Research Findings

Photo 1. Researcher in cabbage field in Vietnam. Photo by the authors.

Effects of Polyhalite Application on Yield and Quality of Cabbage Grown on Degraded Soils in Northern Vietnam

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Abstract

Cabbage (*Brassica oleracea* var. *oleracea*) production in Vietnam recorded a 20-fold increase from 1981 to 2019. Nevertheless, a substantial yield gap exists between the current local mean yield (27 Mg ha^{-1}) and those of leading cabbage producing countries. Low 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. Polyhalite, as a four-in-one fertilizer, has the advantage of providing more balanced mineral nutrition. An experiment was carried out in northern Vietnam, comparing cabbage crop performance under six fertilizer treatments: farmers' practice (150 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 through combinations of polyhalite and MOP at 1:1 ratio at the K_2O level.

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All treatments received farmyard manure (FYM) at 15 tonnes ha^{-1}, 180 kg N ha^{-1} (urea) and 80 kg P_2O_5 ha^{-1} (superphosphate). The combinations of MOP and polyhalite gave rise to significantly higher cabbage yields. The optimum K_2O rate was about 100 kg K_2O ha^{-1}, much lower than at the common farmers' practice. The contribution polyhalite made to prolonged K availability, and to more balanced crop nutrition, was most clearly demonstrated when treatments with a similar K_2O rate (60 kg ha^{-1}) were compared. An economic analysis showed that under the circumstances of the present study, the polyhalite and MOP combination at a rate of 100 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 cabbage production under the climatic and edaphic conditions in northern Vietnam. Furthermore, combinations of polyhalite and MOP can open new horizons in enhancing cabbage and other crops' performance in Vietnam.

Keywords: Balanced plant nutrition; *Brassica oleracea* var. *oleracea*; Polysulphate; potassium; yield gap.

Introduction

The genus Brassica is known for its important agricultural crops, which include species and varieties of cole crops such as broccoli, cauliflower, and cabbage, root crops such as turnip and radish, herb crops like ruccola and choy sum, and oil and spicy seeds such as canola and mustard, respectively. World production of cole crops in 2019 was 70.1 million tonnes (FAOstat, 2021). Cabbage (*Brassica oleracea* var. *oleracea*) – a good source of vitamin K, vitamin C and dietary fiber (White and Broadley, 2005) – is consumed in many different ways: pickled, fermented, steamed, stewed, sautéed, braised, or raw. Over the last three decades, Brassicaceae crops have been the focus of intense research due to their human health benefits (Stoewsand, 1995; Björkman *et al.*, 2011; Šamec *et al.*, 2017; Ware, 2017).

Sulfur-containing secondary metabolites, such as glucosinolates, have been associated with some anti-cancer activities (Higdonm *et al.*, 2007; Cartea and Velasco, 2008; Sarıkamış, 2009) and with a reduced risk for degenerative diseases, cardiovascular diseases and diabetes (Björkman *et al.*, 2011, and references therein). Some S-containing compounds are desired as flavor components in cooked Brassica vegetable products (Schutte and Teranishi, 1974). Glucosinolates' contents largely depend on S availability and significantly varies with S fertilization (Falk *et al.*, 2007).

