Research Findings

Photo 1. Coffee harvest. Photo by the authors.

Polyhalite Effects on Coffee (*Coffea robusta*) Yield and Quality in Central Highlands, Vietnam

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Abstract

Vietnam produces around 1.62 million tons of coffee per year, the second highest yield in the world after Brazil. Improving resource utilization efficiency has recently been identified as the major strategic goal of the industry. Appropriate mineral nutrition practices are pivotal to achieving this goal. The humid, tropical climate and acid soils of Vietnam create considerable challenges to achieving optimum balanced crop nutrition practices. The availability of alkaline elements, particularly potassium (K), calcium (Ca), and magnesium (Mg), is steadily declining. Polyhalite, a natural marine sedimentary mineral consisting of a hydrated sulfate of K, Ca, Mg and sulfur (S, 48%) was examined as a potential additive to composite NPK fertilizers. The mineral was tested in Kon Tum Province, as part of an alternative fertilization program for the coffee industry. A 3-year (2016-2018) experiment testing six fertilization practices was carried out in Dak Mar Commune at Dak Ha District on grey Feralic Acrisol. The region's recommendation, farmers' practice, consisted of 322,

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82.5, and 270 kg ha^{-1} N, P_2O_5, and K_2O (as MOP [muriate of potash]), respectively. The other five treatments had similar N and P_2O_5 rates of 100 and 667 kg ha^{-1}, but differed in K application rates and sources: zero-K control; MOP control with 120 kg K_2O ha^{-1} K (received solely through MOP); mixed MOP and polyhalite (1:1), at rates of 120, 240, and 360 kg K_2O ha^{-1}. Leaf nutrient status exhibited significant fluctuations between pre- and post-application measurements. Almost all crop performance parameters were significantly improved in response to elevated K application rates, reaching a maximum at 240 kg K_2O ha^{-1}. Polyhalite application was at least equivalent to MOP in providing crop K requirements. Moreover, polyhalite improved trees' Ca, Mg, and S status and stopped the decline of these nutrients in the soil. At equivalent K doses, polyhalite combined with MOP brought about higher coffee bean yields and quality, with consequently higher profits for farmers, when compared to MOP alone. In the long run, however, additional modifications to coffee fertilization practices should be examined in the region in order to stabilize tree nutrient status, thus supporting further enhancement of the region's coffee industry.

Keywords: Balanced fertilization; calcium; *Coffea robusta*; mineral nutrition; Polysulphate; potassium; sulfur.

Introduction

Coffee is one of the leading agricultural commodities worldwide. According to FAO's statistical data in 2018, total annual yield of world coffee product (green coffee) was 10.3 × 106 tons, 73.3% of which is produced by just six countries. Brazil led the list with 3.56 × 106 tons, followed by Vietnam, Indonesia, Columbia, Honduras, and Ethiopia, with 1.62; 0.42; 0.72; 0.48; and 0.47 × 106 tons, respectively (FAO, 2020). Vietnam accounts for about 16% of the world's production. The steadily expanding plantation area, currently about 620,000 ha, means coffee is a major economic engine for the developing agricultural sector in Vietnam. The Central Highlands is the key region of coffee production in Vietnam, with nearly 90% of the country's coffee area. More than half of this area, about 360,000 ha, is located in Dak Lak and Lam Dong. Therefore, much effort is made to improve the region's coffee yield and quality.

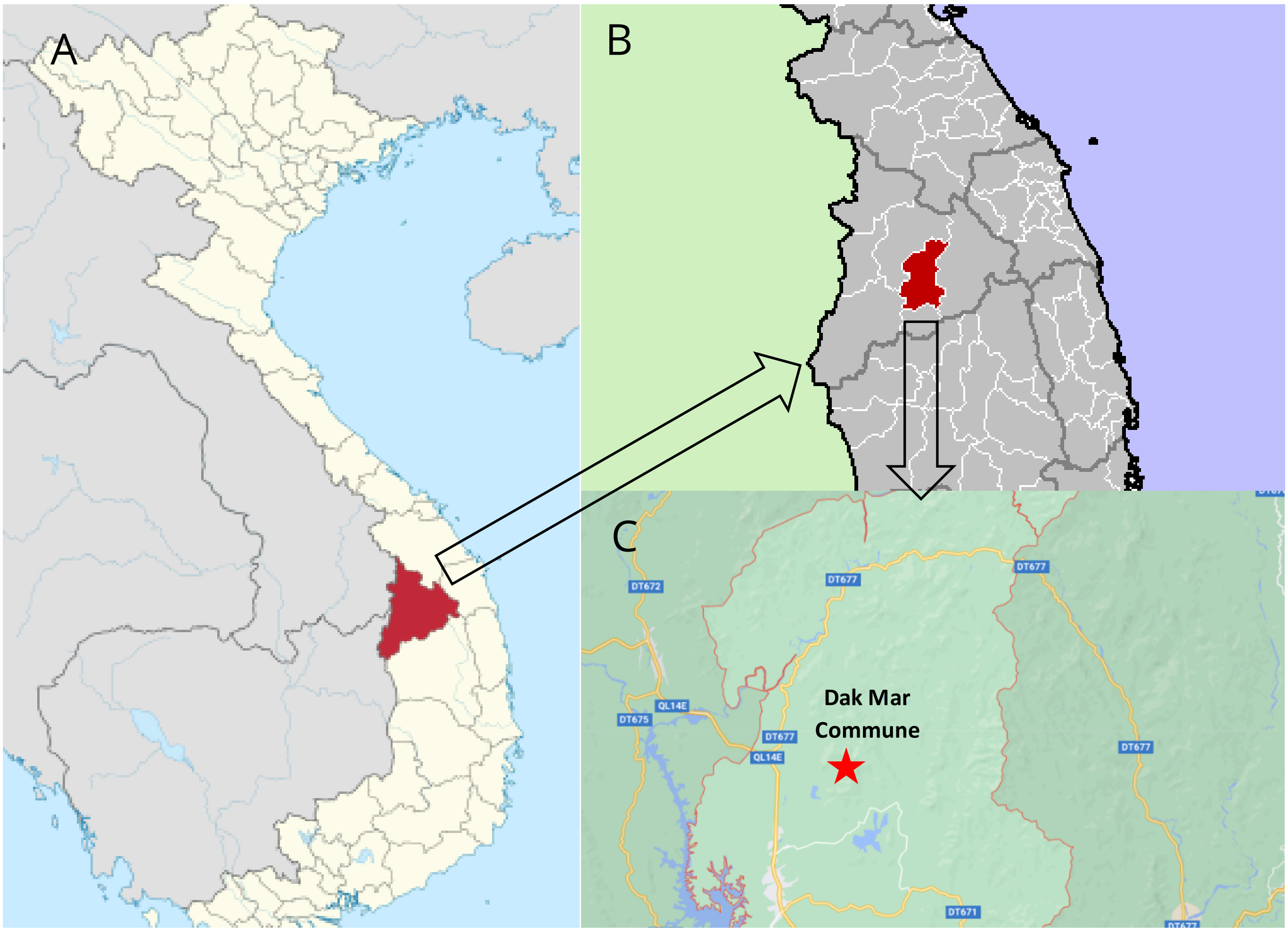
Vietnam has unique achievements in developing Robusta coffee (*Coffea robusta* or *Coffea canephora*) as a high yielding cash crop. This has been made possible by intensification methods, including irrigation during the dry season (Marsh, 2007). Special concern has been devoted to nutrition requirements and fertilization dosage and regime. Coffee displays high demands for fertilizers, particularly nitrogen (N) and potassium (K) (Jessy, 2011); obtaining one ton of Robusta coffee beans would require 30-35 kg N, 5.2-6.0 kg phosphorus pentoxide (P_2O_5), 36.5-50.0 kg potassium oxide (K_2O); 4 kg calcium oxide (CaO); and 4 kg magnesium oxide (MgO), depending on tree age and soil types (Tiemann *et al.*, 2018). A high producing coffee plantation would remove at least 135 kg N, 34 kg P_2O_5, and 145 kg K_2O ha^{-1} (De Geus, 1973).

