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Optimizing Crop Nutrition

Editorial

Dear readers,

Population growth, urbanization, diets becoming more diverse: all these are increasing demand for more vegetables and fruits.

However, consumers do not just want quantity, most of us want quality too. Quality is consistently rated higher in importance than price, brand name or freshness.

Of all essential plant nutrients, potassium is often referred to as the 'quality element' in crop production: grains are bigger; more protein, oil and vitamin C content in grains, fruits and vegetables; increased size of fruits and tubers; enhanced fruit color and flavor; and improved storage, ease of shipping and longer shelf life.

Numerous on-farm trials within IPI projects have proved that balanced fertilization ticks all the quality criteria boxes. The farmer who practices balanced fertilization will have better market opportunities, get higher prices and increased income. Scale this up across a region and it is easy to see how the application of balanced fertilizer benefits the whole nation with better social stability, less migration and, last but not least, better export opportunities of competitive high-quality produce.

In October this year, again we celebrate FAO's World Food Day to promote global awareness and action for those who suffer from hunger. While food security is vitally important, and fertilizers are important in achieving that, we also have a responsibility to farmers everywhere to help them achieve the best quantity and quality in their crops.

In this quality *e-ifc* edition, we present a paper on the experiment in Vietnam with polyhalite on coffee. There is also a paper on cabbage response to potash fertilization in demonstration plots in India.

I wish you an enjoyable read and that you stay safe!

Dr. Patricia Imas
IPI Scientific and Communications Coordinator

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Photo cover page: Almond orchard in Israel. Photo by N. Cohen Kadosh.

Research Findings

Cabbages grown with (right) and without (left) potash fertilizer, from demonstration plots in Nasik, Maharashtra, India. Photo by Potash for Life.

Response of Cabbage to Potash Fertilization in Field Plot Trials Conducted in Jammu & Kashmir, West Bengal and Maharashtra

Bansal, S.K.[(1)*], P. Imas[(2)], and J. Nachmansohn[(3)]

Abstract

Potassium (K) in Indian agriculture operates at an annual deficit of nearly 10 million tonnes (Mt) and has increasingly become a limiting nutrient adversely affecting both yield and quality of agricultural and horticultural produce. Lower additions on the pretext of soils being rich in available potassium have further exacerbated the situation. For demonstrating the usefulness and criticality of potassium as a yield-limiting nutrient, Indian Potash Limited conducted field experiments as a part of the Potash for Life (PFL) project to evaluate the K response in cabbage, and to demonstrate to farmers the increased yield and profitability obtained with muriate of potash (MOP) on the K-depleted soils. A simple and straight forward methodology was applied; the yields of two identical plots positioned side by side were recorded with the only difference that one of them was fertilized with additional K. Results from all trial plot-pairs showed a significant yield increase response to the MOP addition; average yield increase was statistically significant and stable at 3,139 kg ha^{-1} (absolute) or 11.8% (relative).

Keywords: Cabbage, potash fertilization, field plot trials, relative yield, mean, median

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Introduction

Despite concerted efforts towards industrialization, particularly over the past three decades, the Indian economy still continues to be an agricultural one. Contribution of agriculture to the India's GDP is 14% against 7% of China (World Bank, 2019). Value of Indian agriculture to the domestic economy has increased by more than US$ 1 billion since 2010. The size and growth of the Indian economy is dependent on the quality and fertility of soils as it directly influences the sustainability and profitability of agriculture. Soil fertility management is, therefore, central to sustenance of productivity and nutritional security (Prasad and Power, 1997). Fertilizer use is essential in arresting the fertility decline and realizing the potential crop yields.

Fertilizer constitutes one of the highest running costs of agricultural systems. Yet, if used correctly it can also be one of the most profitable investments. Imbalanced and incorrect use of fertilizers is known not only to lower the nutrient use efficiency, but it can also cause deterioration of soil quality (Wallace, 2008). Promotion of balanced fertilizer is, therefore, a must for prevention of both soil fertility decline in case of insufficient use, or soil quality deterioration arising out of over-fertilization exacerbated by the imbalanced use. Depletion of soil potassium (K) is a major factor for decline in soil fertility. Loss of K is most significant in developing countries such as India, where K-deficit is around 11 Mt (Tan *et al.*, 2005); in the developed and least developed areas of the world it is only 900 t and 1 Mt, respectively.

A number of cabbage-specific field trials have been carried out by different researchers in India to examine the effect of different fertilization regimes on yields. These trials are designed to understand the combination of fertilizer inputs best suited to improving soil fertility and therefore yield levels. These have included NPK, farmyard manure and vermicompost in different ratios. However, to date no field trials have been carried out as a means to examine the specific effects of K on cabbage yield levels in the country.

Cabbage is a rich source of vitamins (A, B_1, B_2 and C) as well as vital minerals such as calcium (Ca), sodium (Na), potassium (K) and phosphorus (P) – important to human health. Additionally, edible cabbage leaves contain water, carbohydrates and fiber which serve to improve the human health. Originating in Europe, cabbage found its way to Asia through Egypt and Mesopotamia. It was brought to India by Portuguese settlers during the middle of the second millennium. The absence of Sanskrit words for cabbage suggests that it arrived later than other vegetables.

Today, India ranks among the world's top two cabbage producers by volume (8.8 Mt – Fig. 1) after China. Despite being among the top three producers worldwide, yield levels of cabbage are particularly low in India at just 22 t ha^{-1} compared to 30–35 t ha^{-1} in China and Russia (Fig. 1). Vulnerability of the Indian soils to depletion of nutrients through years of intensive and aggressive agricultural

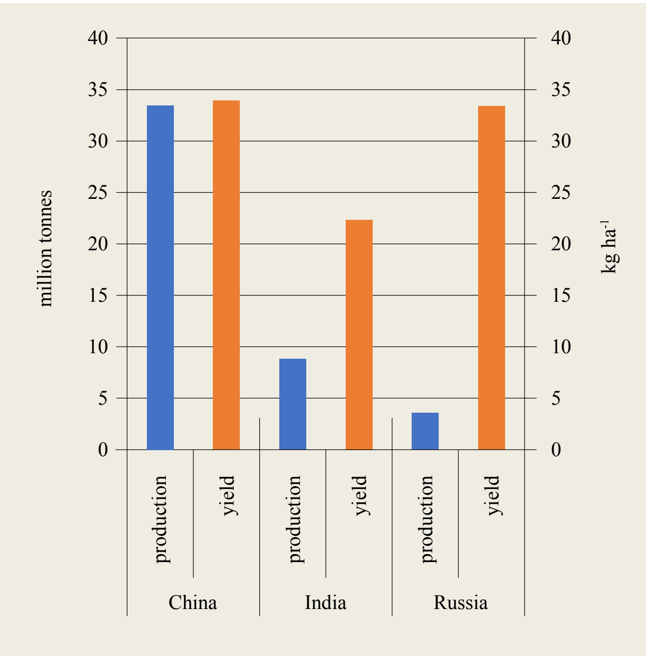


Fig. 1. Annual production and average yields of cabbage in top three countries.

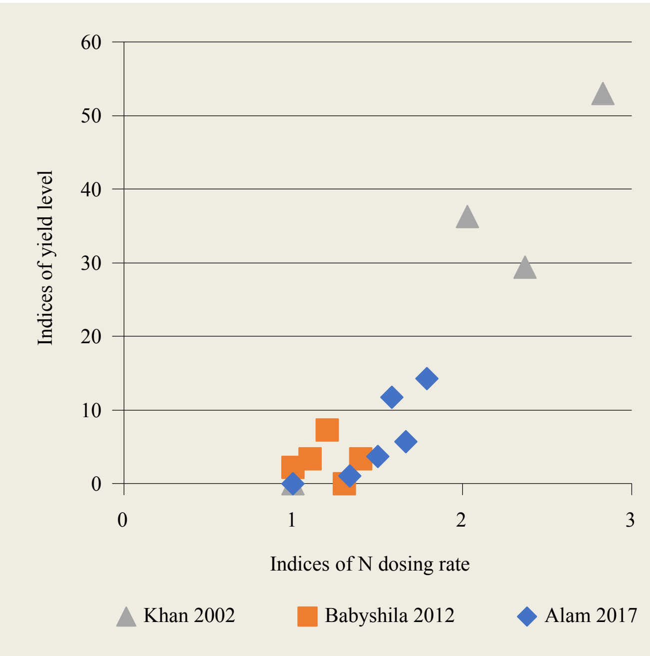


Fig. 2. Examples of results from literature on field trials on cabbage yield levels
Note: Compilation of results on cabbage field trials (nitrogen). Results on the effects of nitrogen in all papers are clear; however there is an absence of field trials on K in cabbage in India (author's own analysis).

Table 1. Fertilizer type and dose applied to the two treatments in both cabbage demo plot trial in Jammu and Kashmir in India.

Fertilizer source	Treatment (size of dosage)*			
	Control	+ K	Control	+ K
	-----------*kg ha*$^{-1}$-----------		----------*kg plot*$^{-1}$----------	
N (from urea + DAP)	75 or 45		30 or 18	
P_2O_5 (from DAP)	60		24	
K_2O (from MOP)	0	35 or 48	0	14 or 19.2
Manure (tonnes)	15-20		6-8	

* There were only two sites in Jammu and Kashmir. Different dosing sizes were used in the two plots as shown here.

Table 2. Fertilizer type and dose applied to the two treatments in both cabbage demo plot trials in Maharashtra in India.

Fertilizer source	Treatment (size of dosage)*			
	Control	+ K	Control	+ K
	----------*kg ha*$^{-1}$----------		----------*kg plot*$^{-1}$----------	
N (from urea + DAP)	150		60	
P_2O_5 (from DAP)	75		30	
K_2O (from MOP)	0	150	0	60
Manure (tonnes)	1 or 2		0.4 or 0.8	

* Of the two plots in Maharashtra, all dosing rates were the same except for manure (either 1 or 2 tonnes per hectare).

practices also makes it imperative to go in for the balanced fertilization in cabbage.

Cabbage is a heavy feeder of N and K and use of these nutrients has been made in its cultivation; rates of application depend on climatic conditions, local soil types and cropping intensity. Interestingly, it was found in a study where technology adoption behaviors by the Indian tomato and cabbage growers were compared that neither the fertilizer cost nor availability of fertilizer was a constraint on adoption of cabbage cultivation technology (Asati *et al.*, 2013).

Response of cabbage to different fertilization treatments in India has been studied (Khan *et al.*, 2002; Babyshila and Irabanta, 2014; Alam *et al.*, 2017; Islam *et al.*, 2017; Chaudhary *et al.*, 2018; Srivastava *et al.*, 2018) (Fig. 2). However only one of these fertilization treatments included specific isolation of K effects on cabbage yield levels (Srivastava, 2018). Recognizing the importance of K as one of the main limiting factors in crop production, a collaborative project between Indian Potash Limited (IPL) and International Chemical Limited (ICL) Fertilizers named "Potash for Life (PFL)" was launched to improve the understanding on effect of potash on economically-significant and heavy-feeding crops such as cabbage; and to demonstrate to farmers the increased yield and profitability through fertilizing with muriate of potash (MOP) on K-depleted soils. It was specifically launched to address the recent negative development in potash (KCl) use in India, and to support the farm sector profitability. Main objectives of the study included to i) demonstrate on the farmers' fields the increased yield and profitability through application of MOP in addition to conventional use of DAP, urea and manure, ii) evaluate cabbage response to MOP according to recommended fertilizer blends on K- deficient soils, and iii) study the influence of secondary factors, if any, on the cabbage yields.

Table 3. Fertilizer type and dose applied to the two treatments in all cabbage demo plot trials in West Bengal in India.

Fertilizer source	Treatment (size of dosage)*			
	Control	+ K	Control	+ K
	----------*kg ha*$^{-1}$----------		----------*kg plot*$^{-1}$----------	
N (from urea + DAP)	180		23.4	
P_2O_5 (from DAP)	50		6.5	
K_2O (from MOP)	0	50	0	6.5
Manure (tonnes)	2-22		0.8-2.9	

* All dosing rates were the same in West Bengal except for manure which varied significantly between plots as indicated.

Materials and Methods

Experimental Setup

Trials for K response in cabbage were conducted in the states of West Bengal, Maharashtra and Jammu and Kashmir. On each farm, a pair of equally-sized cabbage plots was laid side-by-side; one for the control to receive a standard fertilizer treatment containing N and P and other to include the same treatment plus MOP. Plot sizes within each pair were the same; however, the sizes of the plots were either 0.13 or 0.4 ha depending on farm location. Irrigation was either through a canal system or not reported. Plot soil types were either clay-loam, black or not reported. A total of eight cabbage varieties used in the trials were Real Ball, Snowball, Namdhari, Najmi, Green, Resist Crown, Snow Resist and Takiz Coral. All recommended growing practices were followed.

Treatments

The two treatments used consisted of: a) control, where a standard fertilizer treatment of N and P was applied, and: b) '+K treatment', where muriate of potash (MOP) was applied in addition to the other standard treatments. The control and the treatment were, therefore, identical between each plot-pair except for the MOP input in the '+K treatment'. Doses of all three nutrient inputs varied from states to states (Tables 1, 2 and 3).

Statistical Analysis

Outlier test used was 1.5 and 3 times the inter-quartile range for inner and outer fences, respectively. Pairwiset-test was applied to determine the probability whether the differences in the average yield levels between the control and K-treated data sets were due to application of MOP or due to chance. Analysis by pairwise t-test was conducted in one block, comparing all 23 data points in all the three states, with a pairwise t-test (paired two sample for mean), in order to compare control plots with '+K treatment' plots.

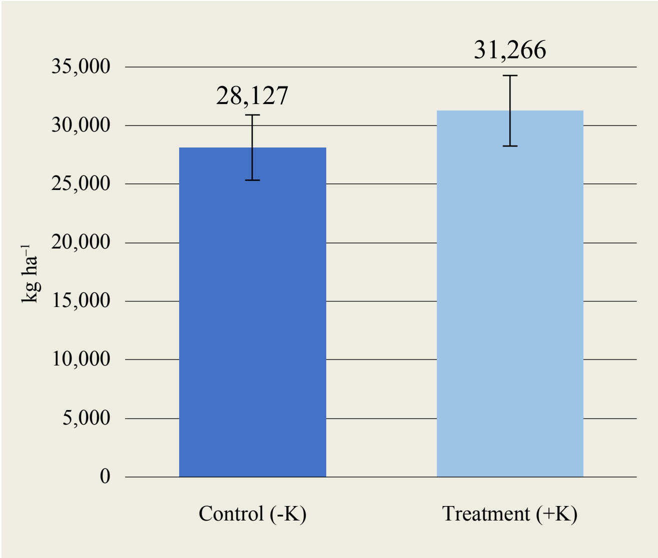


Fig. 3. Average control and +K yield levels. Error bars show one standard error. Results were statistically different despite errors overlapping.