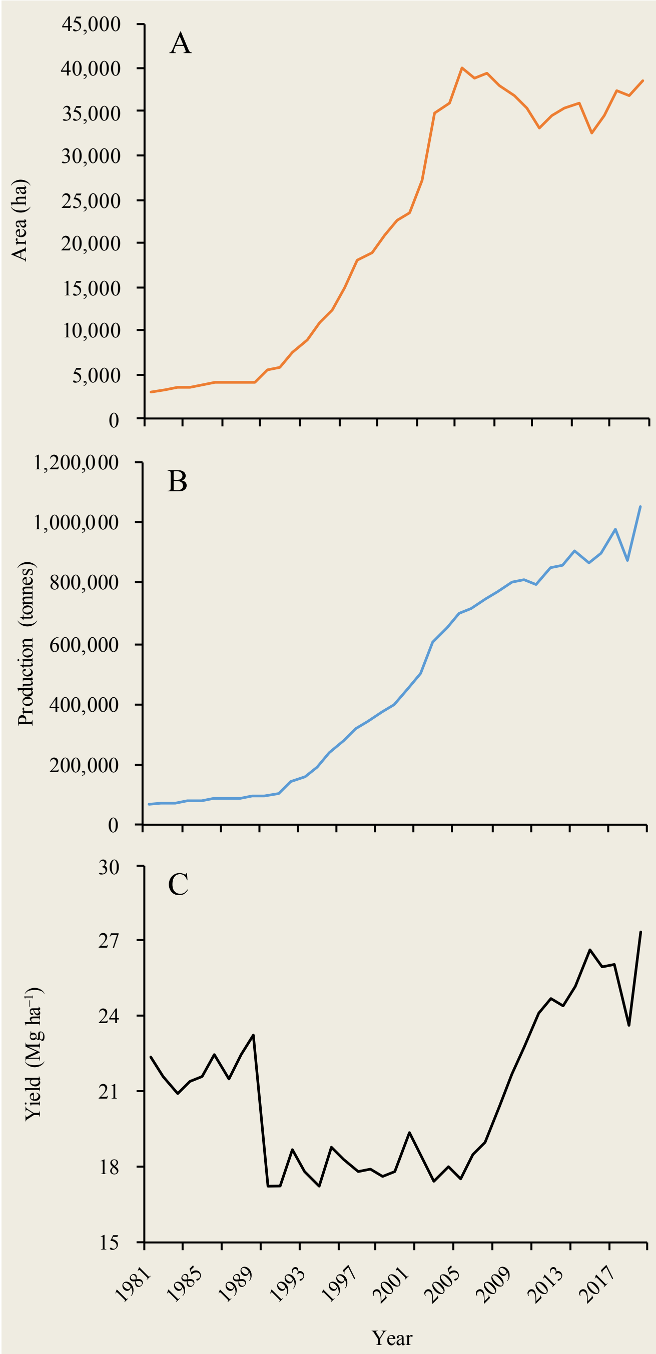


Fig. 1. Development of cabbage and other Brassica crops in Vietnam from 1981-2019. Cultivated area (A); production (B); and, calculated average annual yields (C). Source: FAOstat, 2021.

Cole crop species are highly appreciated in Vietnamese tradition and cuisine. Within less than 15 years (1991-2005), the cole crop cultivation area grew 10-fold, from 4,000 to 40,000 ha, but during the successive 15 years, it fluctuated between 30,000 and 40,000 ha (Fig. 1A). During the last 30 years, the annual cole crop production steadily rose from 100,000 to 1,050,000 tonnes (Fig. 1B). These figures make Vietnam the eighth largest producing country of cole crops. Nevertheless, with mean annual yields ranging from 17-27 Mg ha^{-1} (Fig. 1C), Vietnam lags behind 60 other cole producing countries (FAO, 2021). Obviously, the annual average yield data covers substantially different climate regions in Vietnam, most of which are less suitable for high cabbage production. Cabbage grows best in temperate climate regions, into which the subtropical northern Vietnam partially fits, more so than the central or southern regions of the country.