Potassium is needed for most basic processes in plants' life cycle (Engels *et al.*, 2012). In coffee, K requirements are high during the development of the berries and are at the maximum during their ripening. Peaks in rate of K uptake were observed immediately after bloom, prior to fruit ripening, and after harvest (Mitchell, 1988). Forestier (1969), studying Arabica coffee, showed that chronic lack of K brought about a significantly increased rate of young fruit abortion, degeneration of branches and consequent die-back.

Several studies on soil and fertilizer application for Robusta coffee in the commercial phase have been carried out, resulting in controversial information regarding the annual K requirements of coffee in Vietnam. Ton Nu Tuan Nam and Truong Hong (1993) concluded that reaching a maximum yield would require annual application of 250 kg K_2O ha^{-1}. Le Ngoc Bau (1997), who focused on plantations with particularly high coffee beans yields (>5 Mg ha^{-1}) in the Highland provinces (Gia Lai, Dak Lak and Kon Tum), found that the annual K dose ranged from 400-500 kg K_2O ha^{-1}, twice as much as recommended. Nevertheless, in cases where K was applied at levels 2-3 times higher than recommended, no significant effects on the yield or on the tree growth and development could be observed, and there was no correlation between yield and leaf K content. Nguyen Van Sanh (2009), who studied balanced fertilization in Ea Pok Coffee Cooperative (Dak Lak), showed that the appropriate K dose was 180 kg K_2O ha^{-1}. Truong Hong (1997) concluded that to furnish coffee bean yields higher than 2.6 Mg ha^{-1}, 250-260 kg K_2O ha^{-1} was required on the basaltic soil of Buon Ma Thuot, compared to 125-180 kg K_2O ha^{-1} for the gneiss soil in Kon Tum. A more recent study carried out in 2012-2014 at Dak Lak and Kom Tun Provinces, suggested an optimum application rate of 360 kg K_2O ha^{-1} (Tien *et al.*, 2015a). Displaying a very wide range, from 125-500 kg K_2O ha^{-1}, these studies fail to provide clear advice of the appropriate K application rate for Robusta coffee in the region.

Until the last decade, farmers in Vietnam tended to overuse fertilizers and did not consider the ratio among nutrition elements (Do Thi Nga, 2012). Excess doses of N and P fertilizers were usually applied, whereas K doses were very low. The imbalanced plant nutrition brought about relatively low resistance to pests, diseases, and other stress factors. The increasing awareness in Vietnam of the significance of K nutrition for coffee in recent years (Tien *et al.*, 2015a) has given rise to considerable increases in the recommended K application rate; nevertheless, the optimum K application rate and practice are yet to be determined, requiring further research efforts.

The nature of the soil may be crucial to the quality and productivity. Soils in Vietnam developed from many different parental rocks including basalt, gneiss, granite, shale, limestone, lava and volcanic ash. Soil texture may vary from heavy loam to sandy soils with no obvious effects on coffee production as long as the soil layer is deep, easily drained but porous enough to hold considerable levels



Map 1. Location of the coffee experiment at Kon Tum Province in Vietnam (A); Dak Ha District (B); Dak Mar Commune (C). *Sources:* https://en.wikipedia.org/wiki/Kon_Tum_Province, and Google Maps Ltd.

of water, air, and nutrients (Tiem, 1999). The humid tropic climate of Vietnam, however, creates significant challenges for soil nutrient availability. During the wet season, the liquid soil phase is prone to fluctuate very frequently, within hours or days, depending on the precipitation regime. This liquid phase contains most of the currently available nutrients, including K, that are leached away from the rhizosphere. In addition, the high precipitation rates intensify soil weathering and significantly increase soil acidity (Sanchez, 2019), which further reduces soil cation exchange capacity (CEC) and K availability (Zörb *et al.*, 2014). Consequently, the opportunity window for plants to acquire K following application events is short and scarce, potentially leading to significant gaps between K application and uptake rates, considerable waste of fertilizer, and to environmental consequences.

Beyond K, the availability of alkaline elements – in particular calcium (Ca) and magnesium (Mg) – is steadily declining (Nam and Hong, 1993; Hong, 1997; Tien *et al.*, 2015b). As with K, the tropical climate and frequent heavy precipitation accelerate Ca and Mg loss through leaching from the root zone. Consequently, deficiency symptoms often occur in plantations that were previously highly productive (Nguyen Van Sanh, 2009). Sulfur (S) is recognized as the fourth major plant nutrient after N, P, and K (Khan *et al.*, 2005), and has been associated with high productivity (Zhao *et al.*, 1999; Saito, 2004; Kovar and Grant, 2011). Sulfur often interacts with N to significantly enhance crop productivity (Jamal *et al.*, 2010). However, current information regarding S application to acidic soils under tropical climates is scarce.

The recently introduced composite NPK fertilizers are not diverse enough to meet all nutrient requirements at each stage of growth, and on differing soils. Polyhalite is a natural mineral mined by Cleveland Potash, UK Ltd, and marketed as Polysulphate® fertilizer. It occurs in sedimentary marine

Table 1. Detailed description of the six fertilizer treatments included in the experiment.

Treatment	Nitrogen		Phosphorus		Potassium		
	N	Urea	P_2O_5	FMP	K_2O	MOP (K_2O)	Polyhalite (K_2O)
	--------------------------------			*kg ha^{-1}*	--------------------------------		
Farmers' practice (K_{270})	322	700	82.5	550	270	450 (270)	0
Control K_0	300	652	100	667	0	0	0
Control MOP K_{120}	300	652	100	667	120	200 (120)	0
MOP:polyhalite $K_{60:60}$	300	652	100	667	120	100 (60)	429 (60)
MOP:polyhalite $K_{120:120}$	300	652	100	667	240	200 (120)	858 (120)
MOP:polyhalite $K_{180:180}$	300	652	100	667	360	300 (180)	1286 (180)

Seasonal doses are given for each nutrient (N, P, and K) as N, P_2O_5, and K_2O, and as the rate of the crude fertilizer (urea, fused magnesium phosphate [FMP], and muriate of potash [MOP]).

evaporates and consists of a hydrated sulfate of K, Ca, and Mg with the formula: $K_2Ca_2Mg(SO_4)_4{\cdot}2H_2O$. The deposits found in Yorkshire, in the UK, typically consist of K_2O: 14%, SO_3: 48%, MgO: 6%, CaO: 17%. As a fertilizer providing four key plant nutrients – S, K, Mg, and Ca – polyhalite may offer attractive solutions to crop nutrition. In addition, polyhalite is less water soluble than more conventional sources (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 crop K requirements, but also supply secondary macronutrients that are essential under the present cropping environment of Robusta coffee in Vietnam.

The objectives of the present study were to determine an optimum K application rate for the Central Highlands region, evaluate and compare the effects of combining two K sources, muriate of potash (MOP [potassium chloride, KCl]) and polyhalite, on performance, yield, and quality, and consequently, determine the agronomic and economic efficiencies of the fertilizer combinations in Robusta coffee production.

Materials and methods

The experiment was conducted at Hoang Le Thuy household, Dak Mar commune, Dak Ha district, Kon Tum province in Vietnam (Map 1). Fifteen-year-old Robusta coffee plantations were studied. The experiments lasted three years, from January 2016 to December 2018. The soil at the experiment location was Feralic Acrisol; a grey degraded soil on acid igneous rock.

Table 2. Fertilizer distribution during the season, as percentage of the seasonal dose.

Fertilizer	Application time			
	Dry season	Pre-rainy season	Mid-rainy season	End-rainy season
	------------------		*% of seasonal dose*	------------------
Urea	10	35	30	25
FMP		50	50	
KCl	10	25	30	35
Polyhalite	10	25	30	35

The experiment consists of six treatments (Table 1) with four replications using a randomized complete block design (RCBD). It includes 20 coffee trees plot^{-1} (plot area of 180 m^2). The farmers' practice (FP K_{270}) treatment, which followed the region's recommendations, received 322, 82.5, and 270 kg ha^{-1} N, P_2O_5, and K_2O (as MOP [muriate of potash]), respectively. The other five treatments had similar N and P_2O_5 rates of 100 and 667 kg ha^{-1} but differed in K application rates and sources: zero-K control (K_0); MOP control with 120 kg K_2O ha^{-1} (Control MOP K_{120}), which received K solely through MOP; mixed MOP and polyhalite, with equal K_2O inputs, at rates of 120, 240, and 360 kg K_2O ha^{-1} (treatments MOP:polyhalite $K_{60:60}$, $K_{120:120}$, and $K_{180:180}$, respectively).