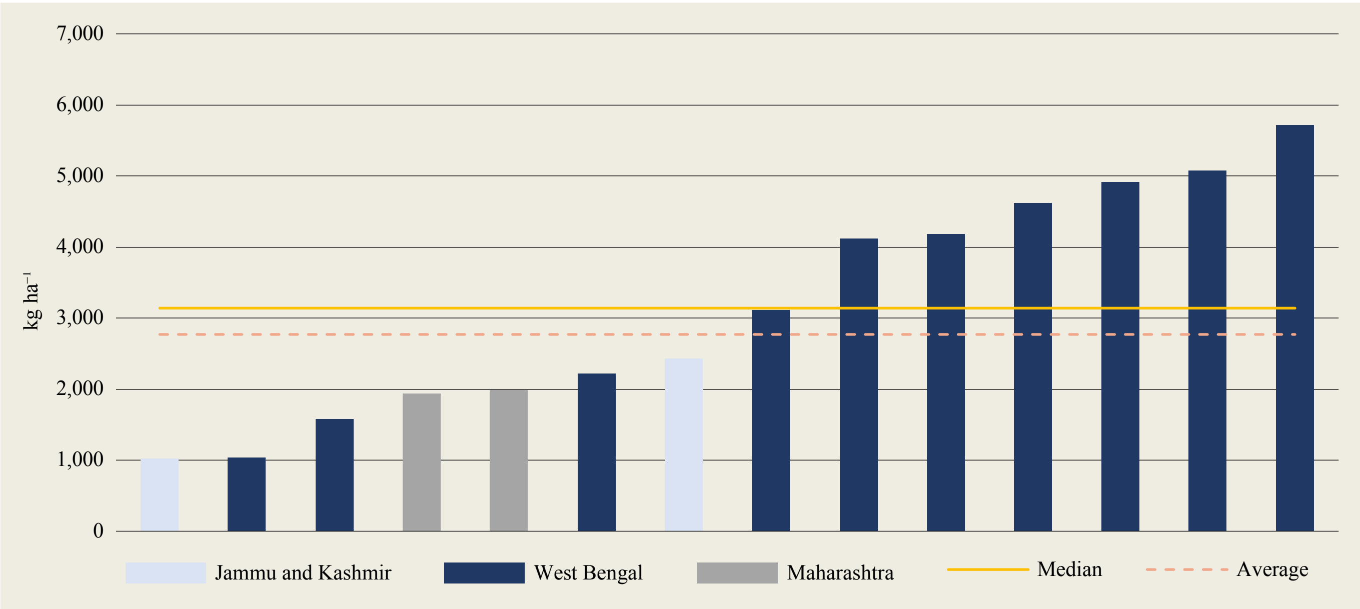


Fig. 4. Absolute yield increases across all sites in order.

Note: Absolute yield increases in all plot-pairs through adding MOP ordered by size. Bar colours represent each state. Solid and orange dotted lines represent average and median values, respectively.

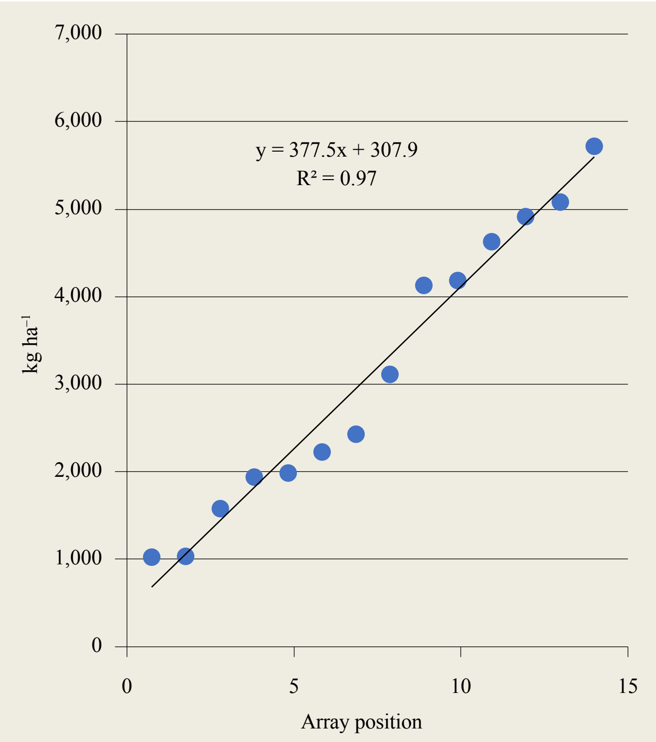


Fig. 5. Actual absolute yield increases (circles) against a linear fit. Data followed the linear distribution closely with an R^2 value of 0.97. The plot annotation indicates the fit of the curve.

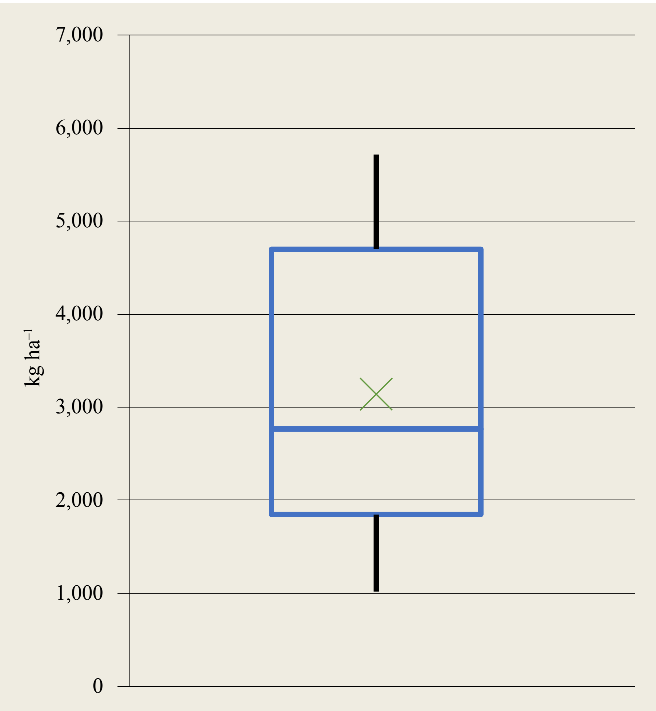


Fig. 6. Spread of absolute yield increases. The median is represented by the middle line, 25th and the 75th percentiles by the upper and lower box edges, the average by the x and maximum and minimum by bar lengths.

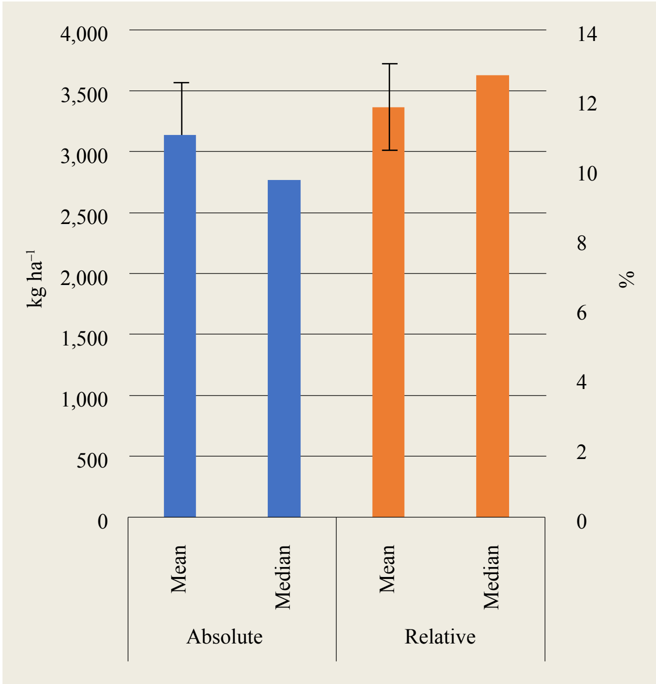


Fig. 7. Average and medians of the yield level increase data. Error bars indicate 1 standard error. The low standard errors indicate stability in the data and the proximities of the average and median values their accurate representation of the data.

ANOVA tests were used to determine which if any independent variables influenced yield metrics. Variables deemed to have influenced results were examined further through post-hoc tests to determine significance between variables. The post-hoc correction type used was Bonferroni with results ranked according to the Holm principle; linear regressions on continuous dependent variables (i.e., fertilizer dosing rates).

On account of flooding, nine out of the 23 plot-pairs had to be abandoned. These data were, therefore, precluded from the analysis leaving a total of fourteen sites of interest. The outlier test indicated no outliers in the remaining datasets.

Results and Discussion

Effect of MOP on Cabbage Yield

The average cabbage yield level in the control plots carried out across the three states was 28,127 kg ha^{-1}; across the +K plots, this increased to 31,266 kg ha^{-1} (Fig. 3). Statistical testing indicated that the increase was significant, and that potassium applied as MOP (KCl) had a positive effect on yield over the standard treatment of N and P. Clear benefits of MOP application were registered through an average yield increase of 3,139 kg ha^{-1} (Fig. 4). Increases were observed across all fourteen plots under study varying from 1,019 kg ha^{-1} to 5,715 kg ha^{-1}. The median increase was 2,770 kg ha^{-1}.

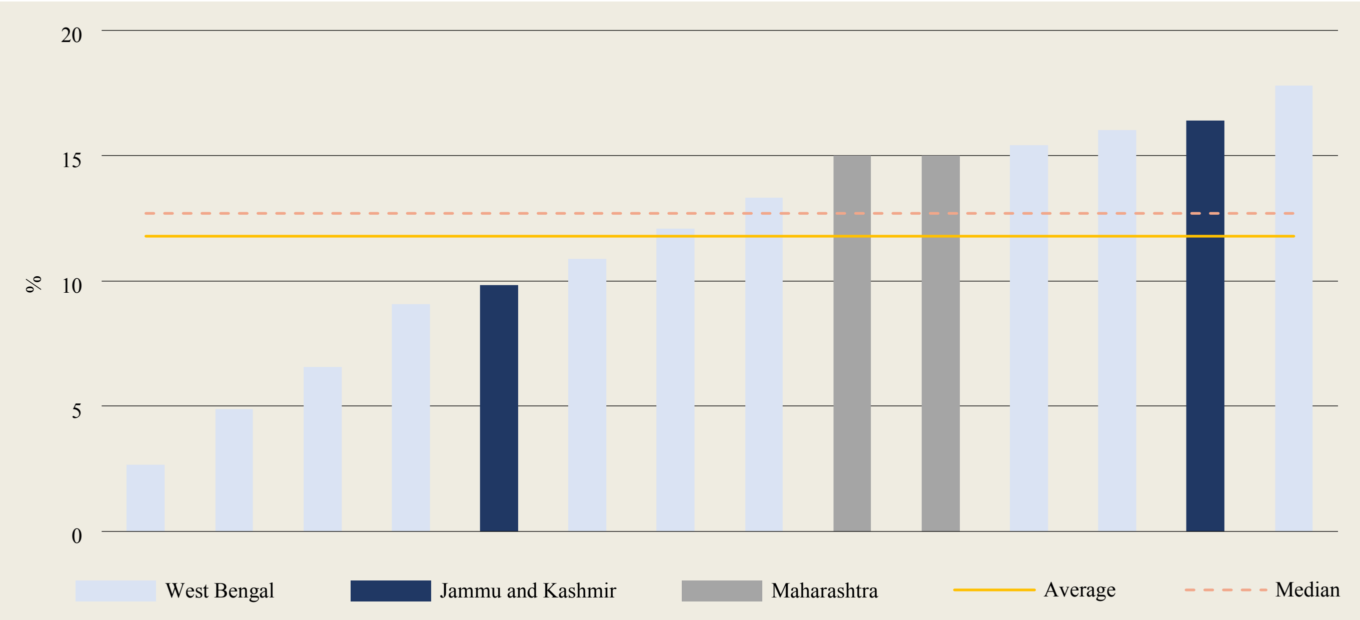


Fig. 8. Relative yield increases across all sites in order.
Note: Relative yield increases in all plot-pairs through adding MOP ordered by size. Bar colors represent each state. Solid and orange dotted lines represent average and median values, respectively.

Verification and Distribution of the Absolute Yield Increase Data

Differences between the control and MOP-treated yield levels were explored through regression analysis (Fig. 5). Absolute yield increase data recorded through the trials demonstrated clear proximity to a linear curve with an R^2 value of 0.97; R^2 value of 1 indicates an exact correlation. The box plot (Fig. 6) illustrates the distribution of the absolute yield increase data. As indicated, the response to MOP application ranged from 1,019 to 5,715 kg ha^{-1}, and the 25th and 75th percentiles were 1,846 and 4,698 kg ha^{-1}, respectively. Plot shows the unequal spread of the data across the range due to a considerable skew towards higher yield increase effects as indicated by the median splitting the data in the lower half of the box. This means that the yield increases at the lower levels were closer together than those at the higher levels. This shape of the data was also confirmed by the median absolute yield increase (box line) being slightly lower than the average ("X" in the box).

Quality of the Yield Increase Data

As in the case of the absolute yield increase data, the average value of the relative yield increase showed stability on account of the standard error (1.2%) being a low proportion of the mean (11.8%) (Fig. 7). Again, as in the absolute yield increase data case, the proximity of the median (12.7%) to the mean (11.8%) indicated their accurate representation of the datasets.

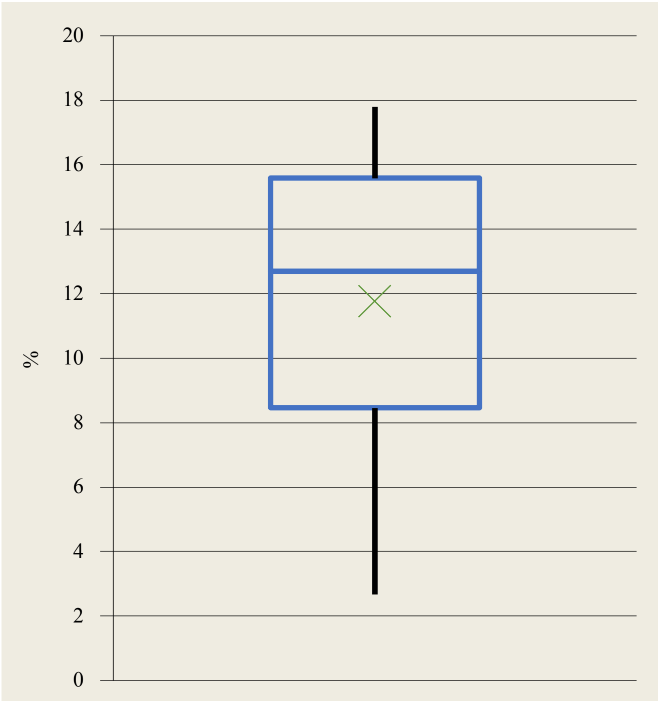
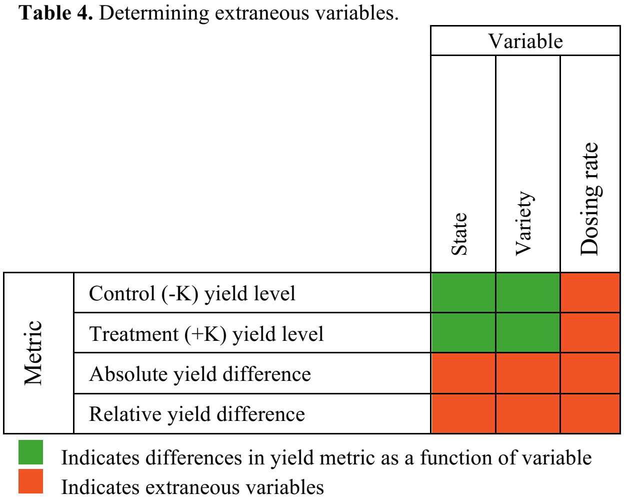


Fig. 9. Spread of the relative yield increases. The median is represented by the middle line, 25th and the 75th percentiles by the upper and lower box edges, the average by the x and maximum and minimum by bar lengths.

