Research Findings

Photo 1. Winter maize crop grown in northern Vietnam. Photo by the authors.

Polyhalite Effects on Winter Maize Crop Performance on Degraded Soil in Northern Vietnam

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Abstract

Maize (*Zea mays*) production in Vietnam, the major component of livestock feed (90%) in this country, recorded a 12-fold increase from 1981-2014, with an impressive mean annual yield increase (10%). Nevertheless, a substantial yield gap exists between the current local mean yield (4.7 Mg ha^{-1}) and those of leading maize producing countries, such as USA (12.8 Mg ha^{-1}). Degraded soil fertility and commonly imbalanced fertilization practices were suggested among the major reasons for this yield gap. Polyhalite, a natural marine sedimentary mineral consisting of a hydrated sulfate of potassium (K), calcium (Ca), and magnesium (Mg) was examined as a potential partial substitute for muriate of potash (MOP) as the K donor, with the advantage of more balanced mineral nutrition being a four-in-one fertilizer. An experiment was carried out from August until early December 2016 in northern Vietnam, comparing maize crop performance under six fertilizer treatments: farmers' practice (120 kg K_2O ha^{-1}); control (no K applied); 60 kg K_2O ha^{-1}, applied through MOP; and 60, 90, and 120 kg K_2O ha^{-1}, applied

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through combinations of polyhalite and MOP at 1:1 ratio at the K_2O level. All treatments received farmyard manure (FYM) at 10 t ha^{-1}, 180 kg N ha^{-1} (urea) and 90 kg P_2O_5 ha^{-1} (superphosphate). The combinations of MOP and polyhalite gave rise to significantly higher fodder yields, in grains as well as husks and corncobs. Interestingly, the differences between the three combinations were not statistically significant for most of the yield parameters, suggesting that lower K rates, such as 60 or 90 kg K_2O ha^{-1}, might be sufficient to obtain reasonable maize yields. The contribution of polyhalite to prolonged K availability, and to more balanced crop nutrition, was especially demonstrated when treatments with a similar K_2O rate (60 kg ha^{-1}) were compared; the combined fertilizer displayed significantly greater vegetative biomass and kernel yield. An economic analysis showed that under the circumstances of the present study, the polyhalite and MOP combination at a rate of 90 kg K_2O ha^{-1} was the most profitable practice, far above the output from farmers' usual practice. The economic analysis also clearly demonstrated that no K application might lead to a substantial loss on investment. In conclusion, adequate K supply is essential to profitable winter maize production under the climatic and edaphic conditions in northern Vietnam. Furthermore, combinations of polyhalite and MOP can open new horizons in enhancing maize and other crops' performance in Vietnam.

Keywords: Balanced plant nutrition; Polysulphate; polyhalite; potassium; yield gap; *Zea mays*.

Introduction

Maize (*Zea mays* subsp. *mays*), also known as corn, is a cereal grain first domesticated by indigenous peoples in southern Mexico about 10,000 years ago (Kane and Rieseberg, 2005). Maize has spread throughout the world since the 16th Century, and has become a staple food in many countries. In addition to being consumed directly by humans, maize is also used to produce ethanol, animal feed, and other products, such as corn starch and corn syrup. Maize is widely cultivated throughout the world, and a greater weight of maize is produced each year than any other grain. In 2018, total world production was 1.15 billion tonnes (FAOstat, 2020).

In Vietnam, maize is the primary material resource for 90% of livestock and poultry feed. The demand for maize has increased due to the strong expansion of animal husbandry (Kha and Tuong, 2019). Thus, the area under maize cultivation grew substantially from 0.37-1.2 million ha from 1981-2014, and the yearly production rose during that period from 0.42-5.2 million tonnes (Fig. 1A). With significant efforts made by the Vietnamese government to enhance local maize productivity (Huong and Yorobe, 2017), the mean annual yield increased linearly from about 1.1 to 4.7 Mg ha^{-1} between 1981 and 2018 (Fig. 1B). This impressive output growth was triggered by more intensive cultivation, increased areas of planting, enhanced yield, and adoption of both open-pollinated variety (OPV) and hybrid seeds starting in 1991 (Tinh, 2009). The introduction of chemical fertilizers, such as nitrogen (N) and phosphorus (P), also made a substantial contribution to the yield increase (Setiyono *et al.*, 2010; Giang *et al.*, 2015). Nevertheless, and in spite of the impressive advances in the Vietnamese maize industry, the present mean yield (4.7 Mg ha^{-1}) is listed 72nd among the world's maize producing countries, less than 40% that of the USA, which is listed 10th (FAOstat, 2020). This significant yield gap is mainly attributed to serious edaphic constraints (Schweizer *et al.*, 2017), and to the conventional farming practices (Keil *et al.*, 2008).

The nature of the soil may be crucial to maize quality and productivity. Conversion of forest to agricultural land for maize cultivation is known to negatively affect soil fertility. According to Schweizer *et al.*, (2017), soil aggregate stability declined simultaneously with a decrease in soil organic carbon and exchangeable Ca^{2+} and Mg^{2+}, which both declined with increasing time since land use