The fertilizers used were urea (46% N), fused magnesium phosphate (FMP; 15% P_2O_5), MOP (60% K_2O), and polyhalite (14% K_2O, 48% SO_3, 6% MgO, 17% CaO). Urea, MOP, and polyhalite applications were divided into four, and FMP into two events throughout the year, as shown in Table 2.

Coffee leaf samples were taken 20 days before and after fertilizer application throughout the 3-year experiment. In each experimental plot, eight leaves per tree were sampled from three trees. Indicative leaves were defined as the fourth couple, counting down from the top of a fruiting branch, but not from internodes bearing fruits. In the laboratory, samples were dried at 105-110°C, stabilized at 80°C for 8-12 hours, ground to a fine powder, and analyzed for mineral content. Samples were digested with sulfuric acid (H_2SO_4) and hydrochloric acid (HCl), then N content was determined by Kjeldahl, K by flame photometer and P by spectrophotometer; Ca and Mg contents were determined by digesting samples with nitrous acid (HNO_2) and HCl, then determined by atomic absorption spectroscopy.

Plant vegetative growth was determined by two measurements a year, at pre-rainy

Photo 2. Inspecting coffee crop. Photo by the authors.

season and just before harvest. Three representative trees per plot were monitored, using one fruiting branch from each of the four sides of the tree, measuring branch elongation (cm) and the number of internodes on the non-bearing part.

The infection rates of rust disease (*Hemileia vastatrix*) and green scale (*Coccos viridis*) were determined monthly by a visual inspection of 50 trees per plot and expressed as the percentage of trees infected. Pre-harvest fruit abscission, an indicator of the realization of the yield potential, was determined by tagging 10 representative bunches per sampled tree and counting the number of fruit per branch just before the rainy season, and again at harvest.

At harvest, fruit and core yields were determined for each plot and fruit samples were used to measure yield and quality parameters (fresh fruit weight, volume, fruit/bean ratio, bean size, bean weight, and bean yield). Sampled beans of each treatment were sent to a lab in the Western Highlands Agriculture and Forestry Science Institute (Buon Ma Thuot, Dak Lak, Vietnam) for quantifying major biochemical determinants of coffee quality, such as caffeine, chlorogenic acid, and trigonelline (analyzed by High Pressure Liquid Chromatography method). The economic efficiency of the fertilizer treatments was evaluated using total costs, revenue, and profit.

Soil samples were collected before the first fertilizer application (Feb 2016) and at the end of the experiment (Nov 2018). Soil was sampled at 5 scattered locations in the experimental plot at a depth of 5-30 cm, and samples were mixed well before analysis. Soil acidity was determined by shaking soil samples with 1N KCl solution prior to pH analysis. Soil organic matter content was determined using the Walkley-Black method (Walkley, 1947). Soil N was determined using the Kjeldahl method, available P by Bray II method (Bray and Kurtz, 1945), available K was extracted by H_2SO_4 0.1N, and measured using flame photometer. Soil Ca and Mg cation exchange were measured using atomic absorbance spectrometry (Walsh, 1955). Soil available S was determined using the turbidity comparison method (Chesnin and Yein, 1951).

Statistical analyses were carried out using IRRISTAT and Excel, using one-way ANOVA.

Results

Leaf nutrient status

Leaf nutrient status, related to N, P, K, S, Ca, and Mg, before fertilizer applications was suboptimal throughout the 3-year experiment (Fig. 1). The response of leaf nutrient status to fertilizer application events was almost immediate; 20 days after application of a particular nutrient, its concentration in the indicative leaves returned to the recommended optimum range, usually corresponding to the application rate (Fig. 1).

Leaf N concentration fluctuated from about 2.6% before each urea application, below the recommended threshold, to 3.4%, within the recommended optimum, after it (Fig. 1A), displaying considerable instability. Leaf P concentration, which varied from 0.09-0.1% before fertilizer application, rose to the recommended range from 0.12-0.13% (Fig. 1B). Before fertilizer application, leaf K concentration ranged from 1.92-1.95%, slightly below the minimum threshold (Fig. 1C). After application, however, it tightly corresponded with K application rate remaining very low (1.82%) at K_0 (where no K was applied), highest (2.21 and 2.25%) at FP (270 kg K_2O ha^{-1} $year^{-1}$) and at MOP:polyhalite $K_{180:180}$ (360 kg K_2O ha^{-1} $year^{-1}$), and moderate (2.12%) but within the recommended optimum where applied with 120 kg K_2O ha^{-1} $year^{-1}$ (Fig. 1C).

Leaf S concentration ranged from 0.1-0.11% before fertilizer application events. Interestingly, leaf S concentration exhibited a slight but consistent rise following fertilizer application, even when the application did not contain the nutrient. However, the leaf S concentration response to polyhalite application rate was linearly positive (Fig. 1D). In the control treatments (FP K_{270}, K_0, and MOP K_{120}), leaf Ca and Mg concentrations tended to slightly but consistently decrease in response to fertilizer application events, remaining well below the recommended range. However, similar to the case of S, polyhalite application brought about considerable increases in leaf Ca and Mg status, which tightly corresponded with the fertilizer application rate (Fig. 1E, F).

Vegetative growth

The vegetative growth and development of the coffee trees were significantly affected by the fertilizer treatments (Fig. 2). Branch elongation and the number of internodes developed during the growing season were both lesser at the K_0 treatment, where K was not included in the fertilization practice. Potassium application rates greater than 120 kg K_2O ha^{-1}, supplied through polyhalite or MOP, brought about the highest vegetative growth, significantly