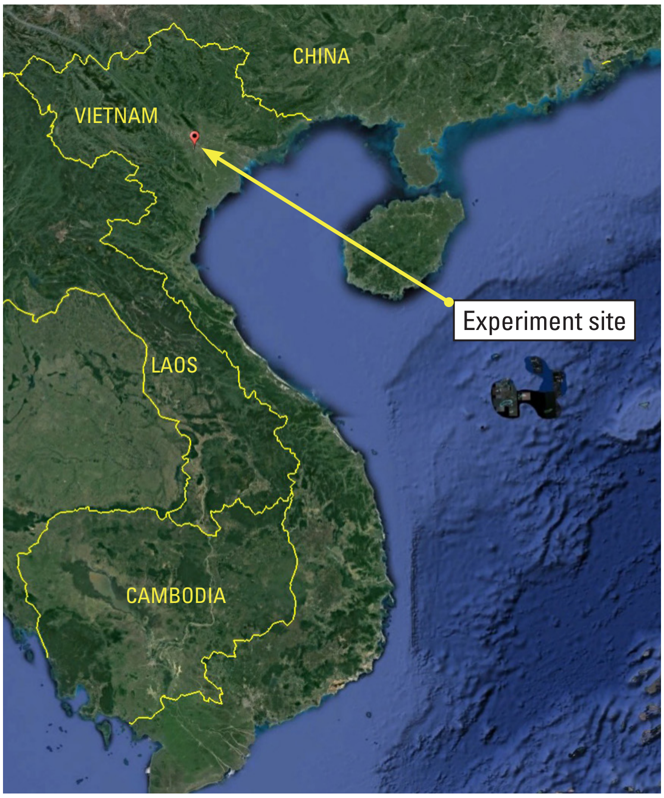
Conversion of forest to agricultural land is known to negatively affect soil fertility. According to Schweizer *et al.*, (2017), soil aggregate stability declined simultaneously with a decrease in soil organic carbon and exchangeable Ca^{2+} and Mg^{2+}, which both declined with increasing time since land use modification. The humid 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). Cole crops prefer soil pH ranging from 6.0-6.8 (White and Broadley, 2005), considerably higher than the typical soil pH range in Vietnam (5.0-5.5). Subsequently, insufficient nutrient availability, particularly K, but also imbalanced mineral nutrition, have been consistently shown to be responsible for yield gaps in numerous crop species in Vietnam (Pandey *et al.*, 2019).

Potassium is essential for most basic processes in plants' life cycle (Zörb *et al.*, 2014). In cole crops, this nutrient is particularly important during the early stages of expansion of the outer leaves (Wien and Wurr, 1997). 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. In recent years, the practice of splitting the fertilizer dose into several application events during the growing season, thus providing better K availability whenever necessary (Joshi *et al.*, 2014), has gradually been disseminated in Vietnam. In addition 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).

It is clear that more balanced fertilization strategies are needed. A partial replacement of the highly soluble chemical K fertilizers, combined with supplementary essential macronutrients appears a promising solution. 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 in regions with high rainfall. So far, polyhalite application has been found to enhance cole crops performance in India (Satisha and Ganeshamurthy, 2016), Turkey (Anac *et al.*, 2019), and Switzerland (Terrones *et al.*, 2020).

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



Map 1. Location of the cabbage field trial at Tien Thang commune, Me Linh district, Hanoi, Vietnam.

Table 1. Detailed description of the fertilizer treatments

Treatment		FYM	Nitrogen (N)	Phosphorus (P_2O_5)	Potassium (K_2O)	
					MOP	Polyhalite
		ton ha⁻¹	*kg ha⁻¹*			
K_{150+0}	(FP control)	15	180	80	150	0
K_0	(control)	15	180	80	0	0
K_{60+0}		15	180	80	60	0
K_{30+30}		15	180	80	30	30
K_{45+45}		15	180	80	45	45
K_{60+60}		15	180	80	60	60

Note: FYM = farmyard manure, FP = Farmers' practice.

Materials and methods

Experiment site

The field experiment was carried out at Tien Thang commune, Me Linh district, Hanoi (Map 1). The climate in this region is subtropical with a mean annual temperature of 23.5°C and a mean annual rainfall of 1,620 mm, of which more than 80% occurs between May and October. Between September to December, during the cabbage growing season, max/min temperatures steadily decline from 32/25°C to 22/16°C, while monthly precipitation decreases from 270 to 30 mm.