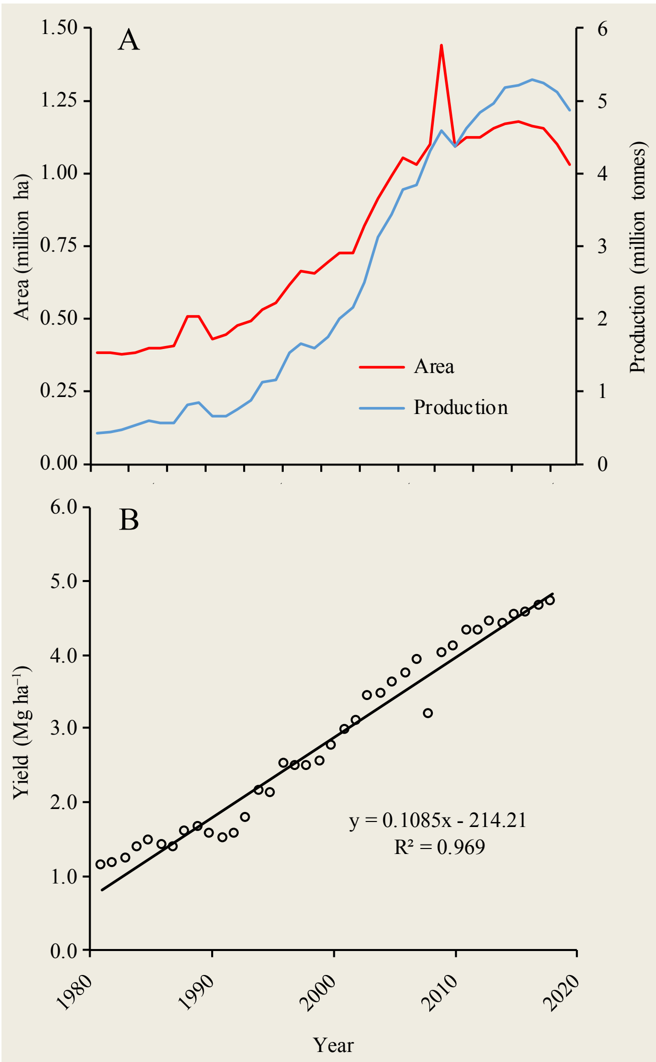
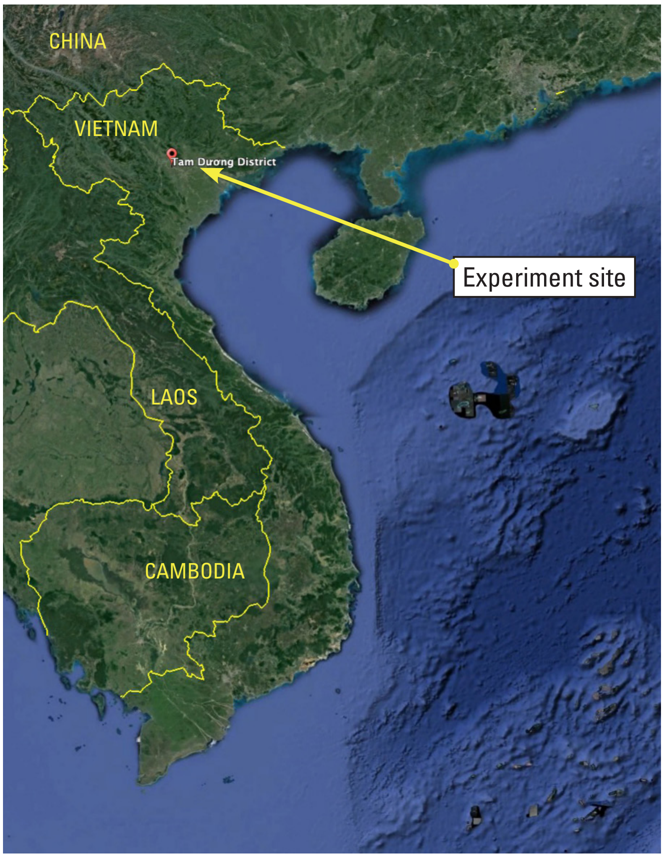


Fig. 1. Maize production in Vietnam 1981-2018. Changes in cultivation area and production (A); and, in maize yield (B). *Source:* FAOstat, 2020.

changed from forest to maize production systems. The Alisol and Luvisol chronosequences were 1.9 times more stable, whereas the Vertisol chronosequence was 2.5 times more stable under primary forest than under maize. Over 18 years' chronosequence, the maize topsoils lost 1.6 kg m^{-2} and 3.2 g kg^{-1} soil organic carbon and Ca^{2+}, respectively. The humid tropic climate of Vietnam creates significant further challenges for soil nutrient availability. During the wet season, the liquid soil phase is prone to swap very frequently, within hours or days, depending on the precipitation regime. This liquid phase contains most of the currently available nutrients, including potassium (K), that are leached away from the rhizosphere. In addition, 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. Consequently, insufficient nutrient availability, particularly K, but also imbalanced mineral nutrition, have been consistently shown to be responsible for the maize yield gap in Vietnam (Witt *et al.*, 2006; Setiyono *et al.*, 2010; Pasuquin *et al.*, 2014; Pandey *et al.*, 2019).



Map 1. Location of the maize field trial at Duy Phien commune, Tam Duong district, Vinh Phuc Province, Vietnam. *Source:* Google maps © 2020.

Potassium is essential for most basic processes in plants' life cycle (Zörb *et al.*, 2014). Many studies have shown that maize is particularly responsive to K application, when the natural nutrient availability cannot fully meet requirements (Jordan-Meille and Pellerin, 2008; Pettigrew, 2008; Samal *et al.*, 2010; Izsáki, 2017; Jiang *et al.*, 2018; Ortas, 2018; Asante-Badu *et al.*, 2020). Potassium application practices were introduced to Vietnam much later than N and P and, therefore, were insufficiently disseminated among farmers (Pandey *et al.*, 2019). Under the climatic and edaphic constraints of Vietnam, K application must be addressed with careful attention to the problem of rapid leaching, which necessitates splitting the fertilizer dose into several application events during the growing season, thus providing better K availability whenever necessary (Joshi *et al.*, 2014; Pandey *et al.*, 2019). Alternatively, less soluble fertilizers that would last for a significantly longer period in the growing season should be considered.