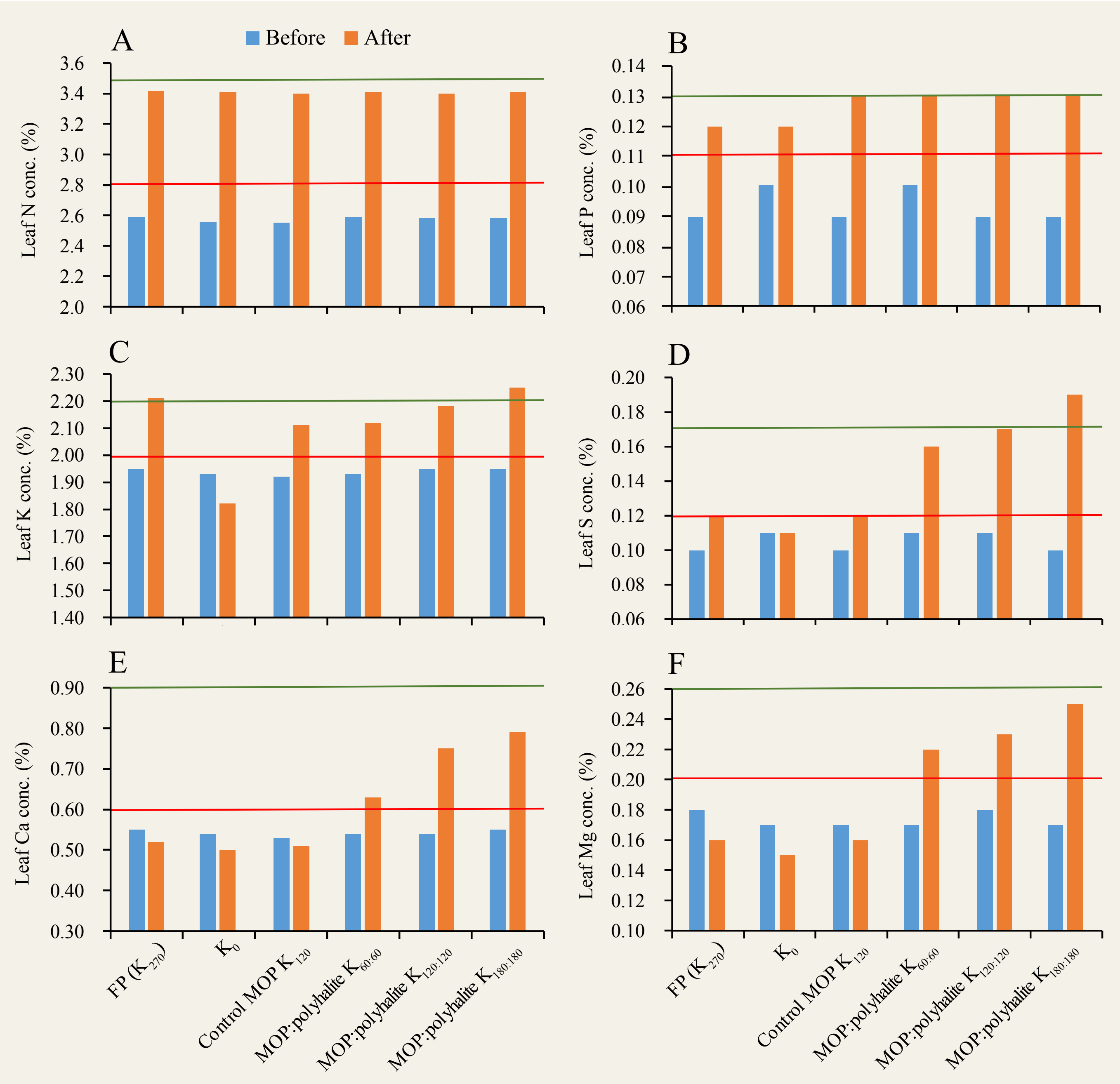


Fig. 1. Effects of fertilizer applications on leaf nutrient concentration in coffee trees grown in the Central Highlands, Vietnam. See Table 1 for the detailed description of the treatments. Measurements were carried out before, and 20 days after fertilizer applications. Values present means of four application events each year (see Table 2), all of which included 3 sampled trees per treatment, with 8 leaves per tree. Red and green horizontal lines indicate the minimum and maximum thresholds, respectively, of the recommended range for each nutrient.

greater than at K_0. The lower K rate (120 kg K_2O ha^{-1}) resulted in intermediate growth levels with no significant differences between trees applied with either MOP or polyhalite + MOP (Fig. 2).

Susceptibility to diseases

The infection rates of coffee rust (*Hemileia vastatrix*) observed during the 3-year experiment were quite low (3.25-4.6%), with no significant influence from the fertilizer treatments (Fig. 3A). In contrast, considerably higher infection rates of green scale (*Coccos viridis*) were observed, with 4.5-13% of the trees infected. The infection rates were significantly higher at treatment

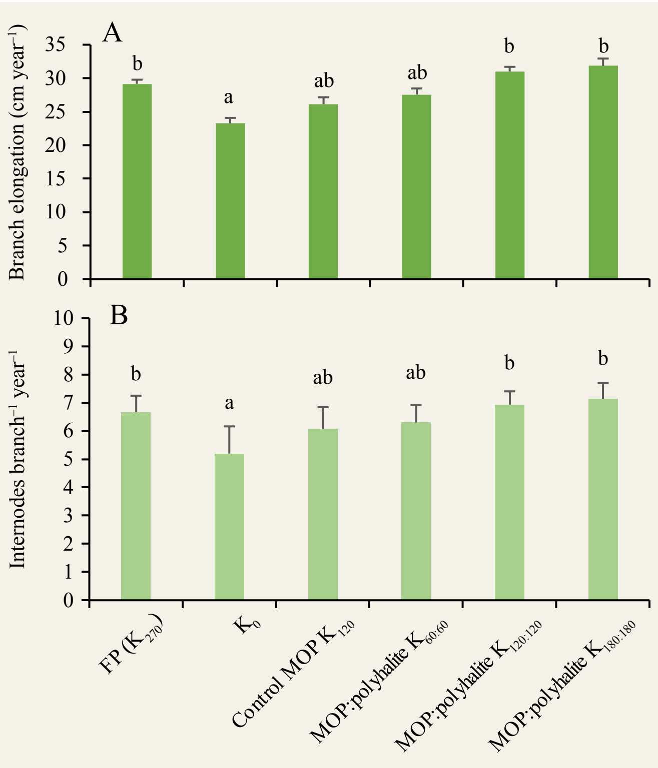


Fig. 2. Effect of fertilizer treatments on branch elongation (A), and the number of internodes per branch (B) as vegetative growth indicators in coffee grown in the Central Highlands, Vietnam. See Table 1 for detailed description of the treatments. Different letters indicate significant differences between treatments (P<0.05).

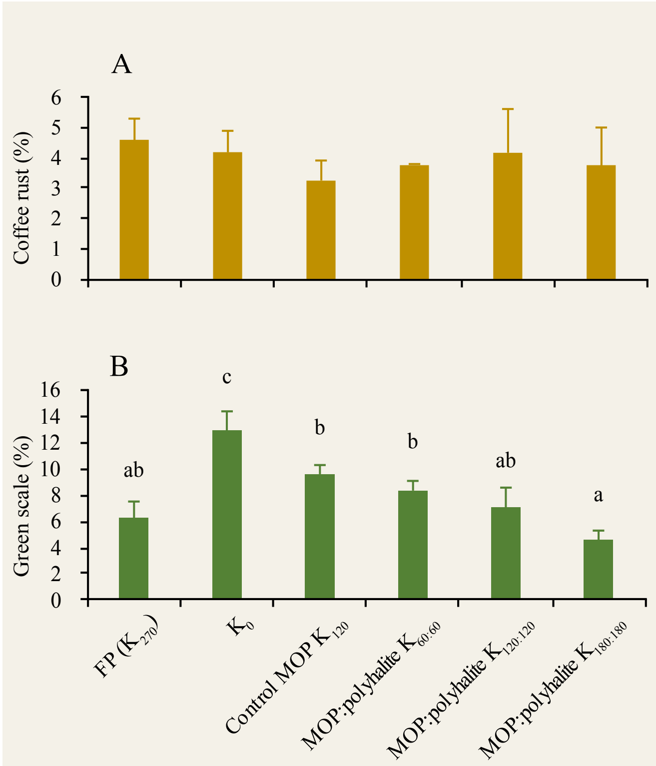


Fig. 3. Effect of fertilizer treatments on coffee rust (A), and green scale infestation rates (B) in coffee grown in the Central Highlands, Vietnam. See Table 1 for detailed description of the treatments. Different letters indicate significant differences between treatments (P<0.05).

K_0, and progressively declined with the increasing K application rate, displaying a significantly lower value at the MOP:polyhalite $K_{180:180}$ treatment (Fig. 3B).

Yield indicators

Pre-harvest fruit shedding was highest, 38%, at the K_0 treatment (Fig. 4A). MOP K_{120} treatment significantly reduced fruit shedding to about 30%; however, fruit shedding was further alleviated at higher K application rates, with shedding rates below 25% when polyhalite was included (Fig. 4A).

Fresh fruit weight (Fig. 4B), as well as fruit size (Fig. 4C), were remarkably affected by the fertilizer treatments. Both parameters exhibited significantly low values at the K_0 treatment and showed clear positive responses to the rise in K application rates. The MOP:polyhalite $K_{60:60}$ gave rise to a higher fruit weight compared to the corresponding MOP K_{120} treatment (Fig. 4B). In addition, MOP:polyhalite $K_{120:120}$, with a rate of 240 kg K_2O ha^{-1}, yielded higher fruit weight and size compared to FP, with 270 kg K_2O ha^{-1} (Fig. 4B, C). Nevertheless, an additional increase of K rate to 360 kg K_2O ha^{-1} (MOP:polyhalite $K_{180:180}$) did not result in a further increase in fruit weight or size.

Fruit/bean ratio was significantly higher (5.60) at K_0, decreased to an intermediate range (4.45-4.60) at rates of 120 and 270 kg K_2O ha^{-1}, but was significantly lower (4.37 and 4.33) under the MOP:polyhalite mixtures at 240 and 360 kg K_2O ha^{-1}, respectively (Fig. 4D).