Table 4. Determining extraneous variables.



Relative Yield Increase Data and its Relative Distribution

In relative terms, the inclusion of MOP into the standard fertilizer treatment of urea, DAP and manure resulted in an average cabbage relative yield increase of 11.8% with a range of 2.7 to 17.8% and a median value of 12.7% (Fig. 8).

Box plot in Fig. 9 shows the distribution of the relative yield increase data. As indicated, the relative response to MOP application ranged from 2.7 to 17.8%. The median value was 12.7% versus an average of 11.8% and the 25th and 75th percentile values were 9.1 and 15.4%, respectively. Shape of the relative yield increase data spread differed from that of the absolute yield increase data in that it was skewed towards lower yield levels. This means that the yield increases of the higher yield increases were closer together than those of the lower yield increases. This shape of the data was also confirmed by the median relative yield increase (box line), which was higher than that of the mean ("X" in the box); the positions of the relative yield increase average and median were also, therefore, reversed when compared to that of absolute yield increase data (wherein the average was higher than the median).

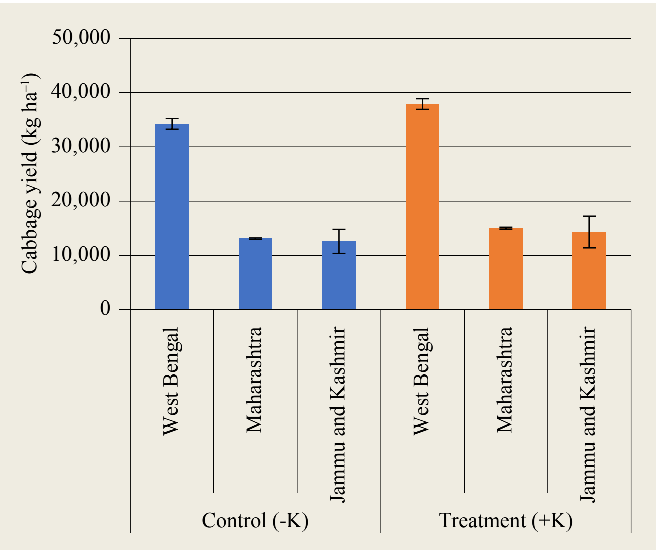


Fig. 10. Effect of state on yield metrics. Control and +K treated yield levels by state. Yield levels were highest in West Bengal compared to Maharashtra and Jammu and Kashmir.

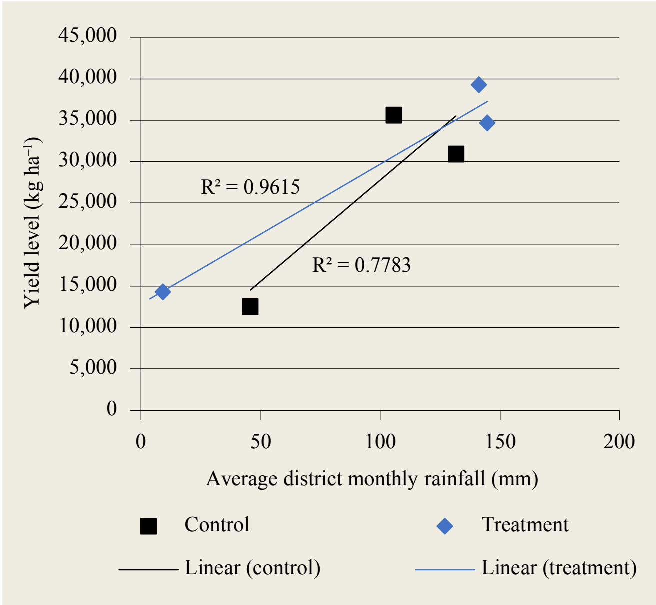


Fig. 11. Possible relationship between average district monthly rainfall and yield levels by district, 2014.

Extraneous Variables

Statistical tests were used to determine whether external variables (namely state, variety of cabbage and dosing rate) had any impact on the yield metric values recorded (Table 4). None of these variables had effect on yield increases; absolute or relative. However, both control yield levels and +K treatment yield levels differed as a function of state and variety of cabbage.

Yield Levels by State

Yield levels were higher in West Bengal than in Maharashtra or Jammu and Kashmir (Fig. 10). The statistical test showed that the average yield levels between Maharashtra and Jammu and Kashmir were effectively the same despite the significant geographic distance between these trials. Errors were markedly higher in the state of Jammu and Kashmir.

It is interesting to note that there may be some correlation between location (district), extent of rainfall and yield levels. A simple regression analysis comparing rainfall in the trial location districts and

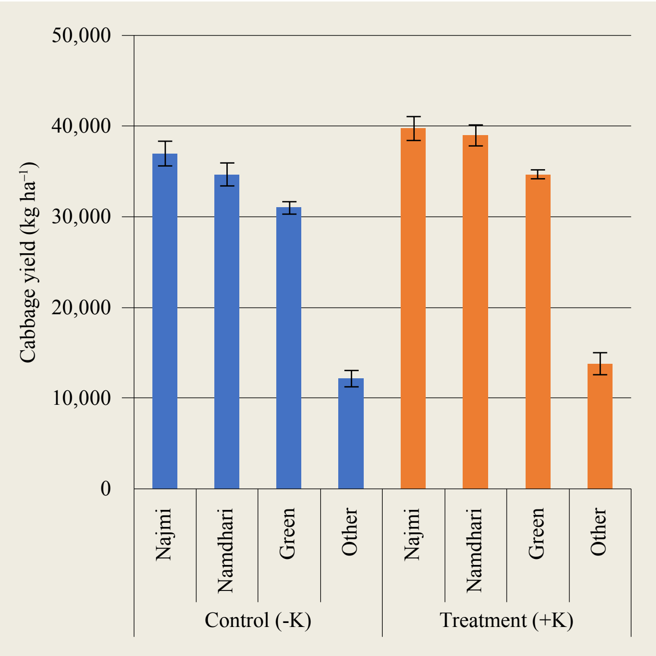


Fig. 12. Effect of variety on yield metrics.

yield levels pointed towards higher rainfall resulting in higher yields in both control and treatment levels (Fig. 11) with R^2 values being 0.78 and 0.96, respectively. No relationship between rainfall and absolute yield levels or relative yield levels was observed. Before any firm conclusions are drawn from the possible relationship between rainfall in trial locations and yield levels, it should be kept in mind that this possible observation is based on only three available data points.

Yield Levels by Variety

Yield levels also differed as a function of cabbage variety. As shown in Fig. 12, yield levels were highest in Najmi and were followed by Namdhari, Green and "Others" (Real ball, Snowball and Takiz Coral – grouped together for brevity). Averages as a function of cabbage variety were shown to be different in all the pairs except for Najmi-Namdhari which indicated no significant difference either in the control yield levels or the +K treated yield levels.

Profitability

Market price of cabbage in this work went largely unreported. Only three sites reported the market price of cabbage; two reported a price of Rs. 35 kg^{-1} and one reported Rs. 20 kg^{-1}. Likewise, cost of MOP was reported in just these three sites alone at a cost of Rs. 16 kg^{-1}. Average benefit to cost ratio of including MOP in the treatment was 82.00 based on average sale price of Rs. 27.5 kg^{-1}, MOP cost of Rs. 16 kg^{-1} and average absolute yield increase of 3,139 kg ha^{-1} (Fig. 13).

Based on a theoretical ±60% – a percentage range chosen based on the spread of yield increases, cabbage price and cost of MOP – the spread of benefit to cost ratios extended from 32.20 to 206.51. Relationship between cabbage price and profitability was linear though the relationship between MOP cost and profitability was non-linear and strongly inversely proportional.

Sensitivity analysis (Fig. 13) depicts the dynamics between cabbage price and cost of MOP on profitability. Analysis indicates that the benefit to cost ratio increases linearly with market price at about 0.8 (i.e. a price increase of 1% from current market price results in an increase in the benefit to cost ratio of about 0.8%). As would be expected, an increase in potash price results in a decrease in benefit to cost ratio. However, this relationship was not linear. It is also worth noting that on account of its non-linearity, rate in the drop of the benefit to cost ratio as a function of MOP cost falls as MOP cost increases; that is to say that at higher MOP costs, its effect on reducing farmer benefit to cost ratios becomes less significant and vice-versa.

It is also noteworthy that the range of MOP prices used in the sensitivity analysis (Fig. 13) includes the range of MOP prices reported across India since 2011 (Rs 8.43 – 28.33 kg^{-1}) (Chanda *et al.*, 2016).

Results of these trail plots clearly show that the inclusion of MOP into fertilization regimes in cabbage in these trials increased the yield levels which were both quantifiable and verifiable through statistical tests. Based on this work, it can be inferred that the cabbage plantation in India can be expected to produce around additional three tonnes per hectare through MOP application. Responses to MOP were positive regardless of location, soil type, fertilizer dosing rates or cabbage

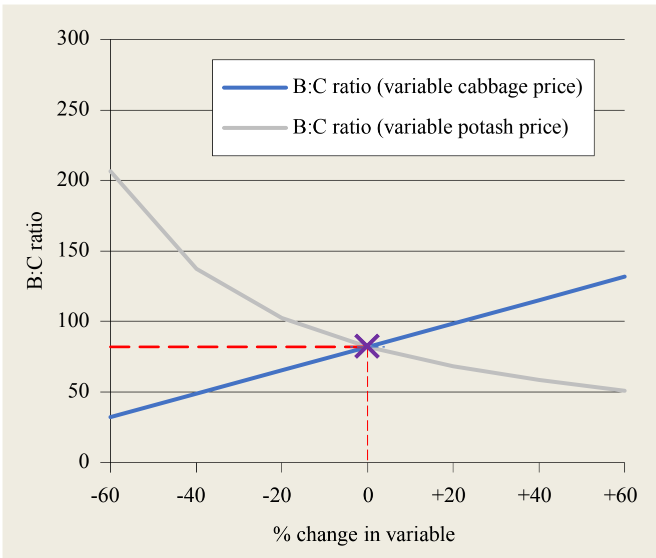


Fig. 13. Benefit:cost ratio sensitivity analysis showing range of benefit:cost ratios for different cabbage prices and potash costs. The red-dotted lines and purple slanted cross indicate the average benefit:cost ratio of 82.00.

variety, and average yield increase values were both high and stable. Even the lowest MOP responses were significant whether considered in relative or absolute terms.

This clear linear distribution trend of the yield increase response from MOP suggests a moderate average natural variability of K depletion within the response range. However, as indicated earlier there is a distinction in yield responses between the states. This indicates differences in the yield levels achievable between states which could be caused by many factors and but these are not simply because of the absence of sufficient K for healthy growth.

Differences in yield levels between the districts can be attributed to differences in geography, practices and levels of K depletion. Climate and topography which are very similar between the states showed different yield levels, e.g. Maharashtra and West Bengal. Therefore, the most likely explanation is the difference in fertilizer dosage (Tables 1, 2 and 3) and management between the districts.

Observations on the possible links between rainfall in district and yield levels are also worthy of discussion. A positive linear correlation between extent of rainfall and yield levels is always expected as the availability of water is inherent to agricultural productivity. However, the fact that correlations between rainfall and yield differences were not found to be significant indicates that the extent of rainfall need not be factored into fine-tuning of guidance with respect to MOP rates. This further confirms that the yield differences reported here are due to MOP and not due to other external factors.

Range in both the control and +K-treated yield levels indicates that demand for K in cultivated soils of India varies significantly. There are currently no means of predicting cabbage response to MOP application at a given location with certainty, other than by conducting comprehensive soil and K crop response tests. A relevant approach could be tailored to include a whole package of solutions.

It is evident that the yield increases reported through this work are of a magnitude comparable to similar work reported elsewhere. Srivastava *et al.* (2018) indicated a relative yield increase of 16% in a cabbage plot trial where rate of K was the only variable (from 5 to 30 kg ha^{-1}). Though the K-response in this work is not identical to the literature results, comparability between the two experiments in terms of order of magnitude provides some confirmation of the results here.

Finalizing nutrient balances at field scale through comprehensive soil testing is not feasible for local smallholder farmers. Rather, raising awareness of balanced fertilizer use with appropriate suggestions for MOP application rates based on empirically verified large scale trials could gradually improve the existing practices of the local smallholders farming systems. Fine-tuning of dosage and nutrient balancing on local field level would then become an inherently cost- and resource-effective trend towards the development of a clear, simple and straight-forward path to productivity, profitability and sustainability on a regional scale.

The Tangible Benefits to Farmers

Dissemination of MOP-fertilization practices has shown considerable potential for increasing cabbage productivity in the states of Jammu and Kashmir, Maharashtra and West Bengal. As indicated in this study and based on the current country production statistics (Fig. 1), it can be inferred that the MOP-fertilizer treatments would increase cabbage yields and push the sector's yields to the levels obtained in China and Russia. Current cabbage yield levels in India are lower than many of the cabbage growing countries of the world.

Assuming that the farmers use the same MOP rates as those used in this study, increases in output levels would provide a rough benefit:cost ratio of 82:1. Such results are likely to interest the country's cabbage farmers. The price sensitivity analysis shown in the results and the high benefit:cost ratios indicate that farmers are likely to experience net profit despite any fluctuations in cabbage prices or cost of MOP.