The soil profile of the research area was classified as Grey degraded soil or Plinthic Acrisols (FAO, 1990) or as Plinthaquults (Soil Survey Staff, 1992). The properties of the basic top-soil (0-25 cm) were 2% clay, 70% silt, 20% fine sand (20-200 µm) and 8% coarse sand (> 200 µm). Soil $pH_{(KCl\ 1M)}$ was 5.0, and the total soil carbon (C), nitrogen (N), phosphorus (P), and potassium (K) contents were 6.6, 1.2, 0.35, and 0.58 g kg^{-1}, respectively.

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 15 t ha^{-1}; 180 kg N ha^{-1}, using urea (46% N); and, 80 kg P_2O_5 ha^{-1} with superphosphate Lam Thao (16.5% P_2O_5). The experiment consisted of six treatments (Table 1) with 4 replications in a randomized complete block design, i.e. 24 plots (24 m^2 $plot^{-1}$).

The treatments differed in K rate (from 0-150 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_{150+0} – farmers' practice, FP) included a high K rate, all of which was applied through MOP (K_{150+0}), and served to compare with the other treatments, agronomically and economically. The second control did not include any K application (K_0), providing an evaluation of K contribution to the cabbage 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 1). Fertilizers were applied at five stages: pre-planting, and irrigated dressings at 10, 30, 40, and 50 days after planting, as shown in Table 2.

Crop management

A locally recommended green cabbage Japanese cultivar was used. Seeds were sown in a nursery on 9 August 2016, and seedlings were transplanted on 3 September 2016 into raised beds, 120 cm width and 30 cm height, spacing between two beds was 30 cm, with a density of 4 plants m^{-2} (40,000 plants ha^{-1}). Harvest started on 2 December 2016.

Observations and measurements

During the growing season, crop phenological development was followed. Estimates of pest and disease infection took place at 30, 45, and 60 days after planting. At harvest, cabbage heads were sampled to determine yield and quality parameters, as well as the concentrations of total soluble solids and vitamin C.

Table 2. Description of fertilizer application schedule during the cabbage crop experiment in northern Vietnam.

Fertilizer	Application time				
		Days after planting			
	Pre-plant	10	30	40	50
	%				
FYM	100				
Urea		30	30	20	20
Superphosphate	50		50		
MOP/polyhalite	20		30	25	25

Results and discussion

In all fertilizer treatments excluding K_0, the cabbage growing season from planting to harvest lasted 115 days, indicating that polyhalite had no significant effects on cabbage phenological development. Potassium deficiency delayed cabbage development by 5 days over the growing season, from the pre-cupping and head formation in October, until harvest at 120 days after planting (DAP).

Significant effects on plant dimensions were observed as early as the pre-cupping stage, in the first week of October (Fig. 2). Plants of all treatments with combined polyhalite and MOP had significantly greater canopy diameter compared to the MOP-applied plants, and K_0 plants displayed the smallest diameter.