Similar to the danger of K shortage, other alkaline nutrients, Ca and Mg, are at risk of deficiency. Calcium is pivotal to numerous structural and physiological functions from the subcellular to the whole plant scale (White and Broadley, 2003). Magnesium is part of chlorophyll in all green plants and is essential for photosynthesis and carbohydrate partitioning (Cakmak and Yazici, 2010; Farhat *et al.*, 2016). 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 (Dick *et al.*, 2008), as it often interacts with N to significantly enhance protein metabolism (Jamal *et al.*, 2010).

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 which occurs in sedimentary marine evaporates and consists of a hydrated sulfate of K, Ca, and Mg with the formula: $K_2Ca_2Mg(SO_4)_4{\cdot}2(H_2O)$. The deposits found in Yorkshire, in the UK, and marketed as Polysulphate®, typically consist of K_2O: 14%, SO_3: 48%, MgO: 6% and 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 (Yermiyahu *et al.*, 2017; Yermiyahu *et al.*, 2019) and is, therefore, a suitable fertilizer to supply these four nutrients during the rainy growing season. Polyhalite was recognized as an effective crop fertilizer, being at least as effective as equivalent soluble sulfate sources of K, Ca and Mg (Hoang *et al.*, 2016; Yermiyahu *et al.*, 2017).

The objective of the present study was to evaluate the agronomic efficiency of polyhalite on yield, quality, and economic returns of winter maize on degraded soils in Northern Vietnam. Demonstrating the advantages of using polyhalite as an alternative to MOP and, moreover, as a key fertilizer for balanced crop nutrition, will encourage Vietnamese farmers to adopt this strategy for maize and other crops.

Materials and methods

Experiment site

The field experiment was carried out at Duy Phien commune, Tam Duong district, Vinh Phuc Province (Map 1). The climate in this region is subtropical with a mean annual temperature of 23.5°C and a mean annual rainfall of 1,600 mm, of which more than 80% occurs between May and October (Fig. 2).

The soil profile of the research area was classifield as Grey degraded soil or Plinthic Acrisols or as Plinthaquults (Sehgal, 1989). The local topsoil was sandy loam with considerable clay content, acidic (pH 5.2), with high organic matter content, but low nutrient status (Table 1).

Experiment plan

Before sowing, a standard basic fertilizer practice was carried out throughout, which included the spreading of farmyard manure (FYM) or composted cattle dung at 10 t ha^{-1}. The experiment included six treatments (Table 2), with four replications in a randomized complete block design, i.e. 24 plots (24 m^2 plot^{-1}).

The treatments differed in K rate (from 0-120 kg K_2O ha^{-1}) and source: muriate of potash (MOP; KCl, 60% K_2O) and polyhalite (19.2% S, 14% K_2O, 6% MgO and 17% CaO). The first control (K_{120+0} – farmers' practice) included a high K rate, all of which was applied through MOP (K_{120+0}), and served to compare with the other treatments, agronomically and economically. The second control K_0 did not include any K application, providing an evaluation of K contribution to the maize crop performance under the experiment conditions. In treatments K_{60+0} and K_{30+30}, the K rate was reduced to 60 kg K_2O ha^{-1}, applied solely through MOP or through a combination of MOP and polyhalite, respectively. In treatments K_{45+45} and K_{60+60}, K application rates rose to 90 and 120 kg K_2O ha^{-1}, respectively, while maintaining a 1:1 ratio between MOP and polyhalite as the sources of K_2O (Table 2).

Nitrogen and phosphorus were applied evenly to all treatments at 180 kg N ha^{-1} and 90 kg P_2O_5 ha^{-1}, using urea (46% N) and locally available Lam Thao superphosphate (16.5% P_2O_5), respectively. The mineral fertilizers were applied three times during the cropping season: before sowing (30% N, 100% P, 40% K and 40% polyhalite); at 4 to 6 leaves (40% N); and, at pollination (30% N, 60% K and 60% polyhalite).

Crop management

LVN4, a locally recommended maize variety, was used. Maize was cultivated on raised beds (6×4 m), 120 cm width and 30 cm height, spacing between two beds was 30 cm, with a density of 5 plants m^{-2}. Seeding date was 16 August 2016 and the harvest start date was 3 December 2016.

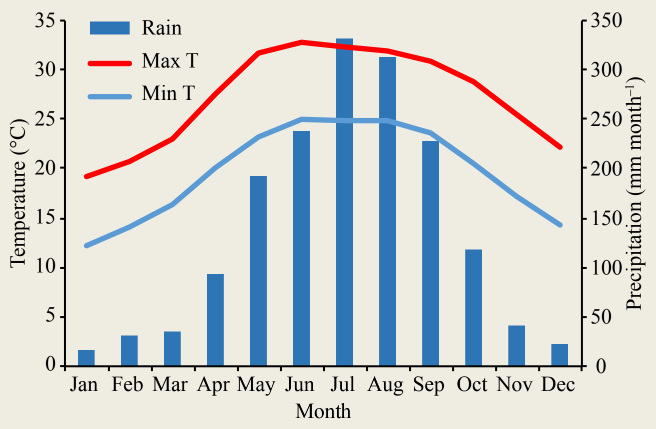


Fig 2. Climate conditions at the experiment site, including mean monthly maximum and minimum temperature and mean monthly precipitation. *Source:* https://en.climate-data.org/asia/vietnam/vinh-phuc-province/tam-duong-35088/#climate-graph