Conclusions

MOP application, in addition to commonly applied N and P fertilizers, had an unequivocal effect in significantly increasing the cabbage yields in the states of Jammu and Kashmir, Maharashtra and West Bengal. The soil status of plant available K was inadequate in meeting the K requirements of cabbage. Hence, MOP inclusive fertilizer regimes became necessary to improve and optimize yields of this important vegetable crop. These results strongly advocate the recommendation of K depending on the states (35, 48, 50 or 150 kg K_2O ha^{-1}) to obtain higher yields and profits.

Variations in MOP response give enough reasons to investigate further experiment having higher MOP dose, as well as ways to fine-tune the recommendations on a local field scale. Further research is recommended to determine the appropriate MOP doses and application practices to ensure balanced crop nutrition, optimal fertilizer use, sufficient K availability whenever needed, and sustainable soil fertility.

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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.

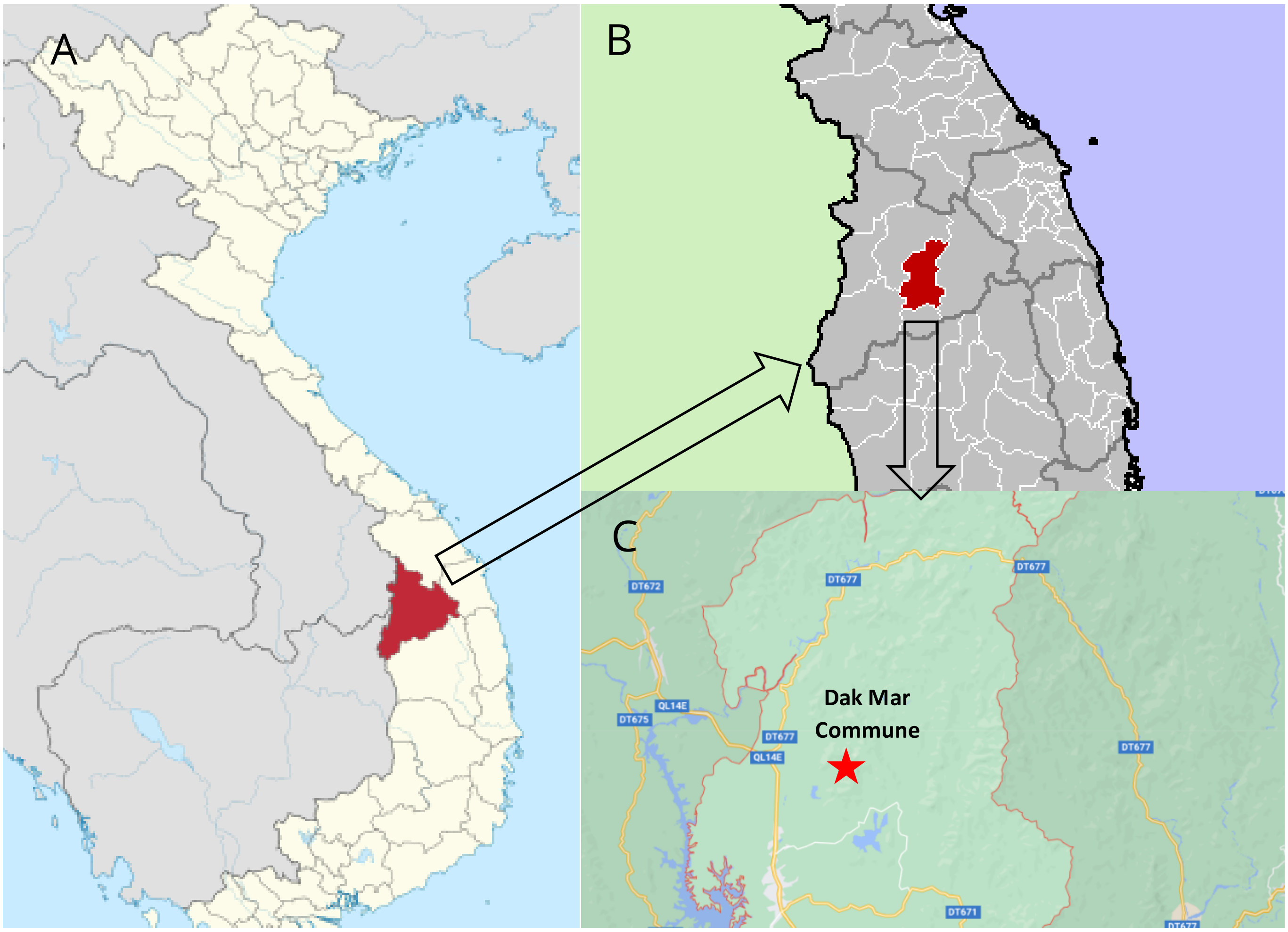
Vietnam has unique achievements in developing Robusta coffee (*Coffea robusta* or *Coffea canephora*) as a high yielding cash crop. This has been made possible by intensification methods, including irrigation during the dry season (Marsh, 2007). Special concern has been devoted to nutrition requirements 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: $K_2Ca_2Mg(SO_4)_4·2H_2O$. 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

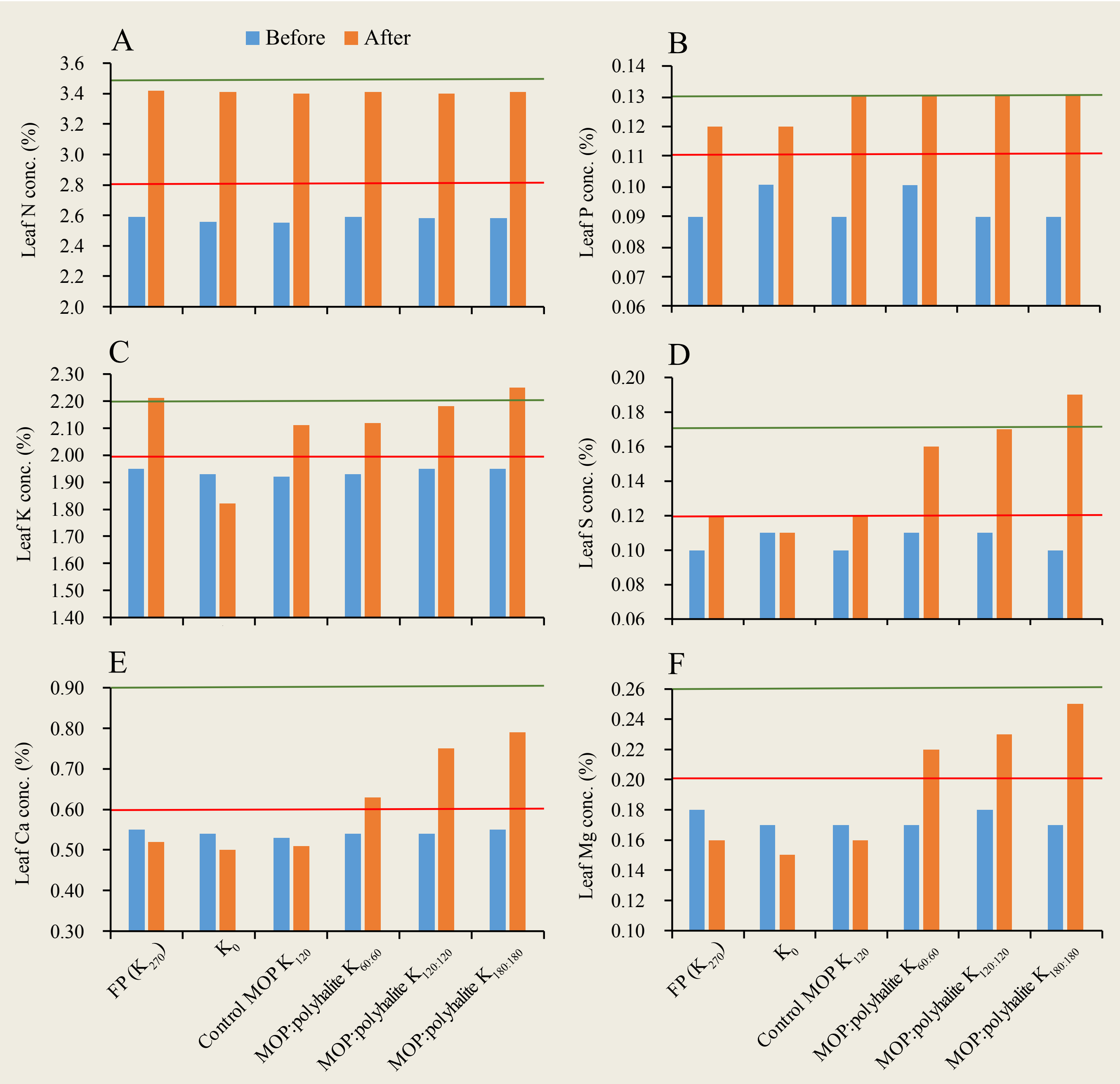


Fig. 1. Effects of fertilizer applications on leaf nutrient concentration in coffee trees grown in the Central Highlands, Vietnam. See Table 1 for the detailed description of the treatments. Measurements were carried out before, and 20 days after fertilizer applications. Values present means of four 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

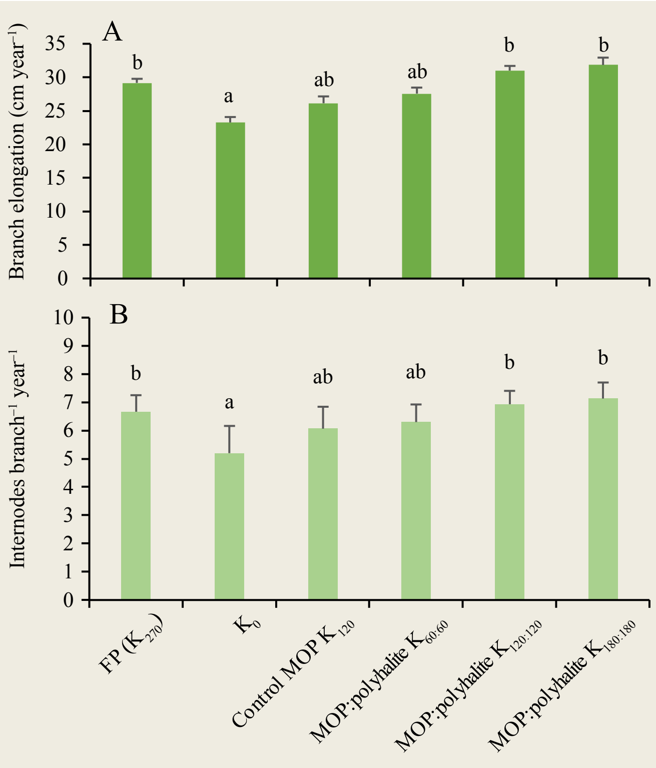


Fig. 2. Effect of fertilizer treatments on branch elongation (A), and the number of internodes per branch (B) as vegetative growth indicators in coffee grown in the Central Highlands, Vietnam. See Table 1 for detailed description of the treatments. Different letters indicate significant differences between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

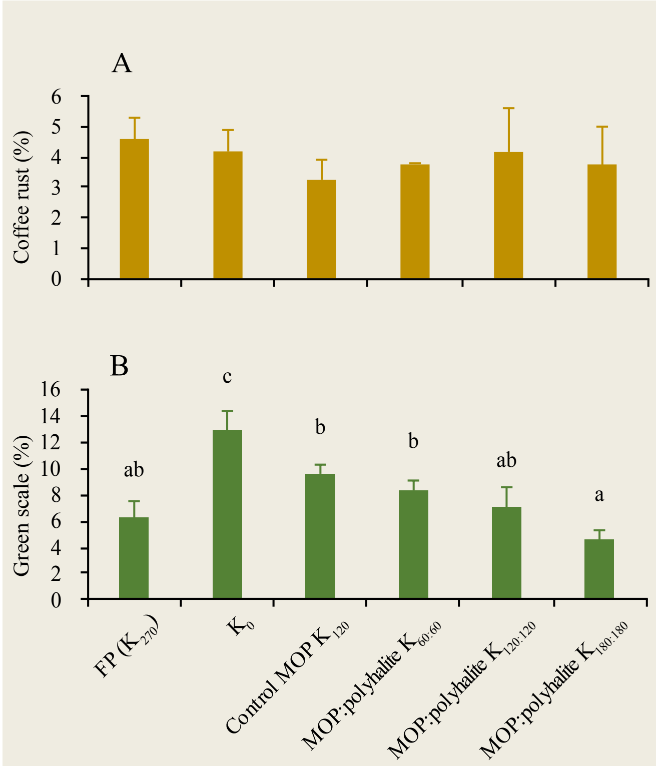


Fig. 3. Effect of fertilizer treatments on coffee rust (A), and green scale infestation rates (B) in coffee grown in the Central Highlands, Vietnam. See Table 1 for detailed description of the treatments. Different letters indicate significant differences between treatments (P<0.05).

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}.