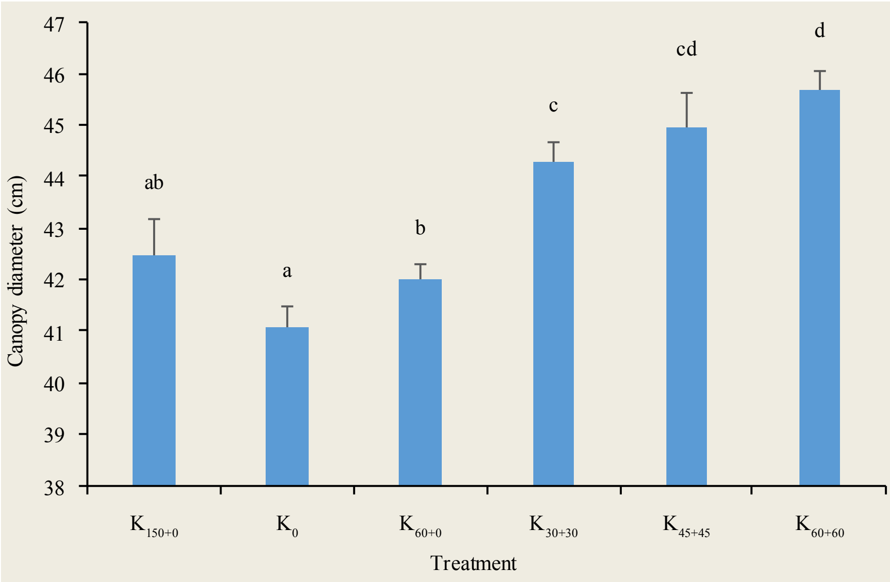


Fig. 2. Effects of fertilizer treatments on the pre-cupping canopy diameter in the first week of October. For detailed description of the fertilizer treatments refer to Table 1. Bars indicate SE. Similar letters indicate no significant differences at P<0.05.

Differences became clearer at harvest (Fig. 3). Total plant weight, which was significantly small at K_0 (2.2 kg plant^{-1}), substantially increased in response to MOP application up to 2.65 kg plant^{-1} at K_{150+0}. Nevertheless, under combined MOP and polyhalite, plant weight further increased, reaching 3.05 kg with much smaller K inputs, 90-120 vs. 150 kg K_2O ha^{-1}. Interestingly, with a similar K input of 60 kg K_2O ha^{-1}, the combined K_{30+30} treatment gave rise to significantly greater plant weight compared to K_{60+0}, 2.85 vs. 2.5 kg plant^{-1}, respectively