Field observations, sampling, and measurements

Plant height and the number of leaves were measured four times during crop development. Bloom date and corncob height were determined. The occurrence of pests and diseases was evaluated at 30, 45, and 80 days after sowing. At harvest, a 4 m long section within each plot was used to determine the yield parameters. Corncobs and vegetative parts were separated and weighed. Five randomly sampled corncobs per plot were used to determine the numbers of kernel rows,

Table 1. Major properties of topsoil at the trial location in northern Vietnam

Soil property	
	%
Clay (< 2 µm)	10
Silt (2-30 µm)	65
Fine sand (20-200 µm)	20
Coarse sand (> 200 µm)	5
	g kg^{-1}
pH (KCl 1M)	5.2
Total C	6.0
Total N	1.1
Total P	0.32
Total K	0.50

Table 2. Detailed description of the fertilizer treatments

Treatment	FYM	N	P_2O_5	K_2O	
				KCl	Polyhalite
	t ha^{-1}	---------------------	-kg ha^{-1}-	---------------------	
K_{120+0}	10	180	90	120	0
K_0	10	180	90	0	0
K_{60+0}	10	180	90	60	0
K_{30+30}	10	180	90	30	30
K_{45+45}	10	180	90	45	45
K_{60+60}	10	180	90	60	60

Note: FYM = farmyard manure

kernels per row, and total kernels per corncob. Kernels were dried to 14% moisture and kernel weight (g 1000^{-1} kernels) was determined. A 100 g sample of kernels from each plot was taken for laboratory determinations of dry matter, starch (Clegg, 1956), and protein (Sáez-Plaza *et al.*, 2013) contents. Dry matter content of husks, corncobs and of the vegetative biomass were determined.

Results

Maize growth and development

The duration of the growing period was 107 days for all fertilizer treatments, excluding K_0, which was extended by 4 days. Differences had already emerged at the pollination stage, with a 5-day delay in K_0, compared to the other treatments (63 vs. 58 days after sowing (DAS), respectively). It appears that in the absence of K fertilizer application, crop growth and development is delayed, while the K source (FYM, MOP or polyhalite) has no significant effect if K is adequately applied.

The number of leaves per plant at harvest ranged from 12.7-13.1, with only treatment K_{60+60} displaying slightly but significantly greater number of leaves compared to K_0 ($P < 0.05$). Plant height and dry biomass at harvest were significantly influenced by the fertilizer treatments (Fig. 3). While K application rate had no significant effect on the plant height, a higher polyhalite rate seemed to support greater plant height (Fig. 3A). Furthermore, the replacement of MOP with equivalent K contribution from polyhalite, at any K application rate, gave rise to significantly greater dry biomass production (Fig. 3B). Notably, plant dry biomass was lowest in the absence of K fertilizer (K_0).

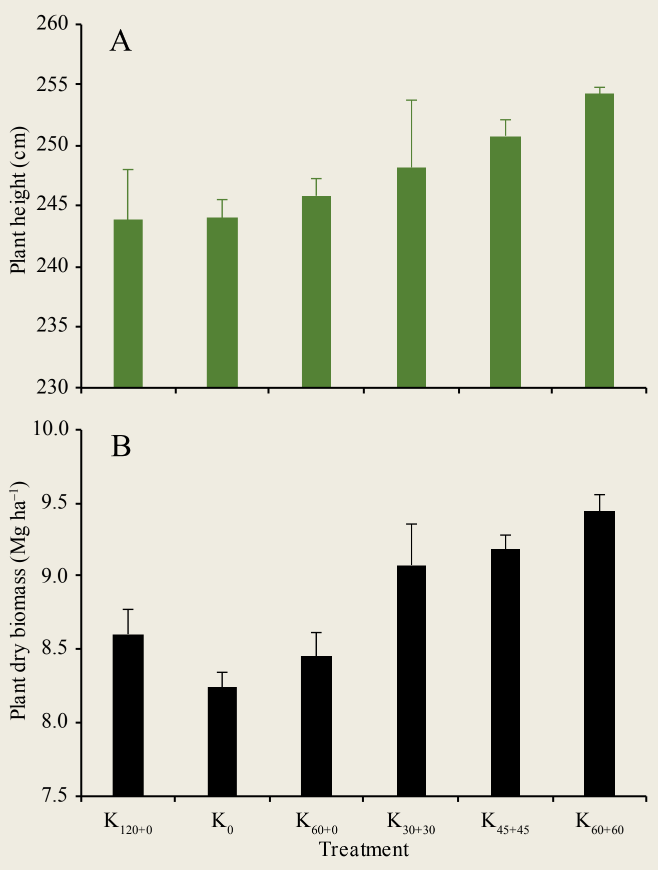


Fig. 3. Effects of fertilizer treatments on plant height (A) and vegetative dry biomass (B) toward harvest in winter maize crop grown in northern Vietnam. Bars indicate SE.

Vulnerability to pests and diseases

During the experiment, the winter maize crop encountered two major pests: corn borer (*Ostrinia nubilalis*) and corn aphid (*Rhopalosiphum maidis*), and two diseases: banded leaf and sheath blight (BLSB) (*Rhizoctonia solani*), and bacterial top and stalk rot (*Erwinia chrysanthemi* pv. Zeae) (Table 3).

The infestation with corn aphids was very mild, not exceeding 1.5% of the plants, and concentrated at the mid cropping season, 45 DAS. Although not statistically significant, the infestation rates of corn aphids were somewhat higher under no K application (K_0), slightly declined where K was applied, and were especially low where polyhalite was part of the fertilization practice (Table 3). BLSB infestation rate was very low, below 2% and 1% at the early and late sections of the growing season, respectively, and considerably higher at the mid cropping season (45 DAS), ranging from 2.5-6.3%, which is perceived as quite low in maize production. Notable, however, was the clear tendency of lower BLSB infestation rates among plants fertilized with polyhalite (Table 3). In the present study, the bacterial top and stalk rot disease only occurred toward the end of the season with very low infestation rates (3.3-4.4%), and with no considerable differences between treatments (Table 3).