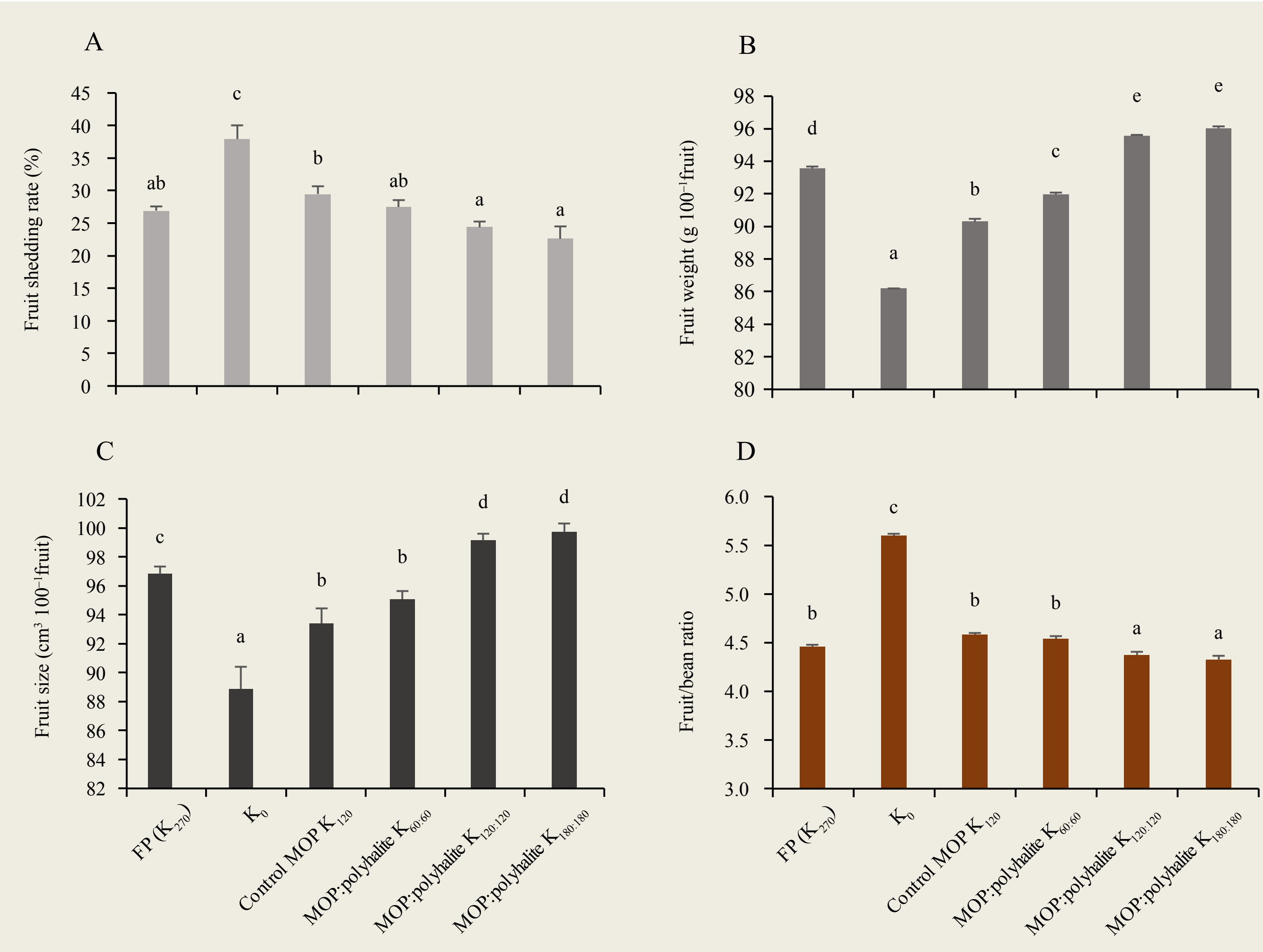


Fig. 4. Effect of fertilizer treatments on coarse yield determinants of coffee grown in the Central Highlands, Vietnam: fruit shedding rate (A); fruit weight (B); fruit size (C); and, fruit/bean ratio (D). See Table 1 for detailed description of the treatments. Different letters indicate significant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

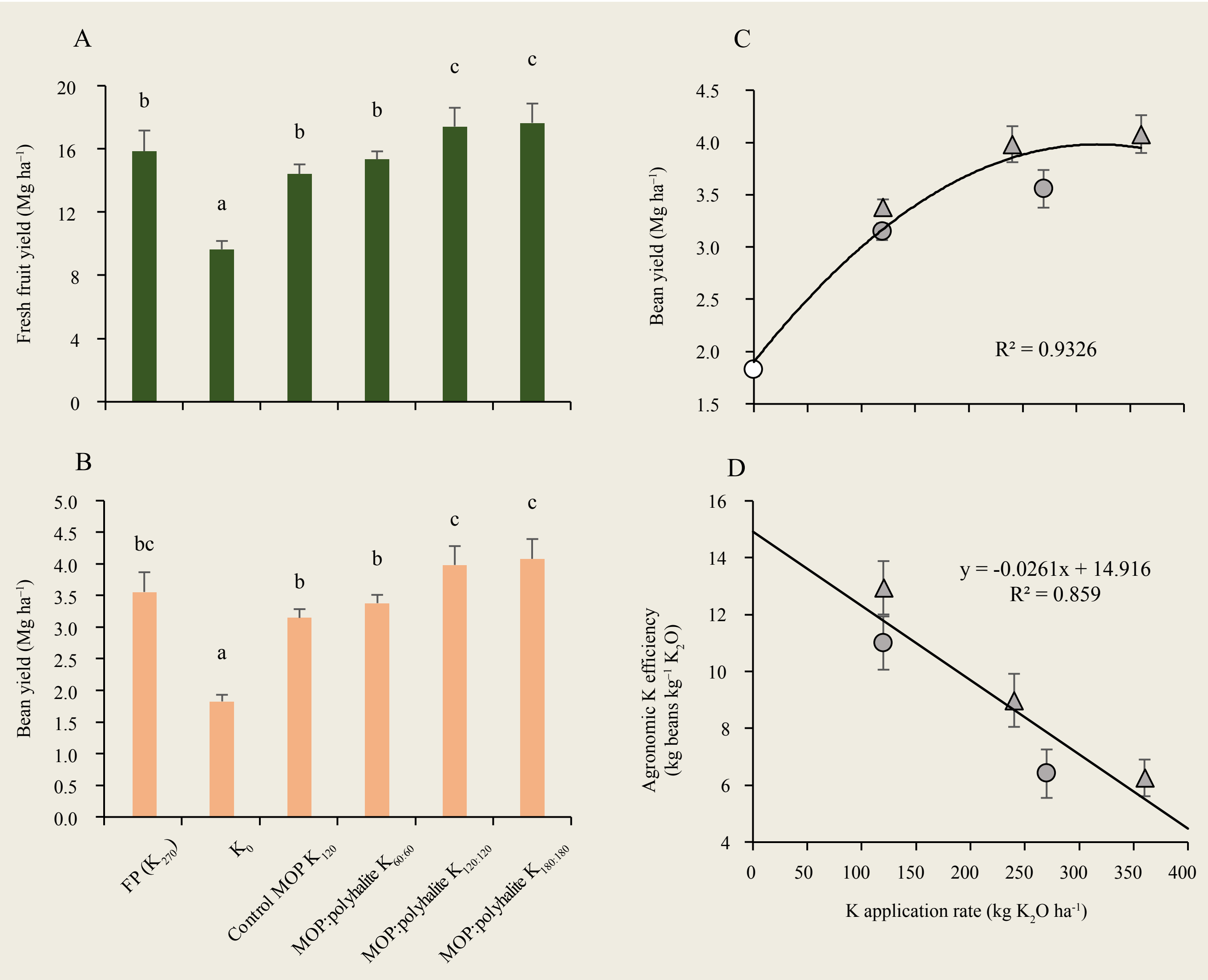


Fig. 5. Effect of fertilizer treatments on fresh fruit (A) and bean yields (B), and the effect of K application rate on bean yield (C) and agronomic K efficiency (D) in coffee grown in the Central Highlands, Vietnam. See Table 1 for detailed description of the treatments. Different letters indicate significant 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).

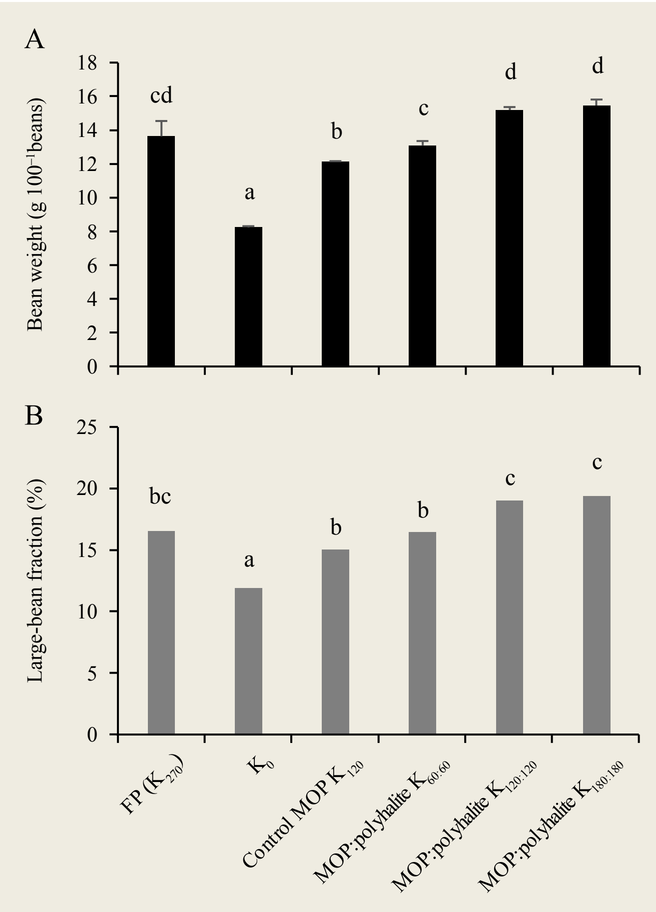


Fig. 6. Effect of fertilizer treatments on coffee bean quality parameters: bean weight (A), and large-bean (> 6.3 mm) fraction (B). See Table 1 for detailed description of the treatments. Different letters indicate significant differences between treatments (P<0.05).

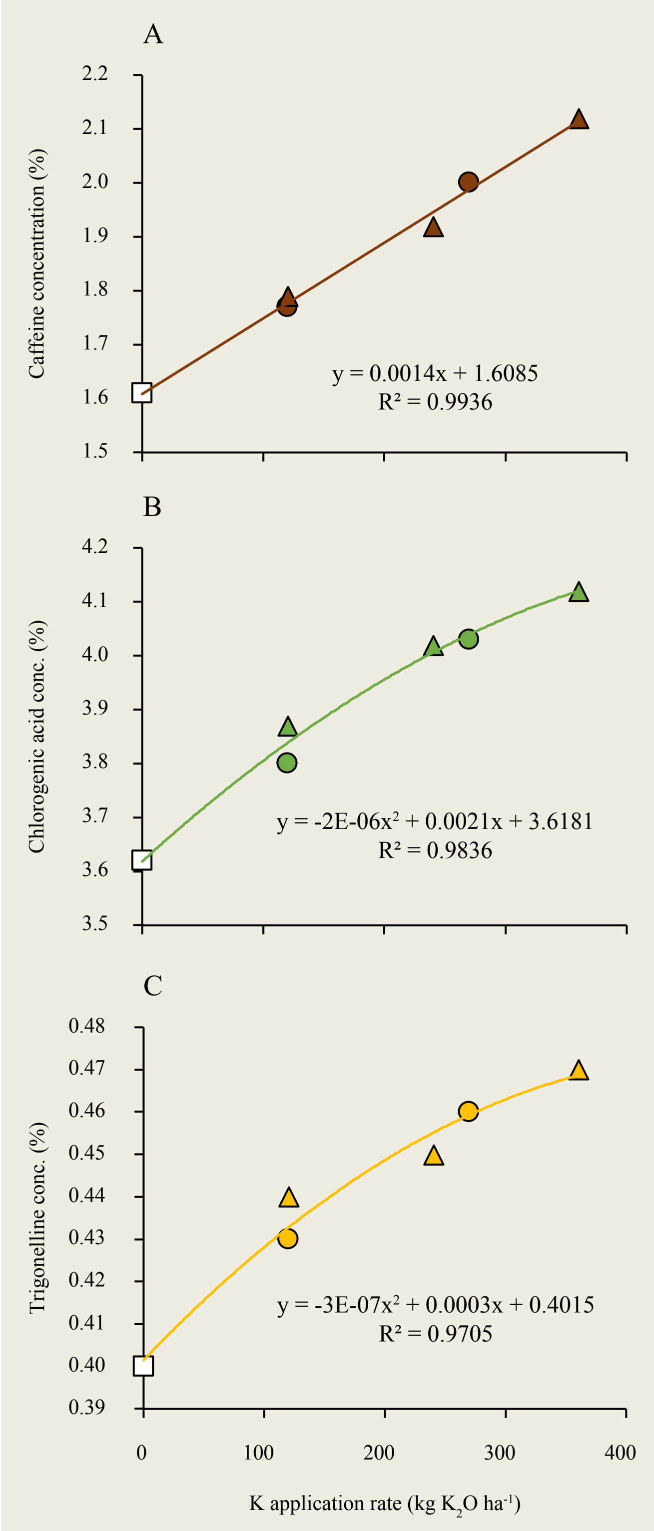


Fig. 7. Effect of K application rate on caffeine (A), chlorogenic acid (B), and trigonelline (C) concentrations in coffee beans. The square, circle, and triangle symbols indicate no K (K_0), MOP, and MOP:polyhalite fertilizer treatments, respectively.

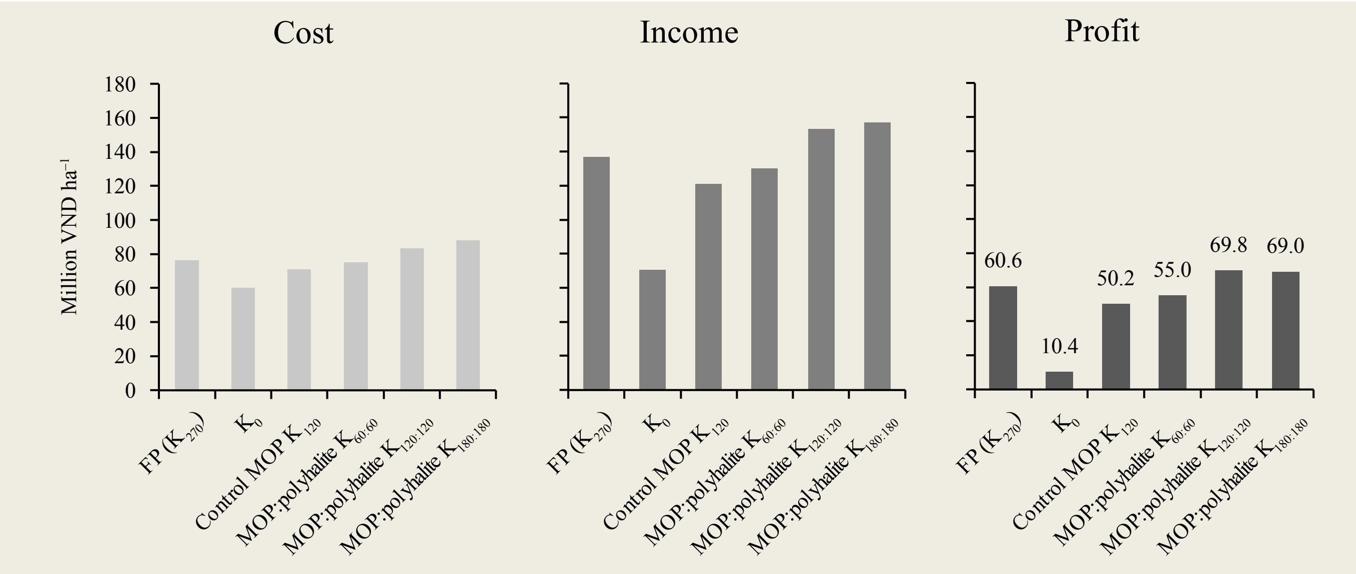


Fig. 8. Effects of the fertilizer treatments on the cost, income, and profit of one hectare of coffee cultivation per year in the Central Highlands, Vietnam. See Table 1 for detailed description of the treatments.

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).