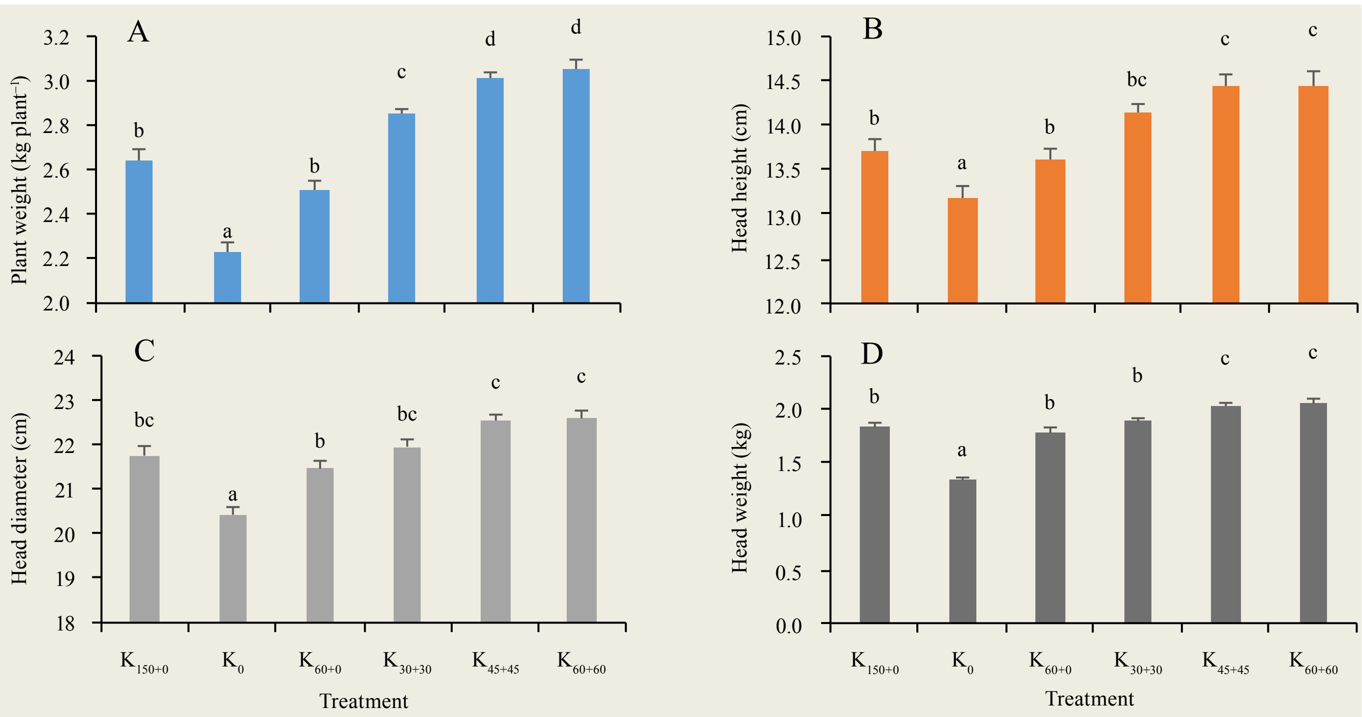


Fig. 3. Effects of fertilizer treatments on cabbage plant weight, and head dimensions at harvest. Total plant weight (A); head height (B); head diameter (C); and, head weight (D). For detailed description of the fertilizer treatments refer to Table 1. Bars indicate SE. Similar letters indicate no significant differences at P<0.05.

(Fig. 3A). Similar response patterns were observed for the cabbage head dimensions (Fig. 3B-D); while K_0 consistently exhibited the smallest head dimensions and weight, and cabbage head size increased significantly in response to K application, the differences between MOP and combined MOP and polyhalite were slightly smaller, being significant only at the higher K dose. Still, the cabbage head weight was significantly greater at the K_{45+45} and K_{60+60} than at the K_{150+0} treatment (Fig. 3D).

Consequently, the response of the total and marketable cabbage yields to the fertilizer treatments follow a similar pattern – lowest at K_0, intermediate under MOP, and significantly higher under MOP and polyhalite combinations. The marketable yield was quite similar, 65-67%, among all treatments, excluding K_0 with only 57% (Fig. 4A). Normalizing the marketable yield to that of K_0 highlights the significance of K fertilizer application to cabbage crop performance on the local degraded soil (Fig. 4B); the increase in the marketable cabbage yield ranged from 33-61%. Nevertheless, the nature of the K source appears very important; using MOP solely, the marketable yield rose by 33 and 40% in response to doses of 60 and 150 kg K_2O ha^{-1}, respectively, compared to the K_0 control. Using a 1:1 combination of MOP and polyhalite at the lower dose tested (60 kg K_2O ha^{-1}) resulted in a further rise of the relative marketable yield, from 33 to 47%. Moreover, increasing the K_2O dose using the same combined fertilizers to 90 and 120 kg K_2O ha^{-1} brought about yield increments of 59 and 61%, respectively, in comparison to the 40% yield increase by MOP alone at a much higher dose of 150 kg K_2O ha^{-1} (Fig. 4B). These results clearly indicate the significant advantage of utilizing polyhalite as a supplementary K fertilizer. This enhanced productivity stems from several advantages of the polyhalite fertilizer: 1) synergistic interactions between S, provided by polyhalite, and N uptake and protein metabolism (Jamal *et al.*, 2010); 2) slower nutrient release from polyhalite, compared to MOP (Yermiyahu *et al.*, 2017); and, 3) polyhalite supplies Ca and Mg, essential macronutrients that might have been insufficiently available in the local soils.

Normalizing the marketable yields to the farmers' practice (K_{150+0}) revealed the inefficiency of that treatment: using solely MOP at 150 kg K_2O ha^{-1} resulted in less than 5% yield increase compared to a substantially smaller dose of 60 kg K_2O ha^{-1} (Fig. 4C). Furthermore, under a similar small dose, the MOP and polyhalite combination yielded 10% more than MOP alone. It appears that the ceiling K_2O dose, above which no significant further yield increase can be reached, is about 100 kg K_2O ha^{-1}, as indicated by the tiny yield contribution of the move from K_{45+45} to K_{60+60} treatment (Fig. 4C). Thus, when applying combined MOP and polyhalite, about a third of the currently recommended K dose can be avoided, while still producing a 15% increase in the marketable yield.