Corn borer (*Ostrinia nubilalis*) damage to the stem was very slight during the early crop stage (until 30 DAS), 3.8-5.4% (Table 3). This type of damage increased considerably during the mid-season (45 DAS) to range from 12.9-15.6%, and declined to 3.3-4.4% toward the end of the season (80 DAS). Corn borer damage to the corn occurred only toward the season's end, ranging at rates from 14.8-17.1%. No significant differences were observed between treatments, however, damage rates tended to be consistently lower among the polyhalite-treated plants (Table 3).

Influence of polyhalite on maize yield and quality parameters

On average, the corn yield was very close to 1 corncob $plant^{-1}$, with no differences between treatments. Nevertheless, the fertilizer treatments had significant influences on other quantitative parameters that determine the yield (Fig. 4). The most important one, kernel yield, was significantly greater in plants applied with polyhalite+MOP combinations, ranging from 8-8.5 Mg ha^{-1}. The control (K_0) kernel yield was 5.7 Mg ha^{-1}, far below all K-applied treatments. MOP-applied plants displayed intermediate kernel yields that ranged from 7.2-7.6 Mg ha^{-1} (Fig. 4A). This response pattern to the fertilizer treatments was preserved also with the dry husk and dry corncob yields, however, the differences were much less significant (Fig. 4B, C). The harvest index (HI) also

Table 3. Infestation rates (% of plants) by corn aphid (*Rhopalosiphum maidis*), banded leaf and sheath blight (BLSB) (*Rhizoctonia solani*), corn borer (*Ostrinia nubilalis*), and bacterial top and stalk rot (*Erwinia chrysanthemi* pv. Zeae) during winter maize crop in northern Vietnam, as influenced by fertilizer treatments. DAS (days after sowing).

	Corn aphid (*Rhopalosiphum maidis*)			BLSB (*Rhizoctonia solani*)			Corn borer (*Ostrinia nubilalis*)						Bacterial top and stalk rot (*Erwinia chrysanthemi* pv. Zeae)		
							Damaged stem			Damaged corn					
DAS	30	45	80	30	45	80	30	45	80	30	45	80	30	45	80
Treatment									%						
K_{120+0}	0	0.8	0	1.7	6.3	0.6	4.8	15.6	3.8	0	0	17.1	0	0	4.2
K_0	0	1.3	0	1.9	5.0	0.8	5.4	15.2	4.4	0	0	16.3	0	0	4.4
K_{60+0}	0	0.8	0	0.8	4.0	0.6	4.0	15.0	4.0	0	0	16.7	0	0	3.8
K_{30+30}	0	0.4	0	0.8	3.5	0.6	4.4	14.0	3.8	0	0	16.3	0	0	3.5
K_{45+45}	0	0.4	0	0.6	2.9	0.6	3.8	13.3	3.3	0	0	15.8	0	0	3.3
K_{60+60}	0	0.4	0	0.4	2.5	0.4	4.0	12.9	3.3	0	0	14.8	0	0	3.3