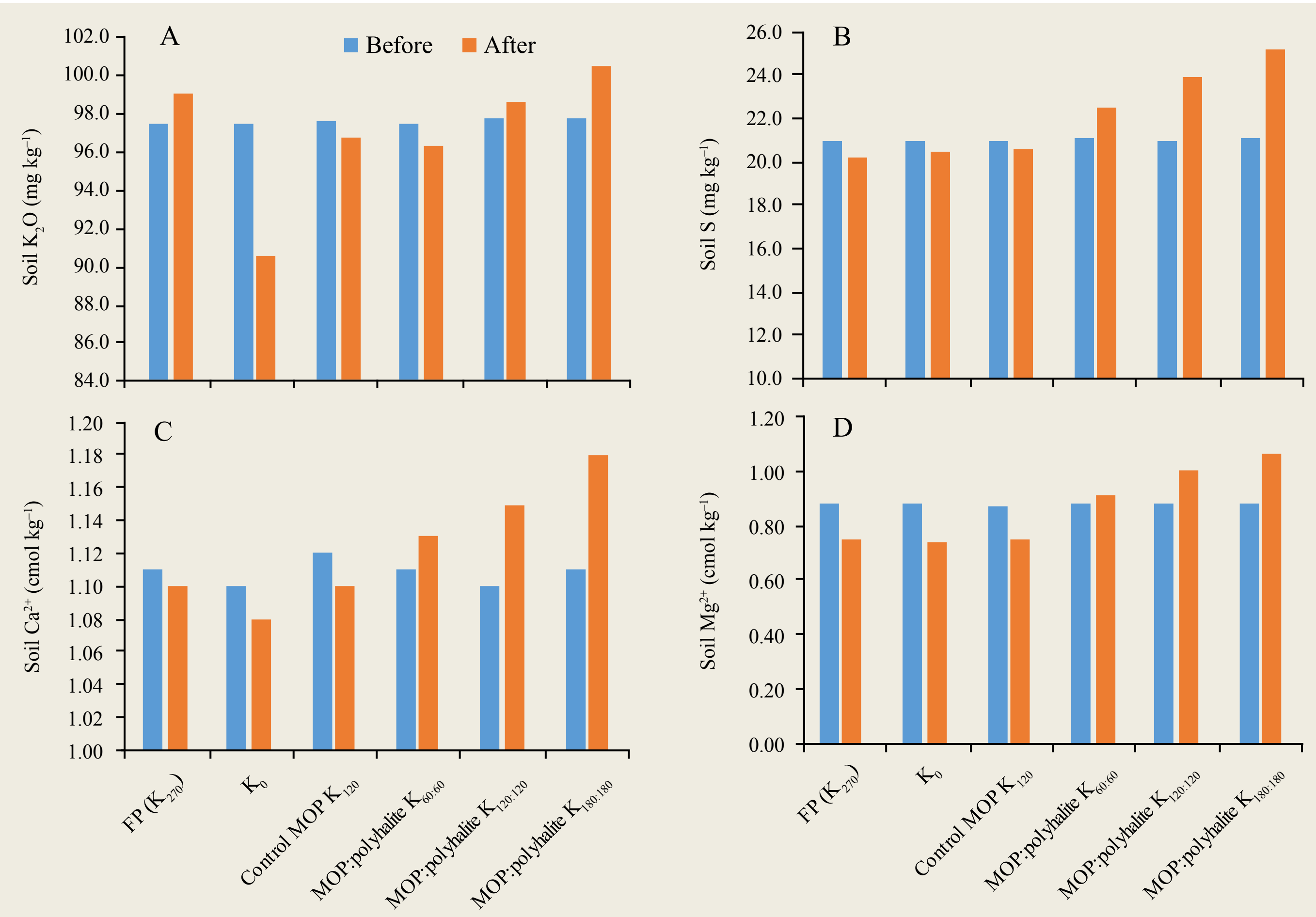


Fig. 9. Effect of fertilizer treatments on the soil nutrient (K, S, Ca, and Mg) status, as measured before the first fertilizer application in 2016, and after the last harvest in 2018, three years later. For detailed description of the treatments refer to Table 1.

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.

Acknowledgements

We thank Dr. Nguyen Van Bo and Mr. Gershon Kalyan for giving their advice and assistance for the study, and we thank Mrs Hoang Le Thuy and staff at the Central Highland Soils and Fertilizers Research Centre for taking care the field experiment. This study was funded by the International Potash Institute via the research project "Investigation of the Agronomic Efficiency of Polysulphate on Yield and Quality of Some Crops in Vietnam".

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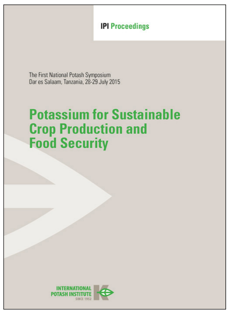
The paper "Polyhalite Effects on Coffee (*Coffea robusta*) Yield and Quality in Central Highlands, Vietnam" also appears on the IPI website.

Publications



Potassium for Sustainable Crop Production and Food Security

Proceedings from The First National Potash Symposium Dar es Salaam, Tanzania, 28-29 July 2015

Over five decades, potassium (K) has been regarded as sufficient in most Tanzanian soils. This generalization has led to limited research with regards to soil K status, plant nutrition and to the development of fertilizer recommendations which include K in fertilizer formulations. Tanzania has K-blended fertilizer recommendations for just a few crops like sisal, tea and tobacco, with other crops depending on inherent K supply from the soil, which is gradually declining due to inadequate K supplies. In recent years, it has been recognized that K levels in some soils are lower than anticipated, and that K deficiency symptoms are now common in certain major crops like cassava, maize, and rice. With such observed deficiencies, it is not possible to provide fertilizer recommendations – that include K – with certainty.

In response to declining potash levels in Tanzanian soils, the first Tanzania National Potash Symposium was held at the Protea Hotel Courtyard, Dar es Salaam, Tanzania from 28-29 July 2015. The Symposium's main theme was "Potassium for Sustainable Crop Production, Food Security and Poverty Reduction". In the Symposium, two keynote and 11 research papers were presented.

The research papers presented were divided into four sub-themes:

- **Sub-theme 1:** Potash distribution in the soils of Tanzania
- **Sub-theme 2:** Role of potash for sustainable crop productivity in Tanzania
- **Sub-theme 3:** Trends of potassium levels in soils of Tanzania
- **Sub-theme 4:** Economics of K-based fertilizers for sustainable crop production

The objectives of the symposion were to:

1. obtain baseline information on K research in Tanzania;
2. synthesize available information; and
3. identify research gaps which will establish a K research agenda.

To download a copy of the proceedings from the IPI website at https://www.ipipotash.org/publications/potassium-for-sustainable-crop-production-and-food-security. For hardcopies, please contact ipi@ipipotash.org.

Scientific Abstracts

K in the Literature

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

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

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

Developing a Model for Soil Potassium Estimation using Spectrometry Data

Mobasheri, M.R., M. Amani, R. Fathi-Almas, S. Mahdavi, and H.R. Zabihi. 2020. Communications in Soil Science and Plant Analysis 51(6):794-803. DOI: 10.1080/00103624.2020.1733002.

Abstract: Erosion is the continuous degradation of the soil surface mainly caused by water and/or wind. In the erosion process, the nutrients of the soil, including potassium, are eroded. Therefore,

developing new models to estimate soil potassium contents prone to erosion is important for soil degradation monitoring. In this study, three different soil types including loam, sandy loam, and silty loam were studied, and different amounts of potassium sulfate (K_2SO_4) fertilizer were added to the samples. Subsequently, lab spectrometry measurements were performed on all samples, and the most informative spectral bands were determined and used for developing models for soil potassium estimation. In this procedure, reflectance curves and their derivatives were used. Finally, several models to assess the potassium content of each soil types separately as well as irrespective of soil type were developed. These models showed a high potential for soil potassium prediction with the correlation coefficients (r) and Root Mean Square Errors varying between 0.95–0.98 and 1.317–1.973 g/kg, respectively.

Diagnosis of Nitrogen Nutrition in Rice Leaves Influenced by Potassium Levels

Hou W., M. Tränkner, J. Lu, J. Yan, S. Huang, T. Ren, R. Cong, and X. Li. 2020. Front. Plant Sci. 11:165. DOI: 10.3389/fpls.2020.00165.

Abstract: Evaluation of nitrogen (N) status by leaf color is a kind of classic nutritional diagnostic method. However, the color of leaves is influenced not only by N, but also by other nutrients such as potassium (K). Two-year field trials with a factorial combination of N and K were conducted to investigate the effects of different N and K rates on soil plant analysis development (SPAD) readings and leaf N, K, magnesium (Mg), and chlorophyll concentrations. Visual inspections in leaf greenness revealed darker green leaves with increasing N rates, while paler green leaves with increasing K rates. Data showed that SPAD readings, chlorophyll, N and Mg concentrations, and the chloroplast area increased significantly with raising N rates, while declined sharply with the increase in K rates due to the antagonistic relationships between K^+ and NH_4^+ as well as Mg_2^+. It was also probable that the increase in K promoted the growth of leaves and diluted their N and Mg concentrations. The paler leaf appearance resulting from the application of K may overestimate the actual demand for N in the diagnosis of rice N status. The strong antagonistic relationships between K^+, NH_4^+, and Mg_2^+ should be considered in rice production and fertilization.

Monitoring Leaf Potassium Content using Hyperspectral Vegetation Indices in Rice Leaves

Lu, J., T. Yang, X. Su *et al.* 2020. Precision Agric. 21:324-348. DOI: https://doi.org/10.1007/s11119-019-09670-w.

Abstract: Potassium (K) is one of three main crop nutrients, and the high rate of potash fertilizer utilization (second only to nitrogen) leads to high prices. Therefore, efficient application, as well as rapid and time monitoring of K in crops is essential. Several turnover box and field experiments were conducted across multiple years and cultivation factors (i.e., potassium levels and plant varieties) yielding 340 groups of leaf samples with different K contents; these samples were used to examine the relationship between reflectance spectra (350–2500 nm) and leaf K content (LKC). The correlation between LKC and the two-band spectral indices computed with random two bands from 350 to 2500 nm were determined for the published K vegetation indices in rice. Results showed that the spectral reflectance, R, of the shortwave infrared (1300–2000 nm) region was sensitive to the K levels and significantly correlated with rice LKC. New shortwave infrared two-band spectral indices, Normalized difference spectral index [NDSI (R_{1705}, R_{1385})], Ratio spectral index [RSI (R_{1385}, R_{1705})], and Difference spectral index [DSI (R_{1705}, R_{1385})], showed good correlations with LKC (R^2 up to 0.68). Moreover, the three-band spectral indices $(R_{1705} - R_{700})/(R_{1385} - R_{700})$ and $(R_{1705} - R_{1385})/(R_{1705} + R_{1385} - 2 \times R_{704})$ were developed by adding red edge bands to improve accuracy. Three-band spectral indices had an improved prediction accuracy for rice LKC (R^2 up to 0.74). However, several previously published K-sensitive vegetation indices did not yield good results in this study. Validation with independent samples showed that the indices $(R_{1705} - R_{700})/(R_{1385} - R_{700})$ and $(R_{1705} - R_{1385})/(R_{1705} + R_{1385} - 2 \times R_{704})$ had higher accuracies and stabilities than two-band indices and are suitable for quantitatively estimating rice LKC. The widescale application of these proposed vegetation indices in this paper still needs to be verified in different environmental conditions. This study provides a technical basis for LKC monitoring using spectral remote sensing in rice.

Crop Nutrients Review and the Impact of Fertilizer on the Plantation in Malaysia: A Mini Review

Chin Hao Lai, Abdul Rasyid Harsha Settinayake, Wan Sieng Yeo, Shiew Wei Lau, and Tze Khiun Jong. 2019. Communications in Soil Science and Plant Analysis 50(17):2089-2105. DOI: 10.1080/00103624.2019.1654510.

Abstract: Improving the production of crops is always a concern in the plantation sector since higher production leads to the economic growth of a country. For developing countries, including Malaysia, one of their incomes is crop production. Focusing on crop nutrients supply using fertilizers to increase the production of the crops is better than expanding the plantation areas. The limited knowledge regarding the appropriate nutrients supply and the relation between the nutrients in Malaysia has caused the yield of the crops not meet expectations. Thus, sharing knowledge about the nutrient requirements and the nutrient availability toward the uptake rate of the plants are required. Hence, this work reviews the nutrient supply, the effect of each nutrient on the crop, and the nutrient availability in Malaysia's plantation. A better understanding of the nutrient requirement to sustain crop health helps to improve

the quality of the crop, its yield, and soil performance for future agriculture work. Moreover, this work also discusses the impact of fertilizer on the plantation and different types of fertilizer. Additionally, their nutrient release patterns will be discussed, along with the pros and cons of these existing fertilizers.

Effects of Potassium Levels on Plant Growth, Accumulation and Distribution of Carbon, and Nitrate Metabolism in Apple Dwarf Rootstock Seedlings

Xu Xinxiang, Du Xin, Wang Fen, Sha Jianchuan, Chen Qian, Tian Ge, Zhu Zhanling, Ge Shunfeng, Jiang Yuanmao. 2020. Front. Plant Sci. 11:904. DOI: 10.3389/fpls.2020.00904.

Abstract: Nitrogen (N) is one of the most required mineral elements for plant growth, and potassium (K) plays a vital role in nitrogen metabolism, both elements being widely applied as fertilizers in agricultural production. However, the exact relationship between K and nitrogen use efficiency (NUE) remains unclear. Apple dwarf rootstock seedlings (M9T337) were used to study the impacts of different K levels on plant growth, nitrogen metabolism, and carbon (C) assimilation in water culture experiments for 2 years. The results showed that both deficiency and excess K inhibited the growth and root development of M9T337 seedlings. When the K supply concentration was 0 mM and 12 mM, the biomass of each organ, root-shoot ratio, root activity and NO_3^- ion flow rate decreased significantly, net photosynthetic rate (P_n) and photochemical efficiency (F_v/F_m) being lower. Meanwhile, seedlings treated with 6 mM K^+ had higher N and C metabolizing enzyme activities and higher nitrate transporter gene expression levels (*NRT1.1*; *NRT2.1*). ^{13}C and ^{15}N labeling results showed that deficiency and excess K could not only reduce ^{15}N absorption and ^{13}C assimilation accumulation of M9T337 seedlings, but also reduced the ^{15}N distribution ratio in leaves and ^{13}C distribution ratio in roots. These results suggest that appropriate K supply (6 mM) was optimal as it enhanced photoassimilate transport from leaves to roots and increased NUE by influencing photosynthesis, C and N metabolizing enzyme activities, nitrate assimilation gene activities, and nitrate transport.

K Fertilizers Reduce the Accumulation of Cd in *Panax notoginseng* (Burk.) F.H. by Improving the Quality of the Microbial Community

Shi Y., L. Qiu, L. Guo, J. Man, B. Shang, R. Pu, X. Ou, C. Dai, P. Liu, Y. Yang and X. Cui. 2020. Front. Plant Sci. 11:888. DOI: 10.3389/fpls.2020.00888.