Fruit and bean yields

The response patterns of both whole fruit and coffee bean yields to the various fertilizer treatments were similar (Fig. 5A, B). Yields were extremely low at K_0 and significantly increased in response to K application at rates ranging from 120-270 kg K_2O ha^{-1}. Maximum yields were obtained at 240 kg K_2O ha^{-1} of mixed MOP and polyhalite, with no further response to the highest K rate (Fig. 5A, B). The response of bean yield to K application rate obeys a quadratic function, where the maximum yield is reached at about 300 kg K_2O ha^{-1}, and begins to decline with further increases in K rate (Fig. 5C). The agronomic K efficiency declines sharply from 15 to 6 kg beans kg^{-1} K_2O as K rate increases up to 360 kg K_2O ha^{-1} (Fig. 5D). Interestingly, both parameters were significantly higher for the combined MOP and polyhalite compared to MOP, at K rates between 120-270 kg K_2O ha^{-1}.

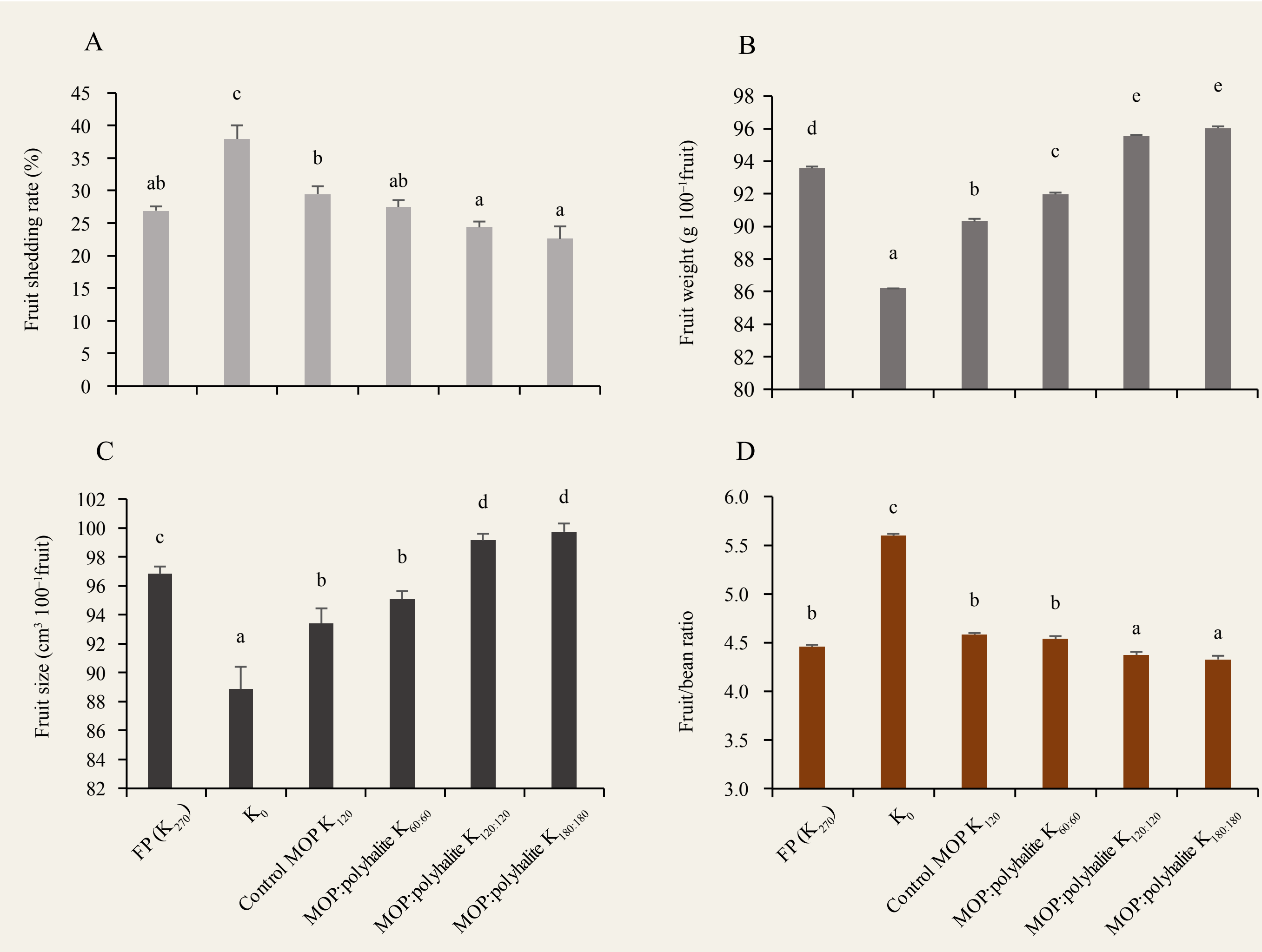


Fig. 4. Effect of fertilizer treatments on coarse yield determinants of coffee grown in the Central Highlands, Vietnam: fruit shedding rate (A); fruit weight (B); fruit size (C); and, fruit/bean ratio (D). See Table 1 for detailed description of the treatments. Different letters indicate significant differences between treatments (P<0.05).

Coffee bean quality

Bean size, an important quality measure in the coffee industry, was evaluated using two parameters: bean weight, and the fraction of large beans (length greater than 6.3 mm). Bean weight, which was very low (8 g 100^{-1}beans) at K_0, significantly increased in response to the stepwise rise in K application rate and was almost double at 240 kg K_2O ha^{-1} (Fig. 6A). Interestingly, bean weight response to the mixed fertilizer (MOP and polyhalite) treatments was significantly stronger than the equal MOP K rate application (120 kg K_2O ha^{-1}). Furthermore, bean weight was slightly greater at the MOP:polyhalite $K_{120:120}$ (240 kg K_2O ha^{-1}) compared to that of the higher MOP K rate (270 kg K_2O ha^{-1}) at the FP (K_{270}). Nevertheless, no further response of bean weight was observed when the K rate was raised to 360 kg K_2O ha^{-1} (Fig. 6A).

The response patterns of bean weight to the fertilizer treatments corresponded closely with the fraction size of large beans (> 6.3 mm); however, the differences between the mixed MOP and polyhalite and the pure MOP treatments were less pronounced (Fig. 6B).

The concentrations of caffeine, chlorogenic acid, and trigonelline, highly desirable natural compounds and important indicators of coffee quality, displayed considerable responses to the fertilizer treatments (Fig. 7). Caffeine concentration showed a significant linear increase as a function of K application rate (Fig. 7A). Chlorogenic acid and trigonelline displayed similar response patterns; however, the response rates slightly decreased with the rising K rates, and hence, a more accurate description was provided using quadratic rather than linear functions (Fig. 7B, C). No consistent effects were observed for polyhalite with regard to these coffee quality indicators.