Cabbage quality analyses revealed the dry matter (about 8%) and vitamin C (14-18 mg 100^{-1} g) contents showed no significant

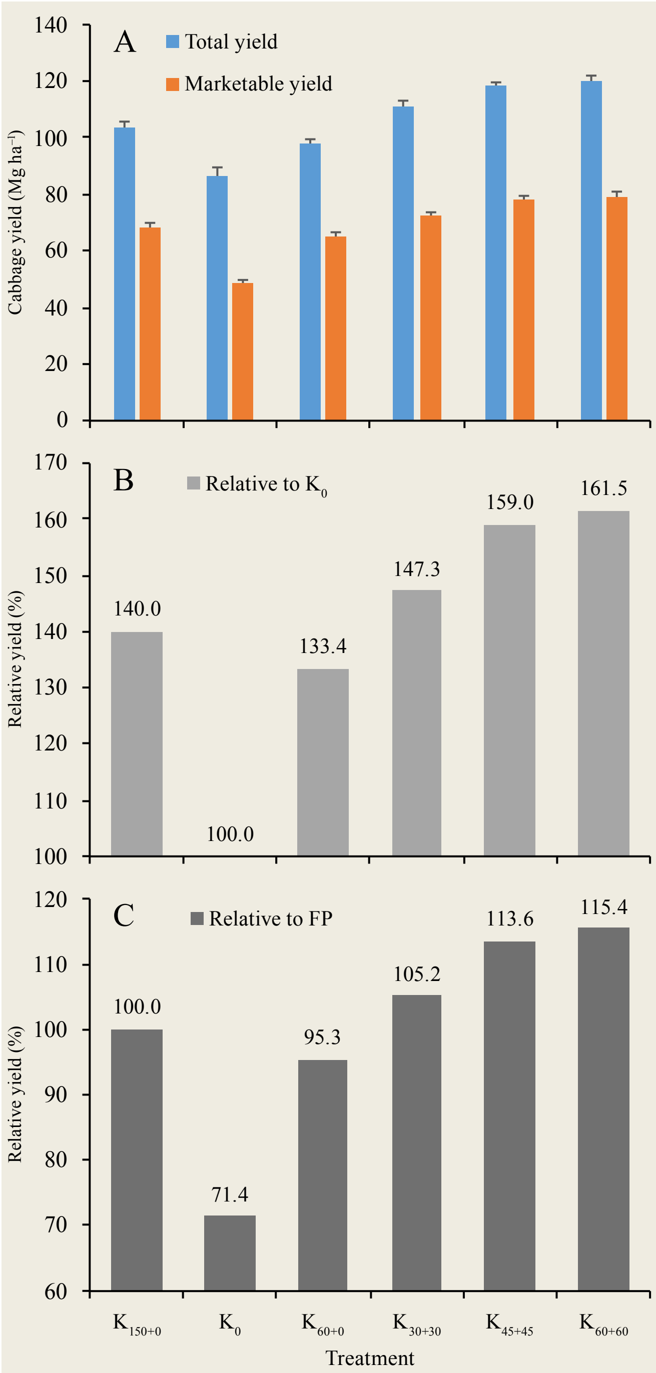


Fig. 4. Effects of fertilizer treatments on cabbage yields on degraded grey soil in northern Vietnam. Total and marketable yields (A); relative marketable yield normalized to the K_0 control (B); relative marketable yield normalized to the local farmers' practice, FP, K_{150+0} (C). For detailed description of the fertilizer treatments refer to Table 1. Bars indicate SE.