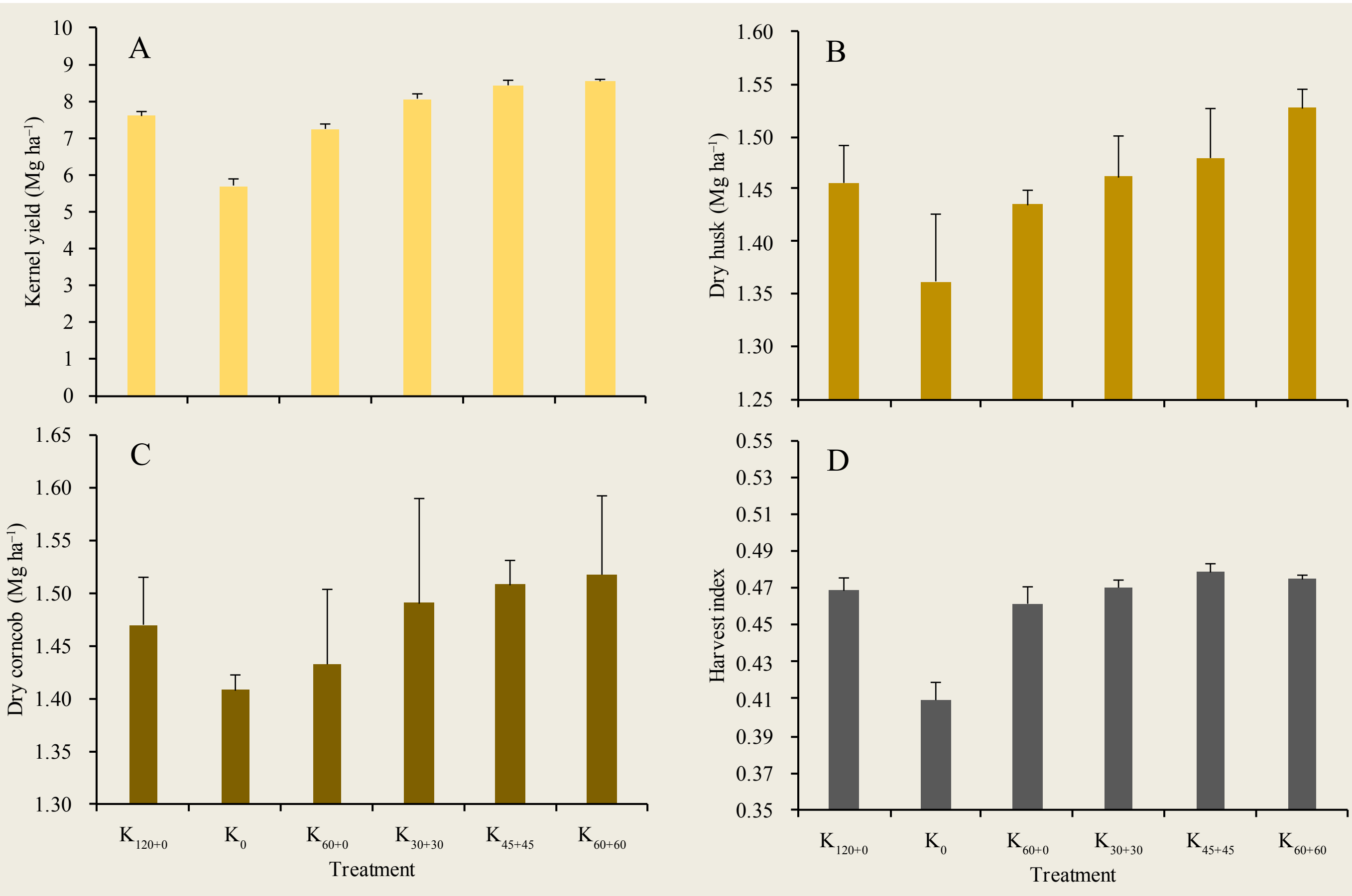


Fig. 4. Effects of fertilizer treatments on yield parameters of winter maize crop grown in northern Vietnam. Kernel yield (A); dry husk yield (B); dry corncob yield (C); and harvest index (D). Bars indicate SE.

tended to be higher among the polyhalite-applied plants, nevertheless, only K_0 plants exhibited significantly lower HI, 0.41, compared to 0.47-0.48 among the K-applied treatments (Fig. 4D).

The polyhalite+MOP fertilizer treatments significantly increased the number of kernel rows in a corncob to about 13.6, compared to 13.3 and 12.9 in the MOP-applied and K_0 plants, respectively (Fig. 5A). Nevertheless, the fertilizer effect on the number of kernels per row was much greater; whereas K_0 and K_{60+0} treatments obtained nearly 35 kernels per row, all other treatments gave rise to significantly higher figures, from 38-41 kernels per row. Noteworthy was the unequivocal advantage of K_{30+30} over K_{60+0} in this yield determinant; with similar low K rates (60 kg K_2O ha^{-1}), the polyhalite+MOP obtained significantly greater numbers of kernels per row. Yet, this advantage was not preserved at the higher K rates (Fig. 5B). Consequently, the total number of kernels per corncob maintained a similar response pattern to the fertilizer treatment, being significantly higher under the higher K rates (Fig. 5C). Kernel size, determined in g $1,000^{-1}$ kernels, was significantly smaller under K_0, compared to K_{60+0} and to the various MOP+polyhalite combinations, while K_{120+0} had an intermediate kernel weight that did not differ from either K_0 or K_{60+0} (Fig. 5D). Grain quality parameters such as dry matter, starch, and protein contents ranged from 58-60%, 40-43%, and 4-5%, respectively, with no significant differences between treatments.

Economic considerations

Replacing MOP with polyhalite brought about a very slight increase in the economic input (cost) per ha of winter maize crop in northern Vietnam, as the fertilizers' prices were 0.09 and 0.11 million VND kg^{-1}, respectively. Outstanding for much lower input was the K_0 control (Fig. 6A), which did not receive any K fertilizer. However, the revenue from this treatment was by far the lowest of all other treatments. Naturally, the revenue response pattern to the fertilizer treatments (Fig. 6A) followed those of the kernel yield and quality (Figs. 4 and 5). The effects of the fertilizer treatments on the farmer's profit was clear (Fig. 6B): while K_0 elicited clear a negative return and the MOP-applied treatments produced very small profits (1.4-1.9 million VND ha^{-1}), the MOP+polyhalite strategy gave rise to considerably higher profits that ranged from 5.1-6.3 million VND ha^{-1}, 170-230% more than the profit obtained from farmer's usual fertilizer practice.

Discussion

An adequate plant K status is essential for maize crop growth and development throughout the growing season (Asante-Badu *et al.*, 2020). This principle is fully demonstrated by the significantly inferior crop performance under the lack of K application (K_0) in almost every parameter measured (Figs. 3-6). Sufficient crop K status is particularly important during the reproductive phase, when carbohydrates are remobilized and translocated from leaf and stem