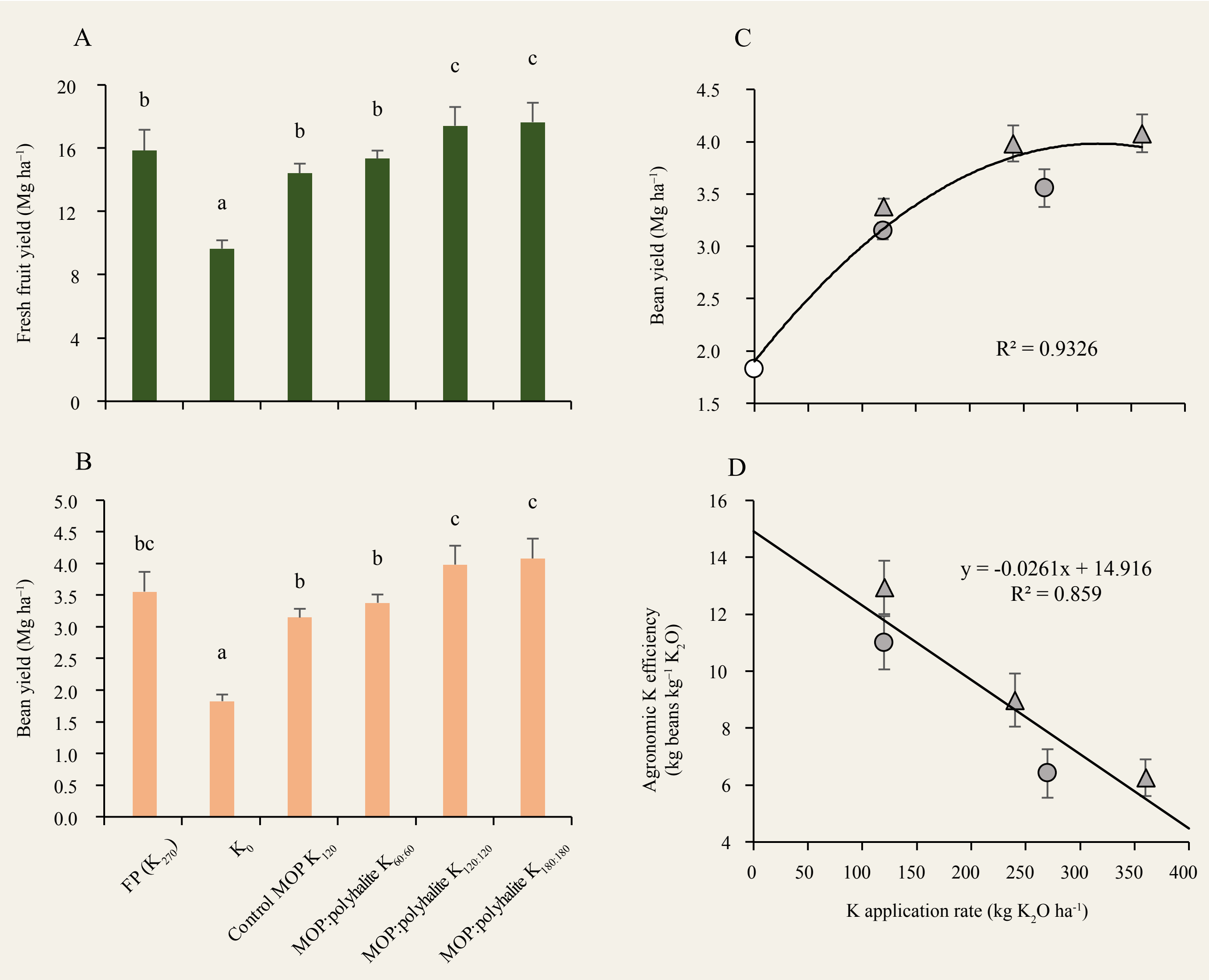


Fig. 5. Effect of fertilizer treatments on fresh fruit (A) and bean yields (B), and the effect of K application rate on bean yield (C) and agronomic K efficiency (D) in coffee grown in the Central Highlands, Vietnam. See Table 1 for detailed description of the treatments. Different letters indicate significant differences between treatments ($P<0.05$). Circle, and triangle symbols indicate MOP and MOP:polyhalite fertilizer treatments, respectively.

Economic considerations

Potassium application, with or without polyhalite, brought about a relatively small increase in the cost of coffee cultivation, ranging from 11-28 million VND ha^{-1} $year^{-1}$, compared to no K application. The difference in cost between the local farmers' fertilization practice and the highest fertilizer rates in the experiment were much smaller – less than 12 million VND ha^{-1} $year^{-1}$ (Fig. 8). In contrast, K application rates ranging from 120-360 kg K_2O ha^{-1} gave rise to 72-123% increase in income compared to no K application (Fig. 8). The boost in profit was especially pronounced, increasing from 10.4 at K_0 to 50-70 million VND ha^{-1} $year^{-1}$ where K fertilization was practiced. The highest profit, 69.8 million VND ha^{-1} $year^{-1}$, was obtained at the MOP:polyhalite $K_{120:120}$ treatment, 9.2 million VND ha^{-1} $year^{-1}$ (15.3%) greater than that of the farmers' practice. Additionally, an increase in K application rate to 360 kg K_2O ha^{-1} (MOP:polyhalite $K_{180:180}$) did not yield any further effect of the profit. At the lower K rates, 120 kg K_2O ha^{-1}, the combined MOP and polyhalite treatment had a slightly higher profit compared to MOP alone, 55 and 50.2 million VND ha^{-1} $year^{-1}$, respectively, but less than that of the farmers' practice (Fig. 8).

Effects on soil fertility

Soil properties and nutrient status were evaluated in 2016, at the beginning, and after three years at the end of the experiment. Soil acidity (pHKCl of 4.0-4.1) and organic matter content (2.85%) did not change throughout the 3-year experiment. Total N, P_2O_5, and K_2O were poor at the beginning of the experiment, with 0.17, 0.08, and 0.11%, respectively. Soil K content extensively declined from 97.4 to 90.5 mg K_2O kg^{-1} at the K_0 treatment. Much smaller decreases were observed at K application levels of 120 kg K_2O ha^{-1}, whereas soil K levels slightly and proportionally increased at rates of 240 kg K_2O ha^{-1} and above (Fig. 9A).

Soil S content slightly decreased but was maintained at a range from 20-21 mg kg^{-1} at the three treatments that were not applied with polyhalite. However, soil S considerably increased in proportion to the polyhalite application rate (Fig. 9B). Similarly, soil available Ca content tended to slightly drop in the absence of Ca application, but clearly and proportionally increased after the polyhalite application during the 3-year experiment (Fig. 9C). A similar pattern was observed for soil available Mg, which decreased in the absence of Mg application, and increased with the polyhalite treatments (Fig. 9D).

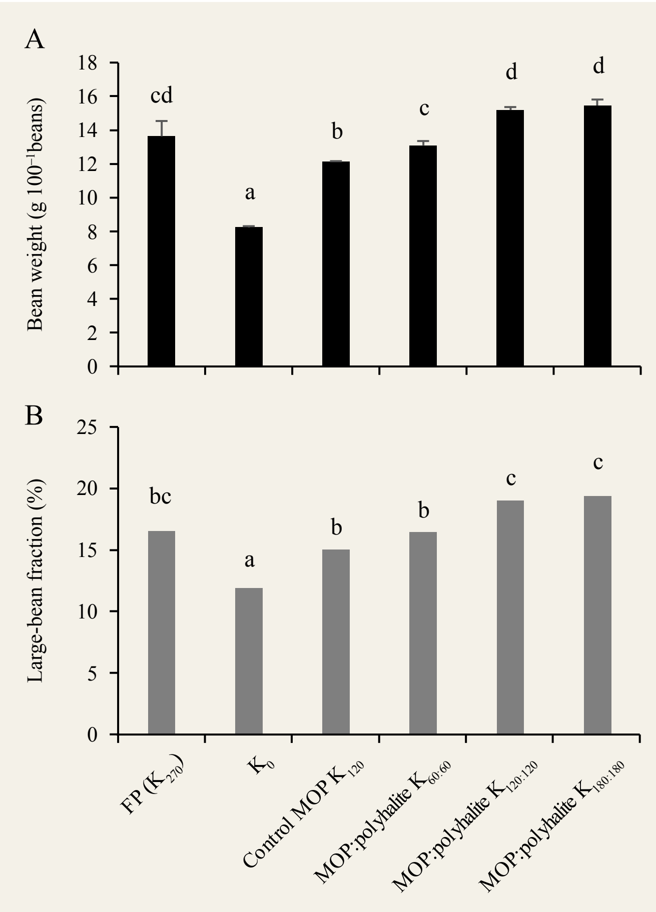


Fig. 6. Effect of fertilizer treatments on coffee bean quality parameters: bean weight (A), and large-bean (> 6.3 mm) fraction (B). See Table 1 for detailed description of the treatments. Different letters indicate significant differences between treatments (P<0.05).

