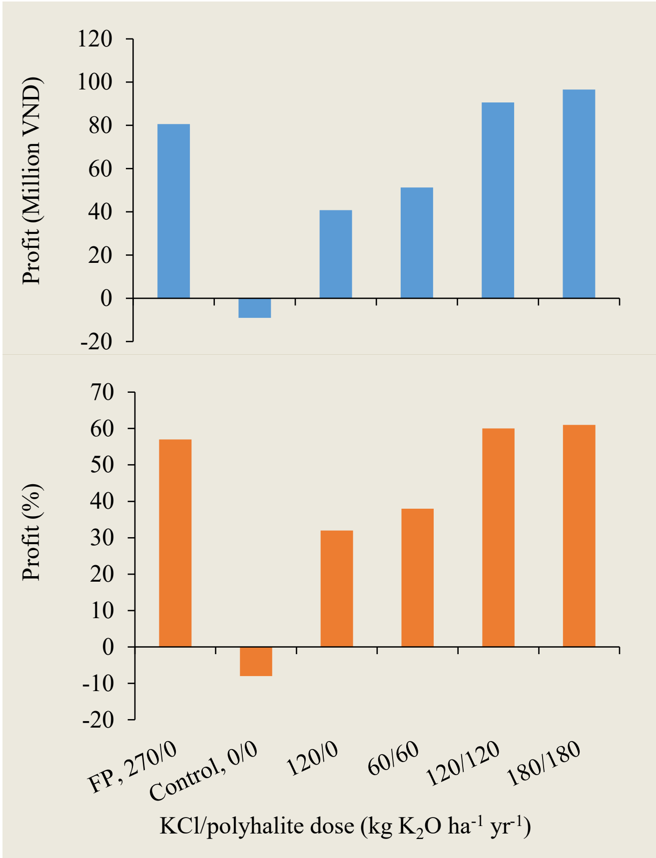


Fig. 6. Effect of KCl and polyhalite applications on the absolute and relative profit from black pepper grown on an acid soil in the Central Highlands of Vietnam, in 2017. *Note:* FP = farmers' practice.

agricultural and economic advantages of using polyhalite as a source of K, Ca, Mg, and S.

Conclusions

The results of this study demonstrate the pivotal role of K application in black pepper cultivation on acid soils. Splitting the K dose into bimonthly applications brought leaf K contents to the required range. Polyhalite application can partially replace MOP as the K source and, furthermore, polyhalite provides the crop with other essential nutrients such as Ca, Mg, and S. The supplemental nutrients strengthened the black pepper vines against mealybug attacks, supported better crop performance, and significantly improved yield and produce quality, resulting in higher profits. However, the exact contribution of polyhalite to soil nutrient status requires further research.

Acknowledgements

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Photo 3. Measurement of black pepper development. Photo by the authors.

Photo 4. Ca and Mg deficiency in black pepper leaf. Photo by the authors.

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The paper "Polyhalite Effects on Black Pepper (*Piper nigrum* L.) Yield and Quality in the Central Highlands of Vietnam" also appears on the IPI website at:

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