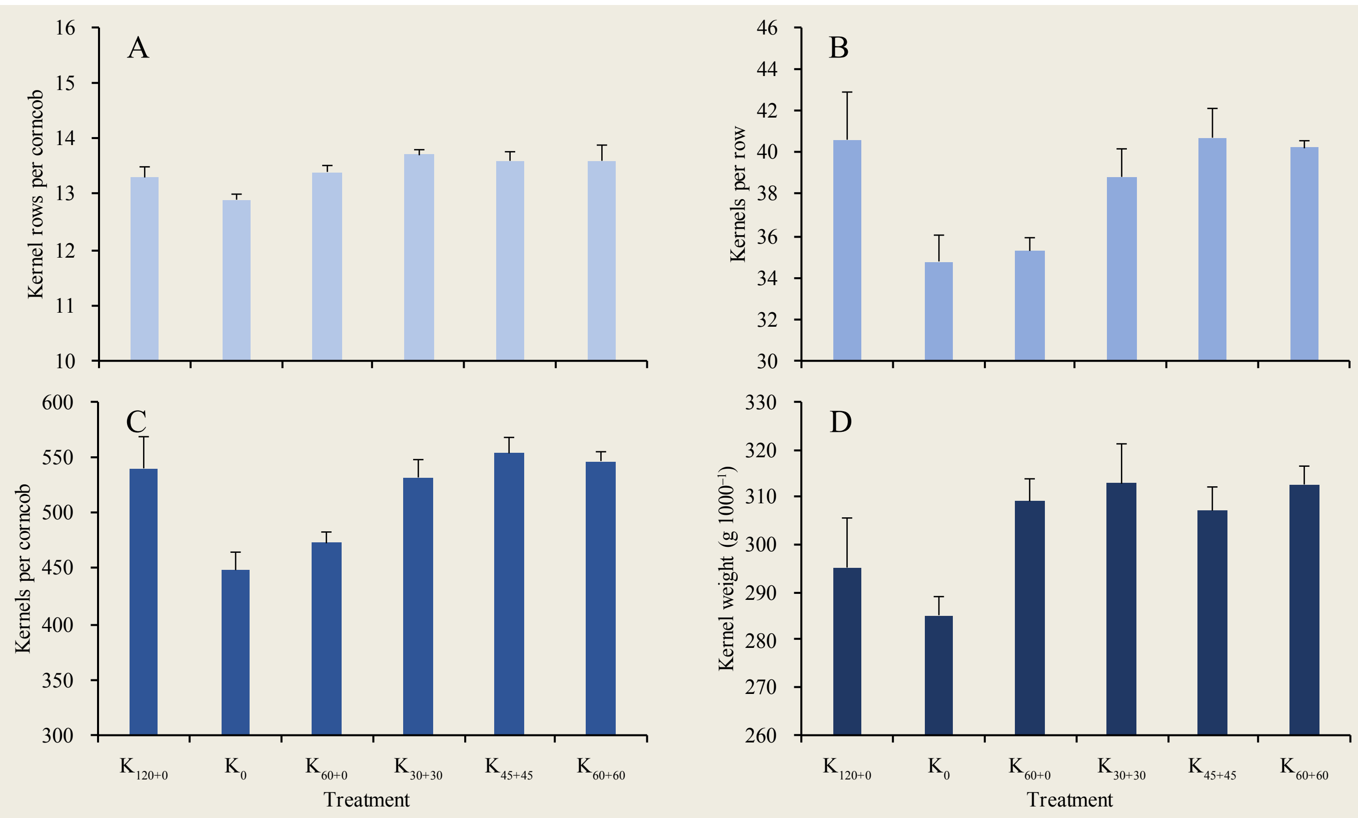


Fig. 5. Effects of fertilizer treatments on kernel yield determinants in winter maize crop grown in northern Vietnam. Kernel rows (A); kernel number per row (B); kernels per corncob (C); and kernel weight in g $1,000^{-1}$ kernels (D). Bars indicate SE.

tissues to the developing corncob and kernels (Pettigrew, 2008). Due to technical and financial reasons, farmers usually perform a pre-planting application of the complete seasonal fertilizer rate. This practice holds two major drawbacks: a transient increase in the soil salinity of the seedbed during the short but salt-sensitive germination and seedling establishment stages, on the one hand, which might be followed by too rapid nutrient depletion typical to the local acidic soils (Table 1) under the heavy rains of August (Fig. 2), on the other hand. Although K fertilizers were split between pre-plant and pollination, the differences in the vegetative biomass at harvest (Fig. 3B) indicate that this might have been the situation under the farmers' practice K_{120+0}, where a high MOP rate was applied. This, in comparison with the three MOP+polyhalite treatments, most of which obtained greater biomass under lower K rates and particularly with less MOP. As a slower-release fertilizer, and with relatively lower salt index (Yermiyahu *et al.*, 2019), polyhalite application seemed to reduce both risks of salt stress during plant establishment and rapid K depletion from the rhizosphere, thus promoting greater biomass.

Furthermore, polyhalite supplies other essential nutrients, such as Ca, Mg, and S that were possibly in deficit on the local soil. Calcium (Ca) is an essential plant nutrient playing multiple roles in the cell. It is important for membrane stability, cell integrity, cell division and elongation (Steward, 1974; Kirkby and Pilbeam, 1984; White and Broadley, 2003) and for multiple signal transduction pathways and activation (Monshausen, 2012). However, Ca can only transfer from one part of a plant to another through the xylem sap and hence, the plant cannot remobilize calcium from older tissues. To provide crop Ca requirements throughout the season, a steady availability level of this nutrient must therefore be preserved in the soil. Magnesium is part of chlorophyll in all green plants and is essential for photosynthesis and carbohydrate partitioning (Cakmak and Yazici, 2010; Farhat *et al.*, 2016). Gransee and Führs (2013) unraveled new insights into the role of Mg in increasing crop tolerance to various stresses that indicate changes in the crop Mg demand under adverse growth conditions. 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 (Kovar and Grant, 2011). Sulfur often interacts with N to significantly enhance crop productivity (Jamal *et al.*, 2010).

The contribution of polyhalite to prolonged K availability, and to more balanced crop nutrition was especially demonstrated when treatments K_{60+0} and K_{30+30} are compared. Although both treatments held similar K rates (60 kg K_2O ha^{-1}), the latter displayed significantly greater vegetative biomass (Fig. 3B) and kernel yield (Fig. 4A). The larger plant biomass under the polyhalite-applied treatments enhanced the reproductive potential of the maize crop, as indicated by the greater corncob dimensions (Fig. 4C), thus allowing additional kernel rows (Fig. 5A), significantly more kernels per row (Fig. 5B), and consequently, higher total kernel numbers (Fig. 5C). In addition, polyhalite application enhanced kernel weight (Fig. 5D), another indication of the higher capacity that this fertilizer provided to the maize crop productivity.