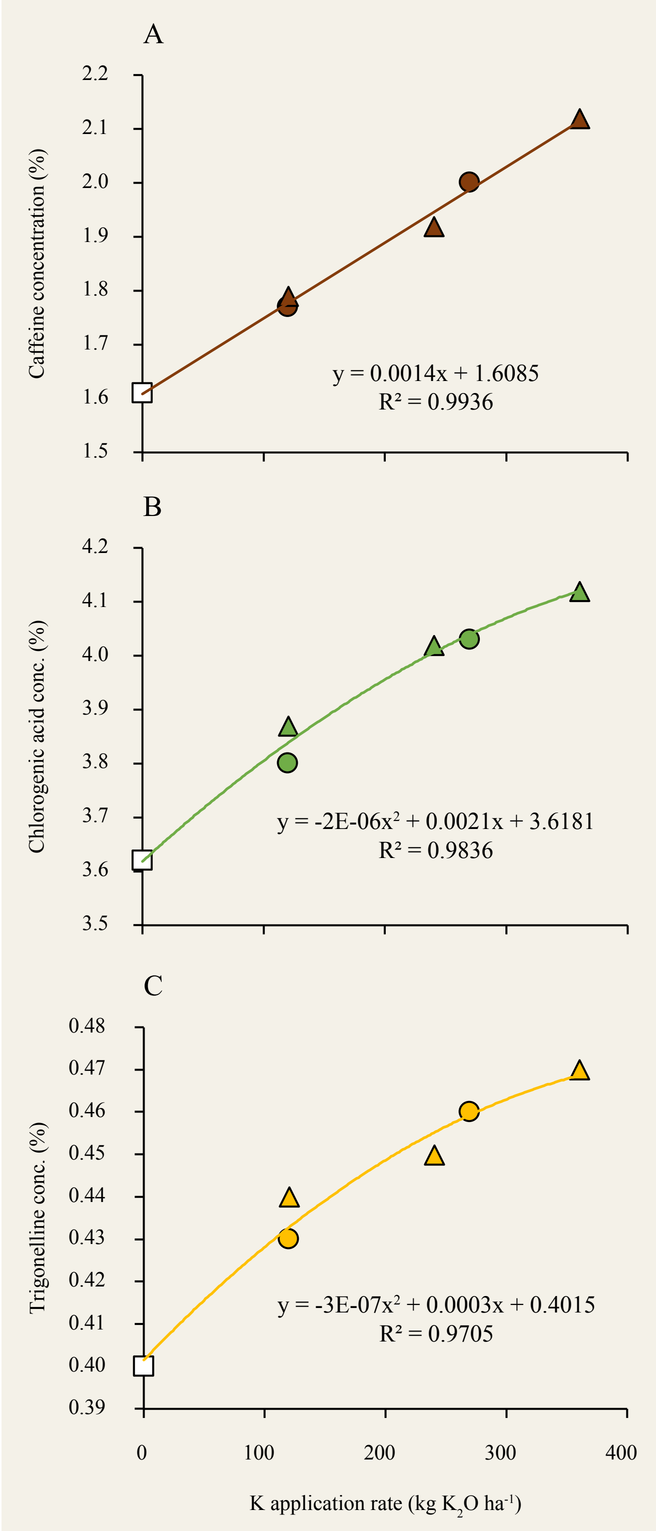


Fig. 7. Effect of K application rate on caffeine (A), chlorogenic acid (B), and trigonelline (C) concentrations in coffee beans. The square, circle, and triangle symbols indicate no K (K_0), MOP, and MOP:polyhalite fertilizer treatments, respectively.

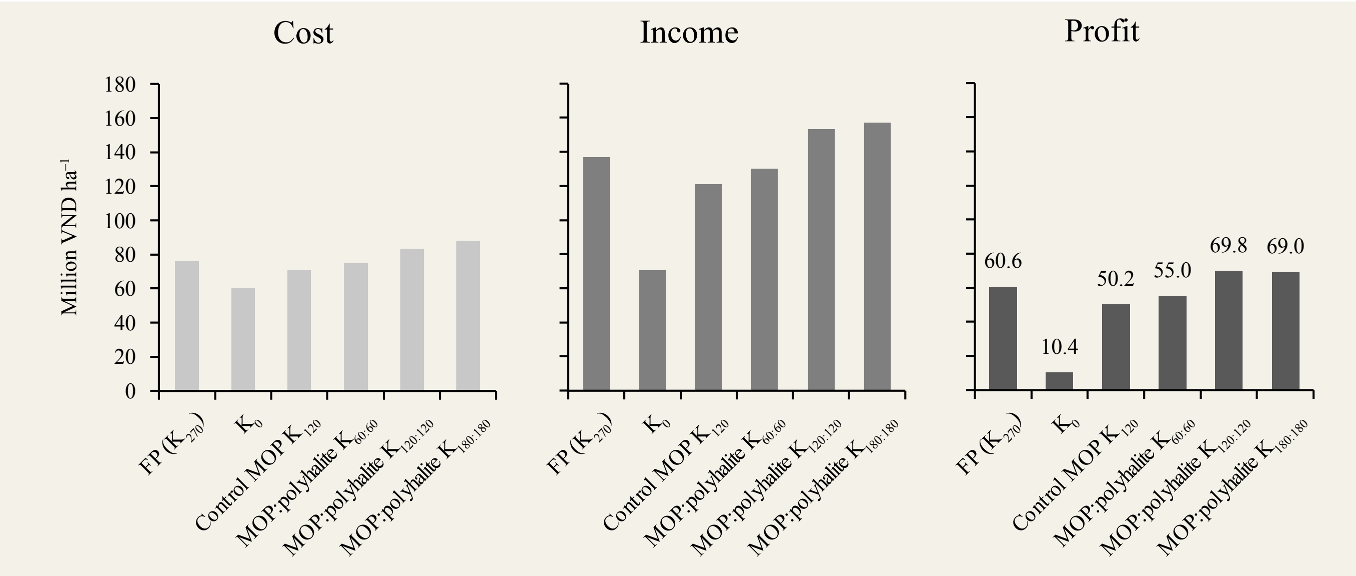


Fig. 8. Effects of the fertilizer treatments on the cost, income, and profit of one hectare of coffee cultivation per year in the Central Highlands, Vietnam. See Table 1 for detailed description of the treatments.

Discussion

None of the fertilizer treatments had a long-term effect on soil acidity, which remained very high (pHKCl 4.0-4.1). High soil acidity, a serious problem typical of humid tropical regions (Mintesnot *et al.*, 2015; Tiemann *et al.*, 2018; Byrareddy *et al.*, 2019; Sanchez, 2019), requires systematic solutions that are beyond the scope of the present study. The significant degradation of soil available K in the absence of K application (K_0) indicates that the intrinsic soil sources for this nutrient are poor and cannot support long-term coffee production. Soil K recovery was slightly improved at 120 kg K_2O ha^{-1}, however, a tendency for soil K buildup was noticed only at an application rate of 240 kg K_2O ha^{-1} and above (Fig. 9A). Polyhalite demonstrated a capacity to support soil K status at a level which was at least similar to that of MOP. In this sense, however, polyhalite application halted the degradation of soil available Ca, Mg, and S, demonstrating considerable improvement in soil nutrient status, from poor soil S, and very poor soil Ca and Mg at the beginning of the experiment to more acceptable levels at its end (Fig. 9). Consecutive polyhalite applications, therefore, may enrich the soil with these nutrients, among which Ca has significant effects on soil structure and texture (Sanchez, 2019).

Nevertheless, the substantial fluctuations in the leaf nutrient concentrations, before and after fertilizer applications (Fig. 1), indicate a chronic inability of productive coffee trees to rely on the fertility of the local soil. Moreover, this phenomenon highlights the fragile nutrient supply under the current fertilizer practices. Although the duration of maintained optimal leaf nutrient status between applications remains obscure, the fluctuations during the growing season were significant even under the high application rates suggesting a need for further efforts to stabilize the mineral nutrition of coffee trees in the region.

Although not within the focus of the present study, N may serve as a suitable example for such needs. Nitrogen was applied in the form of urea, a fertilizer known for providing very high N availability to plants, but also for having a very short durability in the soil (Witte, 2011). Nitrogen use efficiency in crop production is generally well below 50%, resulting in economic losses and creating ecological problems including groundwater pollution and emission of nitric oxides (Ladha *et al.*, 2005; Yadav *et al.*, 2017). The seasonal N dose in the experiment was 300-322 kg ha^{-1}, which might be suitable for coffee production on the Feralic Acrisol of Dak Ha, Kon Tum province. However, N fertilization practice for coffee in the region seems to require reassessment in order to optimize tree nutrition, increase the farmers' profits, and avoid negative environmental consequences.

The tight relationship between nutrient availability and leaf nutrient concentration was demonstrated for K, Ca, Mg, and S (Fig. 1); however, stabilizing nutrient flux and subsequently leaf nutrient concentration during the growing season is essential in the efforts to enhance coffee yields and quality. Nitrogen appears to be very important in this regard; it seems that once N is applied, the uptake and temporary leaf concentration of all the other nutrients examined increase, depending on their availability (Fig. 1). Sooner or later, when N concentration diminishes, the other nutrients decline as well. The pivotal role of N in plant metabolism and growth, and the strong interactions it has with other nutrients (Jamal *et al.*, 2010; Marschner, 2012) provide a reasonable explanation for the leaf nutrient fluctuations.