Abstract: The high background value of cadmium (Cd) in the *Panax notoginseng* planting soil is the main reason for the Cd content in *Panax notoginseng* exceeding the limit standards. The main goal of this study was to reveal the mechanism by which potassium (K) reduces Cd accumulation in *Panax notoginseng* from the perspective of the influences of soil microbial communities on soil pH, total organic matter (TOM) and cation exchange capacity (CEC). Pot experiments were conducted to study the effects of different types and amounts of applied K on the Cd content in *Panax notoginseng*, and on the soil pH, TOM, CEC, and bioavailable Cd (bio-Cd) content in soil. Field experiments were conducted to study the effects of K_2SO_4 fertilizer on the microbial community, and its correlations with the soil pH, TOM and CEC were analyzed. A moderate application of K_2SO_4 (0.6 g·kg^{-1}) was found to be the most optimal treatment for the reduction of Cd in the pot experiments. The field experiments proved that K fertilizer (K_2SO_4) alleviated the decreases in pH, TOM and CEC, and reduced the content of bio-Cd in the soil. The application of K fertilizer inhibited the growth of Acidobacteria, but the abundances of Mortierellomycota, Proteobacteria and Bacteroidetes were promoted. The relative abundances of Acidobacteria and Proteobacteria in the soil bacteria exhibited significant negative and positive correlations with pH and CEC, respectively. In contrast, the relative abundance of Mortierellomycota was found to be positively correlated with the pH, TOM and CEC. The bio-Cd content was also found to be positively correlated with the relative abundance of Acidobacteriia but negatively correlated with the relative abundances of Proteobacteria and Mortierellomycota. The application of K fertilizer inhibited the abundance of Acidobacteria, which alleviated the acidification of the soil pH and CEC, and promoted increase in the abundances of Mortierellomycota, Proteobacteria and Bacteroidetes, which ultimately increased the soil TOM and CEC. Soil microorganisms were found to mitigated decreases in the soil pH, TOM, and CEC and reduced the bio-Cd content in the soil, which significantly reduced the accumulation of Cd in *Panax notoginseng*.

Nutrient Storage in the Perennial Organs of Deciduous Trees and Remobilization in Spring – A Study in Almond (*Prunus dulcis*) (Mill.) D. A. Webb

Muhammad, S., B.L. Sanden, B.D. Lampinen, D.R. Smart, S. Saa, K.A. Shackel, and P.H. Brown. 2020. Front. Plant Sci. 11:658. DOI: 10.3389/fpls.2020.00658.

Abstract: The annual dynamics of whole mature almond tree nutrient remobilization in spring and the accumulation of nutrients in perennial tissues during the year were determined by sequential coring, tissue sampling, nutrient analysis, whole tree excavation and biomass estimation for trees grown under four nitrogen rate treatments 140 kg ha^{-1} N (N140), 224 kg ha^{-1} N (N224), 309 kg ha^{-1} N (N309), and 392 kg ha^{-1} N (N392) over 2 years. Whole tree perennial organ N content was greatest in dormancy then declined through bud swell, flowering and fruit set, achieving the lowest total whole tree nutrient content of perennial organs by March 12 [12–14 days after full bloom (DAFB)] coincident with 60–70% leaf expansion. During this period no net increment in whole tree N content (annual plus perennial N) was observed indicating that tree demand for N for bud break, flowering, fruit set and leaf out was met by remobilized stored N and that there was no net N uptake from soil. Remobilizable N increased with increasing N application up to N309 and was maximal at 44.4 ± 4 kg ha^{-1} and 37.5 ± 5.7 kg ha^{-1} for the optimally fertilized N309 in 2012 and 2013 respectively. Net increases in perennial organ N (stored N) commenced 41 DAFB and continued through full leaf abscission at 249 DAFB. Total annual N increment in perennial organs varied from 25 to 60 kg ha^{-1} and was strongly influenced by N rate and tree yield. N remobilized from senescing leaves contributed from 11 to 15.5 ± 0.6 kg ha^{-1} to perennial stored N. Similar patterns of nutrient remobilization and storage were observed for P, K, and S with maximal whole tree perennial storage occurring during dormancy and remobilization of that stored P, K, S to support annual tree demands through to fruit set and 70–100% leaf development. Net annual increment in perennial organ P, K, S commenced 98 DAFB and continued through full leaf abscission at 249 DAFB. Organ specific contribution to remobilizable and stored nutrients changes over the growing season are presented. Details of the pattern of perennial organ nutrient allocation, storage, and remobilization provides a framework for the optimal management of nutrients in almond with relevance for other deciduous tree species.

Protective Effect of 24-Epibrassinolide on Barley Plants Growing Under Combined Stress of Salinity and Potassium Deficiency

Liaqat, S., S. Umar, P. Saffeullah *et al.* 2020. J. Plant Growth Regul. DOI: https://doi.org/10.1007/s00344-020-10163-8.

Abstract: Evaluation of the effects of 24-epibrassinoide (24-EBL) was done on two genotypes of barley (*Hordeum vulgare* L.) plants (salt tolerant-RD-2508 and salt sensitive-RD-2660) grown under combined stress of salinity and potassium deficiency. Salt-stressed (200 mM NaCl) and K-deficient plants were subjected to different concentrations of 24-EBL (1 ppm, 100 ppm, 1000 ppm) to analyse its effect on combinatorial abiotic stress. Individually both salinity stress and potassium deficit resulted in decrease of plant growth, chlorophyll content and relative water content (RWC). However, the combination of salinity stress and potassium deficient was found to be more harmful for plants. Supplementation of 24-EBL ameliorated the negative effects of combined stress and promoted the growth of stressed plants. This ameliorative effect of 24-EBL could be accounted by the improved activity of antioxidant enzymes, osmolytes such as proline and sugar that affected the oxidative stress by reducing Na^+ accumulation and improved K^+ concentration and K^+/Na^+ ratio in stressed plants. Enhancement of K^+ accumulation and increase in K^+/Na^+ ratio through restriction of Na^+ accumulation could be considered as a key feature for 24-EBL-induced tolerance along with improved RWC and chlorophyll content. 24- EBL at 100 ppm was more promising in alleviating the stress conditions. Thus, BR-induced manipulation in ion haemostasis can be a prominent trait and can be used as a criterion for developing salt stress and K-limited tolerant barely genotypes.

High Potassium Application Rate Increased Grain Yield of Shading-Stressed Winter Wheat by Improving Photosynthesis and Photosynthate Translocation

Wang, Y., Z. Zhang, Y. Liang, Y. Han, Y. Han, and J. Tan. 2020. Front. Plant Sci. 11:134. DOI: 10.3389/fpls.2020.00134.

Abstract: Wheat (*Triticum aestivum* L) production on the Huang-Huai Plain of China has substantially affected in the past 50 years as a result of the decreasing total solar radiation and sunshine hours. Potassium has a significant effect on improving leaf photosynthesis ability under stress conditions. Five potassium application rates (K), 0 (K0), 50 (K50), 100 (K100), 150 (K150), and 250 (K250) mg K_2O kg^{-1} soil, combined with two shading levels, no shading (NS) and shading at early filling stage for 10 days (SE), were used to investigate the effects of K application on winter wheat growth under SE condition. Under NS condition, the parameters related to chlorophyll fluorescence characteristics, dry matter productivity and grain yields reached the maximum values at a middle K application rate (100 mg K_2O kg^{-1} soil). Shading stress significantly reduced leaf SPAD value, showed negative effects on chlorophyll fluorescence characteristics and reduced grain yield of winter wheat. However, as the result of the interaction of K×S, compared to NS condition, higher K application rate (150 mg and 250 K_2O kg^{-1} soil) was beneficial in terms of achieving a higher grain yield of winter wheat under SE by improving leaf SPAD value, alleviating the damage of SE on the winter wheat photosynthetic system, and increasing fructan content and dry matter translocation percentage.

Production of Low-Potassium Onions based on Mineral Absorption Patterns During Growth and Development

Okada, H., T. Abedin, A. Yamamoto, T. Hayashi, and M. Hosokawa. 2020. Scientia Horticulturae 267:109252. DOI: https://doi.org/10.1016/j.scienta.2020.109252.

Abstract: The production of low-potassium onions (*Allium cepa*) for patients with kidney disease is an important horticultural goal because onion is one of the most highly consumed vegetables in the world. To advance progress toward this goal, we conducted two experiments. In Experiment 1, we monitored the potassium content of each organ of the onion cultivar ‘Kaizuka Wase Ki’ during growth and development to determine whether potassium accumulates in the bulb as a result of translocation from other organs or direct absorption from the roots by hydroponic culture using granular polyester medium. We found that the plants developed green leaves under a short-day (12 -h) photoperiod and thickened their leaf sheaths and formed bulbs under a long-day (16 -h) photoperiod. The

total potassium content of the green leaves decreased from 3 weeks after the start of the long-day treatment, which was thought to be due to the transfer of nutrients to the bulbs during bulb formation. The potassium contents in bulbs increased by 42.9 mg from week 12–15 after transplanting, it is considered that 14.2 mg of potassium was translocated from the leaves to the bulbs, while the remaining 28.7 mg was directly absorbed by the roots. In addition, there appeared to be a homeostatic mechanism in the onion bulb that maintained the potassium content at approximately 100 mg/100 g fresh weight, so a strategy to overcome this homeostasis is considered necessary for the production of low-potassium onions. In Experiment 2, the supply of potassium after a long-day photoperiod was reduced to 75%, 50%, 25%, and 0% of the usual amount in an attempt to reduce the potassium content of the bulbs by the same culture method as Exp. 1. This showed that decreasing the potassium supply to 25 % and 0% reduced the potassium content of the bulbs to 184.0 g and 146.7 g, respectively, compared with 303.5 g for 100% supply. These results show that the extreme restriction of potassium fertilization after the bulb enlargement period is effective for overcoming the homeostatic mechanism, resulting in the production of low-potassium onions.

Nondestructive Determination of Nitrogen, Phosphorus and Potassium Contents in Greenhouse Tomato Plants Based on Multispectral Three-Dimensional Imaging

Sun, G., Y. Ding, X. Wang, W. Lu, Y. Sun, H. Yu. 2019. Sensors 19(23):5295. DOI: https://doi.org/10.3390/s19235295.

Abstract: Measurement of plant nitrogen (N), phosphorus (P), and potassium (K) levels are important for determining precise fertilization management approaches for crops cultivated in greenhouses. To accurately, rapidly, stably, and nondestructively measure the NPK levels in tomato plants, a nondestructive determination method based on multispectral three-dimensional (3D) imaging was proposed. Multiview RGB-D images and multispectral images were synchronously collected, and the plant multispectral reflectance was registered to the depth coordinates according to Fourier transform principles. Based on the Kinect sensor pose estimation and self-calibration, the unified transformation of the multiview point cloud coordinate system was realized. Finally, the iterative closest point (ICP) algorithm was used for the precise registration of multiview point clouds and the reconstruction of plant multispectral 3D point cloud models. Using the normalized grayscale similarity coefficient, the degree of spectral overlap, and the Hausdorff distance set, the accuracy of the reconstructed multispectral 3D point clouds was quantitatively evaluated, the average value was 0.9116, 0.9343 and 0.41 cm, respectively. The results indicated that the multispectral reflectance could be registered to the Kinect depth coordinates accurately based on the Fourier transform principles, the reconstruction accuracy of the multispectral 3D point cloud model met the model reconstruction needs of tomato plants. Using back-propagation artificial neural network (BPANN), support vector machine regression (SVMR), and gaussian process regression (GPR) methods, determination models for the NPK contents in tomato plants based on the reflectance characteristics of plant multispectral 3D point cloud models were separately constructed. The relative error (RE) of the N content by BPANN, SVMR and GPR prediction models were 2.27%, 7.46% and 4.03%, respectively. The RE of the P content by BPANN, SVMR and GPR prediction models were 3.32%, 8.92% and 8.41%, respectively. The RE of the K content by BPANN, SVMR and GPR prediction models were 3.27%, 5.73% and 3.32%, respectively. These models provided highly efficient and accurate measurements of the NPK contents in tomato plants. The NPK contents determination performance of these models were more stable than those of single-view models.

Hazenite: A New Secondary Phosphorus, Potassium and Magnesium Fertiliser

Watson C., J. Clemens, F. Wichern. 2020. Plant Soil Environ. 66:1-6. DOI: https://doi.org/10.17221/492/2019-PSE.

Abstract: Secondary fertilisers are becoming an important alternative to conventional mined fertilisers. For the first time, the struvite "relative" hazenite ($KNaMg_2(PO_4)_2 \cdot 14\ H_2O$) has been artificially synthesised. A pot trial assessed whether hazenite-fertilised ryegrass had comparable potassium (K), magnesium (Mg), or phosphorus (P) uptake and shoot yields with treatments receiving conventional K (muriate of potash), Mg (kieserite) or P (triple superphosphate, TSP) fertilisers. Ryegrass shoot biomass production and K/Mg uptake in replicates receiving hazenite were as good as or superior to those amended with conventional fertilisers. Phosphorus uptake of plants whose P source was TSP was significantly higher than that of the hazenite-amended replicates without significantly higher shoot biomass, indicating luxury P uptake. Hazenite's constituent sodium (Na) makes it a potentially useful soil amendment for forage grasses or natrophilic crops such as sugar beet. Its component Mg would also be desirable in forage grasses to pre-empt ruminant hypomagnesemia or in crops with a relatively high Mg demand, for example, maize. Furthermore, hazenite represents a good alternative to KCl for chlorophobic crops such as potatoes. However, given its unusual ratio of Mg, P, and K, the ideal application of hazenite would probably be in combination with other fertilisers.

Managing Soils for Recovering from the COVID-19 Pandemic

Lal, R., E.C. Brevik, L. Dawson, D. Field, B. Glaser, A.E. Hartemink, R. Hatano, B. Lascelles, C. Monger, T. Scholten, B.R. Singh, H. Spiegel, F. Terribile, A. Basile, Y. Zhang, R. Horn, T. Kosaki, and L.B.R. Sánchez. 2020. Soil Syst. 4(3):46. DOI: https://doi.org/10.3390/soilsystems4030046.

Abstract: The COVID-19 pandemic has disrupted the global food supply chain and exacerbated the problem of food and nutritional insecurity. Here we outline soil strategies to strengthen local food production systems, enhance their resilience, and create a circular economy focused on soil restoration through carbon sequestration, on-farm cycling of nutrients, minimizing environmental pollution, and contamination of food. Smart web-based geospatial decision support systems (S-DSSs) for land use planning and management is a useful tool for sustainable development. Forensic soil science can also contribute to cold case investigations, both in providing intelligence and evidence in court and in ascertaining the provenance and safety of food products. Soil can be used for the safe disposal of medical waste, but increased understanding is needed on the transfer of virus through pedosphere processes. Strengthening communication between soil scientists and policy makers and improving distance learning techniques are critical for the post-COVID restoration.