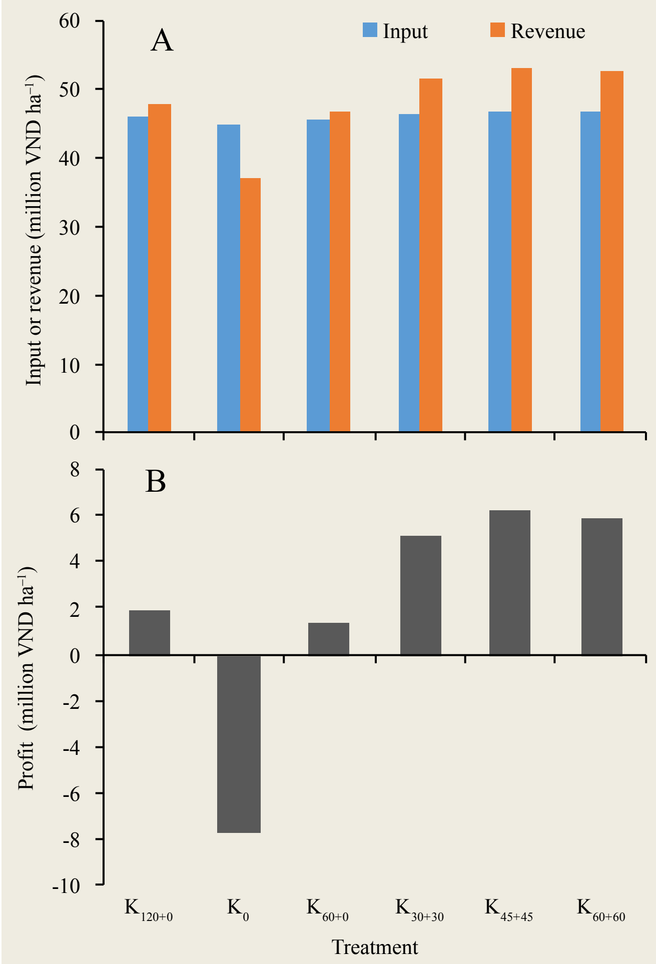


Fig. 6. Effects of fertilizer treatments on the input costs and revenue (A), and on the consequent profit (B) of winter maize crop in northern Vietnam, in local terms.

Winter maize crops in tropical regions commonly suffer from various pests and diseases due to the high temperature and humidity. Among pests, *Ostrinia nubilalis* is a stalk boring pest, whose feeding injury in maize might result in yield loss, increased infection of secondary pathogens that cause stalk and ear rots, ear drop, stalk breakage and lodging, all of which impedes harvest (Mason and Sappington, 2018). Corn aphids (*Rhopalosiphum maidis*) might also cause severe damage to tropical maize crops (Kuo *et al.*, 2006). Among microbial and fungal diseases, the bacterial stalk rot disease (*Erwinia chrysanthemi* pv. Zeae) has emerged in the recent years as one of the most important diseases in winter sown maize crops in India (Kumar *et al.*, 2017). Winter maize has the most susceptible stage coinciding with the annual monsoon rainfall, which aggravates the disease's development. This might have been the situation in northern Vietnam, where the maize winter crop encounters the peak of the rainy season (Fig. 2). BLSB (*Rhizoctonia solani*) is also considered as one of the emerging and severe pathogens limiting maize crop production under a changing climatic scenario (Singh and Shahi, 2012). Balanced mineral nutrition was often shown to enhance crop tolerance to various pests and diseases, simply because the healthier the plant the less vulnerable it is (Dordas, 2008; Huber *et al.*, 2012). Such a tendency was observed in the present study with all mentioned pathogens, with somewhat lower infestation rates occurring under the MOP+polyhalite treatments (Table 3). Nevertheless, no significant advantages could be elucidated for polyhalite regarding any of those pathogens. For unknown reasons, none of the pests or diseases reached infestation rates high enough to challenge the hypothesis.

Altogether, the combinations of MOP and polyhalite gave rise to significantly higher fodder yields, in grains as well as husks and corncobs (Fig. 4). Interestingly, the differences between the three combinations were not statistically significant for most of the yield parameters, suggesting that low K rates, such as 60 or 90 kg K_2O ha^{-1}, might be sufficient to obtain reasonable maize yields. However, this may be true under very few fertilizer application events. Assumingly, where fertilizer dose could be split into multiple application events, higher K rates might support greater yields (Witt *et al.*, 2006; Joshi *et al.*, 2014; Pandey *et al.*, 2019). Anyway, the economic analysis, which lacks statistical considerations, showed that under the circumstances of the present study, the polyhalite and MOP combination at a rate of 90 kg K_2O ha^{-1} was the most profitable practice, leaving the farmers' usual practice far behind. The economic analysis also clearly demonstrated that no K application (K_0) might lead to substantial loss of investment (Fig. 6B). In agreement with an increasing number of recent studies (Hoang *et al.*, 2016; Pavuluri *et al.*, 2017; Foxhoven and Below, 2018; Lillywhite *et al.*, 2020), the results obtained in the present one strongly support the inclusion of polyhalite in maize nutrition practices.

Conclusions

Adequate K supply is essential to profitable winter maize production under the climatic and edaphic conditions in northern Vietnam. Combining polyhalite and MOP at a K source ratio of 1:1 enhanced most of the aspects of maize crop performance, compared to local farmers' usual fertilizer practice. Moreover, the fertilizer input can be reduced from 120 to 90 kg K_2O ha^{-1}, with its positive environmental consequences.

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