In addition to the need for stabilizing nutrient uptake during the growing season, it is necessary to increase fertilizer supply during the dry season, before plant growth and reproductive development restart (Tiemann *et al.*, 2018). In fact, well-furnished tree nutrient reserves at the beginning of the growing season were shown to significantly enhance coffee crop performance and yield (Forestier, 1969; Lima-Filho and Malavolta, 2003; Malavolta, 2003). With the threatening effects of climate change on the coffee industry in the tropics (Thioune *et al.*, 2020), supplementary irrigation during the dry season should be revisited (D'haeze *et al.*, 2017; Byrareddy *et al.*, 2019) and furthermore, be used for nutrient supply through fertigation.

In an era of climate change and the rising risk of transient water-stress periods, the significance of adequate K supply is highlighted. Among many other important roles in plant physiology, K is pivotal to plant-water relations and management (Marschner, 2012; Zörb *et al.*, 2014). Unequivocally, K application rates ranging from 120-270 kg K_2O ha^{-1} brought about tremendous enhancements in all aspects of coffee crop performance, including vegetative growth (Fig. 2), pest tolerance (Fig. 3B), fruitlet persistence and yield determinants (Fig. 4), fresh fruit and bean yield parameters (Fig. 5), and coffee bean quality traits (Fig. 6). In most cases, no advantages could be identified for any further increase in K rates. These results suggest a slight reduction of the recommended K dose, particularly if it would be partially supplied through polyhalite.

The effects of polyhalite on coffee crop performance were less significant compared to those of the K rates, which might be attributed to the present study's three year duration being inadequate for long-term evaluations. Nevertheless, polyhalite demonstrated reasonable capacity as a K donor fertilizer, which was even better than MOP in several aspects such as fresh fruit weight (Fig. 4B), bean weight (Fig. 6A), and agronomic K efficiency (Fig. 5D). However, the exact reasons for the differences between MOP alone and MOP + polyhalite treatments require further research, as there was only one case where K rates were similar (MOP K_{120} and MOP:polyhalite $K_{60:60}$). Clearly, polyhalite application enhanced the crop nutrient status, increasing leaf Ca, Mg, and S concentrations (Fig. 1).

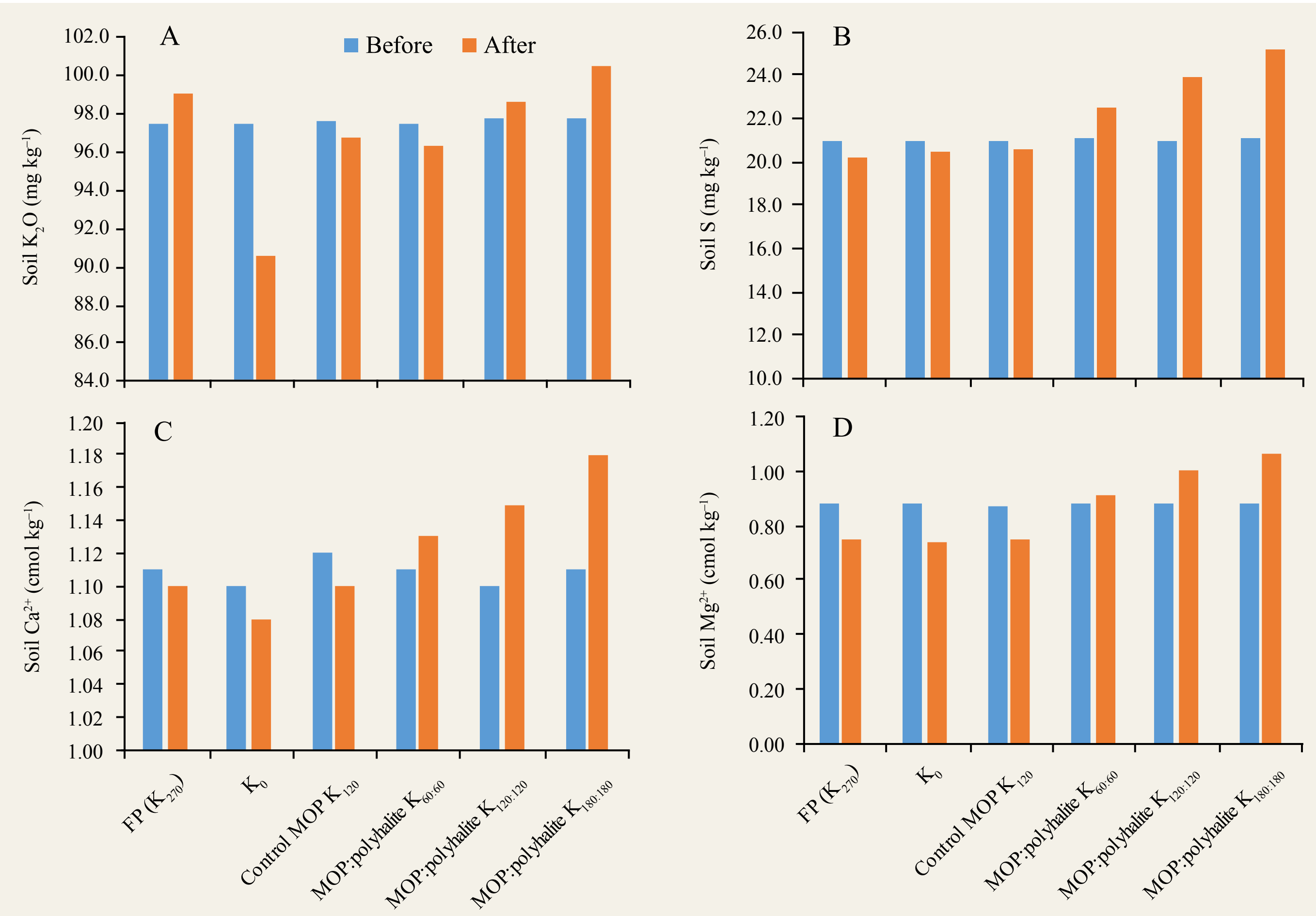


Fig. 9. Effect of fertilizer treatments on the soil nutrient (K, S, Ca, and Mg) status, as measured before the first fertilizer application in 2016, and after the last harvest in 2018, three years later. For detailed description of the treatments refer to Table 1.

Most of the recent analyses of the Vietnamese coffee industry point to the essential need to optimize crop fertilizer practices through a more balanced macro and micronutrient application in order to increase coffee yield and quality, and to avoid nutrient pollution of soil and water resources due to excess spreading of fertilizer (De Geus, 1973; Tiemann *et al.*, 2018; Byrareddy *et al.*, 2019). Interestingly, the current farmers' practice in the region meets N, P, and K requirements, but it fails to supply essential macronutrients such as Ca, Mg, and S, as evidenced by leaf nutrient status (Fig. 1D-F) and by the degrading soil status of these nutrients (Fig. 9B-D). Polyhalite application appears to pave a way toward addressing imbalanced nutrition and introducing nutrients into the coffee production system that are currently lacking. An economic analysis shows that polyhalite application also helps farmers' to increase their profits. At an application rate of 240 kg K_2O ha^{-1}, replacing 50% of dose with polyhalite gave rise to much greater profits, compared with equivalent or even higher MOP application rates (FP K_{270}) (Fig. 8C).

Conclusions

Balanced mineral nutrition is essential for maintaining and enhancing coffee production in the Central Highlands of Vietnam. Without balanced nutrition, coffee yield and quality, as well as soil fertility, would continue to degrade. Polyhalite application was at least equivalent to MOP in providing crop K requirements. Moreover, polyhalite improved trees' Ca, Mg, and S status, while also stopping the decline of these nutrients in the soil. At equivalent K doses, polyhalite mixed with MOP brought about higher coffee bean yields and quality, with consequently higher profits to farmers, compared to MOP alone. In the long run, however, additional modifications of coffee fertilization practices should be examined in the region in order to stabilize tree nutrient status, thus supporting further enhancement of the region's coffee industry.

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The paper "Polyhalite Effects on Coffee (*Coffea robusta*) Yield and Quality in Central Highlands, Vietnam" also appears on the IPI website.