Potassium fertilization combined with crop straw incorporation alters soil potassium fractions and availability in northwest China: An incubation study

Li X., Y. Li, T. Wu, C. Qu, P. Ning, J. Shi *et al.* 2020. PLoS ONE 15(7):e0236634. DOI: https://doi.org/10.1371/journal.pone.0236634.

Abstract: Potassium (K) input is essential for the improvement of soil fertility in agricultural systems. However, organic amendment may differ from mineral K fertilization with respect to modifying the soil K transformation among different fractions, affecting soil K availability. We conducted a 60-day lab incubation experiment to evaluate the response of soil K dynamics and availability in various fractions with a view to simulating crop residue return and chemical K fertilization in an Anthrosol of northwest China. The tested soil was divided into two main groups, no K fertilization (K0) and K fertilization (K1), each of which was subjected to four straw addition regimes: no straw addition (Control), wheat straw addition (WS), maize straw addition (MS), and both wheat straw and maize straw addition (WS+MS). Soil K levels in the available (AK) and non-exchangeable (NEK) fractions were both significantly increased after K addition, following the order of K>WS>MS. Fertilizer K was the most efficient K source, demonstrating a 72.9% efficiency in increasing soil AK, while wheat and maize straw exhibited efficiencies of 47.1% and 39.3%, respectively. Furthermore, K fertilization and wheat and maize straw addition increased the soil AK in a cumulative manner when used in combination. The mobility factor (M_F) and reduced partition index (I_R) of soil K were used to quantitate the comprehensive soil K mobility and stability, respectively. Positive relationships were observed between the M_F and all relatively available fractions of soil K, whereas the I_R value of soil K correlated negatively with both M_F and all available fractions of soil K. In conclusion, straw amendment could be inferior to mineral K fertilization in improving soil K availability when they were almost equal in the net K input. Crop straw return coupled with K fertilization can be a promising strategy for improving both soil K availability and cycling in soil–plant systems.

Potash Fertilization for Enhancing the Productivity of Pearlmillet-Safflower Sequence under Dryland Condition

More, N.B., V.M. Amrutsagar, A.B. Pawar, G.R. Charry. 2020. Int. J. Chem. Stud. 8(2):2958-2963. DOI: 10.22271/chemi.2020.v8.i2at.9201.

Abstract: Indian *Rainfed* and Dryland agriculture is predominantly dependant on monsoon rainfall accounts for 72% in India of the net cultivated area in India and plays an important role in country's economy. Generally farmers takes only one crop, either sorghum or safflower on medium deep black soils in scarcity zone of Maharashtra. However, taking double or sequence cropping may be one of the alternative for doubling the farmers income. Keeping such aspects in view the present investigation on potash fertilizer management in dryland field crops viz. pearlmillet- safflower sequence is undertaken, with objectives i.e. i) To maintain higher potassium status in soil and ii) To study the effects of potassium levels on yield and moisture use efficiency and monetary returns of sequence crops. The field experiments with different potash fertilizer levels for pearlmillet-safflower was undertaken at AICRPDLA, Solapur for three years (2015-2016 to 2017-18) with three replications in randomized block design for *kharif* crop and split plot design for *rabi* crop. In the sequence cropping of pearlmillet – safflower showed significantly higher yield and MUE of *kharif* pearlmillet with application of 50 kg K_2O ha^{-1}, rabi safflower and *Rabi* safflower with 20 kg K_2O ha^{-1} respectively. The non-exchangeable K increased with increase in potassium application to both crops, which could be maintained the exchangeable and water soluble K in soil solution, which might be contributed to significantly higher uptake of K and moisture use efficiency by both the crops as compared to farmers practice.

The Effect of Macronutrient Availability on Pomegranate Reproductive Development

Lazare, S., Y. Lyu, U. Yermiyahu, Y. Heler, G. Kalyan, and A. Dag. 2020. Plants 9(8):963. DOI: https://doi.org/10.3390/plants9080963.

Abstract: Pomegranate cultivation has expanded significantly in the last two decades. However, there is limited information on its fertilization requirements and the effect of macronutrient availability on its reproductive development. Two commercial pomegranate cultivars—"Wonderful" and "Emek"—were grown in 500-L containers for 3 years, using a fertigation system. Development and reproduction indices were measured to explore the trees' responses

to elevated levels of nitrogen (N), phosphorus (P) and potassium (K) in the irrigation solution. Andromonoecy rate was affected by nutrient levels only in the first year of the experiment, with higher levels of N and P leading to a greater proportion of hermaphrodites out of total flowers. P level had a positive effect on the total number of hermaphrodites per tree in both varieties. Differences recorded between hermaphroditic and staminate flowers included nutrient concentrations and dry weight. Fruit set and aril number were positively affected by N concentration in the irrigation solution. We conclude that only a severe deficiency of N and P affects the andromonoecy trait, and that at the levels examined in this study, K hardly influences pomegranate reproduction.

Improving Nutrient and Water Use Efficiencies Using Water-Drip Irrigation and Fertilization Technology in Northeast China

Jiangchuan Fan, Xianju Lu, Shenghao Gu, and Xinyu Guo. 2020. Agr. Water Manage. 241:106352. DOI: https://doi.org/10.1016/j.agwat.2020.106352.

Abstract: Fertilizer along with water-drip irrigation is the process of Fertilizer entering to the field with water, a new technology of combination with irrigation and Fertilizer, product of the combination with a precise and accurate irrigation and fertilizer. The filed experiments were conducted at two sites in Hei Longjiang province respectively in 2015 and 2016 to compare the effect of precision fertilization management and traditional management on maize plant height, aboveground biomass, leaf area index and yields. For two years, the precision fertilization management reduce the nutrient supply and did not affect maize growth and reduce grain yield. In 2015, the precision fertilization management reduce the nitrogen and phosphorus supply by 8% and 10%, but increase potassium supply by 15%. In 2016, the precision fertilization management reduce the nitrogen, phosphorus and potassium supply by 9%, 25%, and 17%. The maize plant height, leaf area index, aboveground biomass and yield did not significantly decrease due to the decrease in fertilizer application. As a result precision fertilization management increased the nutrients and rainfall use efficiency and net-profit. Thus proving fertigation help to increase maize production, which is of great significance for increasing food production.

Nutrient Budgeting of Primary Nutrients and their Use Efficiency in India

Sahu, G., S. Das, and S. Mohanty. 2020. International Research Journal of Pure & Applied Chemistry 21(11):92-114. DOI: 10.9734/IRJPAC/2020/v21i1130227.

Abstract: The imbalanced use of fertilizers in India is evident from the fact that the current ratio of nitrogen, phosphorus and potassium in agricultural soil in several states is skewed towards nitrogen. This imbalance causes problems, right from stagnating or declining productivity to soil sickness, widespread deficiency of macro nutrients and micronutrients, and soil alkalinity and salinity. Eventually, it results in reduced efficiency of fertilisers, low yields and low profitability for farmers. Also, nitrogen pollution of surface and groundwater due to excessive fertiliser use has reached alarming levels in several states. Chemical fertilizers are currently the major emitters of nitrous oxide gas, a potent greenhouse gas and ozone depleting substance. Nutrient budget is an important tool to provide an early indication of potential problems arising from nutrient surplus and nutrient deficit. Balanced use of all types of fertilizers, including traditional organic manures and biofertilizers are needed to bring about a change in the prevailing regime that encourages excessive use of chemical fertilizers. However, meeting future food security targets in an over-populated developing country like India, needs to increase the nutrient use efficiency. This ultimately leads to site-specific need-based nutrient application and minimizing nutrient losses from fields. This leads to the 4R Nutrient Stewardship concept, applying the Right Source of nutrients, at the Right Rate, at the Right Time and in the Right Place. This paper provides a historical overview of the nutrient budgeting efforts and systematically reviews major challenges, opportunities, in defining, quantifying, and applying nutrient budgets and improving nutrient use efficiency.

Effect of Overexpression of JERFs on Intracellular K^+/Na^+ Balance in Transgenic Poplar (*Populus alba* × *P. berolinensis*) Under Salt Stress

Ding C, Zhang W, Li D, Dong Y, Liu J, Huang Q and Su X. 2020. Front. Plant Sci. 11:1192. DOI: 10.3389/fpls.2020.01192.

Abstract: Salt stress is one of the main factors that affect both growth and development of plants. Maintaining K^+/Na^+ balance in the cytoplasm is important for metabolism as well as salt resistance in plants. In the present study, we monitored the growth (height and diameter) of transgenic *Populus alba* × *P. berolinensis* trees (ABJ01) carrying *JERF36s* gene (a tomato jasmonic/ethylene responsive factors gene) over 4 years, which showed faster growth and significant salt tolerance compared with non-transgenic poplar trees (9#). The expression of *NHX1* and *SOS1* genes that encode Na^+/H^+ antiporters in the vacuole and plasma membranes was measured in leaves under NaCl stress. Non-invasive micro-test techniques (NMT) were used to analyse ion flux of Na^+, K^+, and H^+ in the root tip of seedlings under treatment with100 mM NaCl for 7, 15, and 30 days. Results showed that the expression of *NHX1* and *SOS1* was much higher in ABJ01 compared with 9#, and the Na^+ efflux and H^+ influx fluxes of root were remarkable higher in ABJ01 than in 9#, but K^+ efflux exhibited lower level. All above suggest that salt stress induces *NHX1* and *SOS1* to a greater expression level in ABJ01, resulting in the accumulation of Na^+/H^+ antiporter to better maintain K^+/Na^+ balance in the cytoplasm

of this enhanced salt resistant variety. This may help us to better understand the mechanism of transgenic poplars with improving salt tolerance by overexpressing *JERF36s* and could provide a basis for future breeding programs aimed at improving salt resistance in transgenic poplar.

Potassium Deficiency Significantly Affected Plant Growth and Development as Well as microRNA-Mediated Mechanism in Wheat (*Triticum aestivum* L.)

Thornburg T.E., J. Liu, Q. Li, H. Xue, G. Wang, L. Li, J.E. Fontana, K.E. Davis, W. Liu, B. Zhang, Z. Zhang, M. Liu, and X. Pan. 2020. Front. Plant Sci. 11:1219. DOI: 10.3389/fpls.2020.01219.

Abstract: It is well studied that potassium (K^+) deficiency induced aberrant growth and development of plant and altered the expression of protein-coding genes. However, there are not too many systematic investigations on root development affected by K^+ deficiency, and there is no report on miRNA expression during K^+ deficiency in wheat. In this study, we found that K^+ deficiency significantly affected wheat seedling growth and development, evidenced by reduced plant biomass and small plant size. In wheat cultivar AK-58, up-ground shoots were more sensitive to K^+ deficiency than roots. K^+ deficiency did not significantly affect root vitality but affected root development, including root branching, root area, and root size. K^+ deficiency delayed seminal root emergence but enhanced seminal root elongation, total root length, and correspondingly total root surface area. K^+ deficiency also affected root and leaf respiration at the early exposure stage, but these effects were not observed at the later stage. One potential mechanism causing K^+ deficiency impacts is microRNAs (miRNAs), one important class of small regulatory RNAs. K^+ deficiency induced the aberrant expression of miRNAs and their targets, which further affected plant growth, development, and response to abiotic stresses, including K^+ deficiency. Thereby, this positive root adaption to K^+ deficiency is likely associated with the miRNA-involved regulation of root development.

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The FRST National Soil Fertility Database

https://acsess.onlinelibrary.wiley.com/doi/abs/10.1002/csan.20218

Wheat crops can be significantly affected by potassium deficiency. Photo by N. Cohen Kadosh.

Obituary

Obituary of Professor Emeritus Joseph Hagin (1921-2020)

We are sorry to announce the death of our dear Professor Emeritus Joseph Hagin of the Faculty of Civil and Environmental Engineering Technion, Israel Institute of Technology, Haifa. In a lifelong commitment to excellence, he specialized in fertilizers, soil chemistry and wastewater treatment and reuse in agriculture, and was respected as a world-leading researcher.

Professor Hagin was one of the first developers of effective fertilization approaches to benefit the plant and protect the environment. This was achieved in a ground-breaking collaboration with the fertilizer industry in Israel and contributed significantly to the advancement of innovative approaches to fertilizers' development and their proper application in agriculture.

In parallel with his research activities, he devoted part of his time to management positions in academic and research frameworks. In 1960, he was appointed head of the Land and Fertilizers Unit in the Faculty of Agriculture of the Hebrew University of Rehovot. In 1963, he moved to Haifa, with his wife and children, in order to serve as an associate professor in the Faculty of Agricultural Engineering at the Technion. In 1967 he received a professorship. In the same year he was appointed director of the Technion's Institute for Research and Development of the Technion, and in 1970 he also assumed the position of Vice President of the Technion for Research. In the following years, he served as chief scientist at the Israeli Center for Fertilizer Research.

He wrote many books including "Fertilization of Dryland and Irrigated Soils", "Nitrogen Dynamics Model Verification and Practical Application", "Treatment and Use of Wastewater for Agricultural Irrigation" and IPI Research Topics No. 23 "Fertigation: Fertilization through irrigation" which is an important reference for students, advisors in water and fertilizer management, and for farmers.

Professor Hagin was a member of the Israel Society of Soil Science (Chairman 1959-1961, 67-68, 78-80), the American Soil Science Society and the International Fertilizer Society. He also managed the Palestinian-Jordanian-Israeli water desalination project from 1997 to 2011 to establish sewage treatment facilities throughout Israel, as well as in Jordan and the Palestinian Authority.

Among his many collaborations with the fertilizer industry, one of the most important to him was with Dr. Dalia Greidinger, who died of cancer in 1979. Her family created the Dalia Greidinger Foundation which has promoted fertilizer research for forty years. Professor Hagin headed the international conference held in her memory.

IPI remembers Professor Emeritus Joseph Hagin.

Thanks to his connections with leading researchers in Israel and around the world, the conference became a very effective framework for disseminating innovative knowledge in the field. Thirteen international conferences have deepened global understanding of plant health and nutrition, soil and water issues and the effect of changing climatic conditions and have helped formulate sustainable approaches to global food security.

Professor Hagin worked, scientifically and publicly, with modesty and courtesy. He showed great determination and dedication to solving agricultural problems and disseminating the acquired knowledge to his peers, his research successors and students.

There is no doubt that Joseph Hagin was a special man, one of a kind. He was a great researcher with an amazing personality: humble, kind and very much loved by all. Those of us who knew him feel fortunate and privileged to have worked with him and learned from him.

His example and influence lives on in the memory and work of all who were fortunate to know him. May his memory be blessed.

Written by

Prof. Emeritus Avi Shaviv, Faculty of Civil and Environmental Engineering Technion, Israel Institute of Technology, Haifa

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