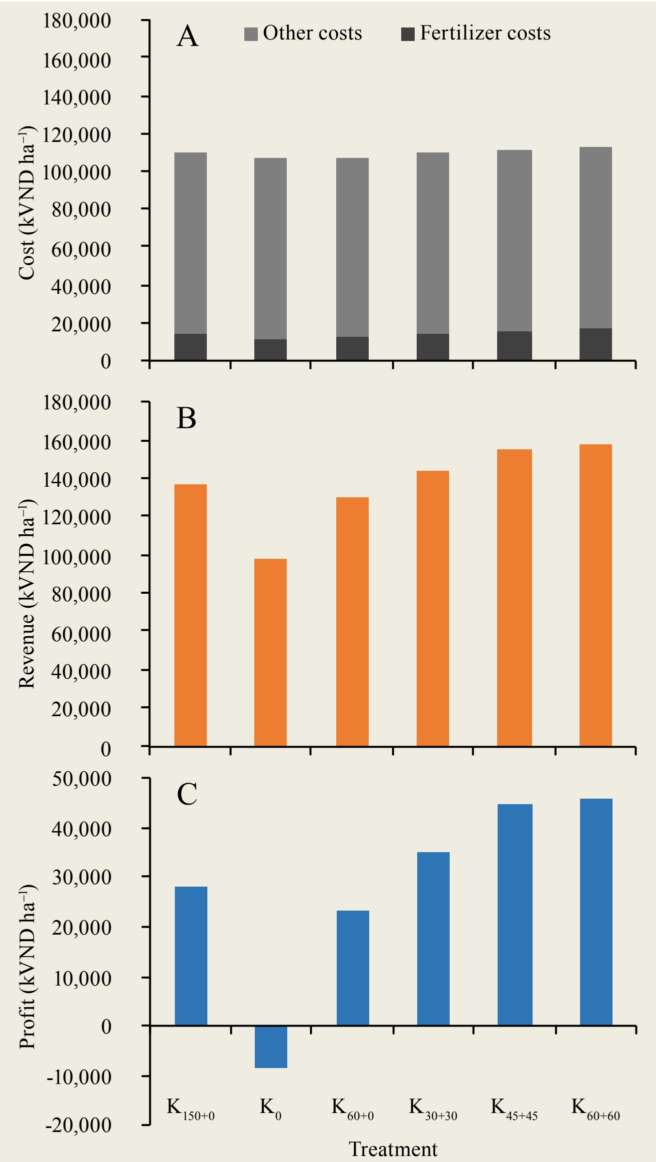


Fig. 5. Effects of fertilizer treatment on the costs (A); revenue (B); and, on the profit (C) of cabbage crop grown on degraded grey soil in northern Vietnam. For detailed description of the fertilizer treatments refer to Table 1.

differences between treatments. Significant differences did occur in the total soluble solids content of the cabbage heads that ranged from 2.8-3.7%, however, these could not be attributed to any consistent response to the fertilizer treatments (data not shown).

The incidence of pests was low and similar between treatments. There were two main insect types, Diamondback moth (*Plutella xylostella*) and cabbage white butterfly (*Pieris rapae*), the influences of which were very light during 30-45 DAP, and quite normal at 60 DAP. Two cabbage diseases, black rot of crucifers (*Xanthomonas caminsectris*) and bacterial soft rot (*Erwinia carotovora*), occurred very slightly (less than 1% leaf area damage) until 45 DAP. At 60 DAP, the bacterial soft rot severity substantially increased. Nevertheless, the diseases' influence was similar among all treatments.

Economic analyses of the influences of the various fertilizer treatments on cabbage crop at the farm gate showed a negligible increase in farmer's costs when polyhalite was combined with MOP. At the highest combination dose (K_{60+60}), the fertilizer cost was only 3,152 kVND ha^{-1} higher than that of the FP, K_{150+0}, while all other costs remained constant (Fig. 5A). In contrast, moving from the K_{150+0} approach to the K_{60+60} treatment, the farmer's revenue substantially increased from 137,300 to 158,420 kVND ha^{-1} (Fig. 5B). The profit analysis (Fig. 5C) revealed that without application of any K fertilizer (K_0), farmers would have lost about 9,000 kVND ha^{-1}, compared to an expected profit of 28,000 kVND ha^{-1} at the FP control. At a dose of 60 kg K_2O ha^{-1}, the expected profit was a bit smaller than FP when MOP was solely used (K_{60+0}), but was higher than at FP when combined with polyhalite (K_{30+30}). The expected profit continued to rise with the increasing K dose up to 90 kg K_2O ha^{-1}, and even a bit further at 120 kg K_2O ha^{-1}, demonstrating that using a 1:1 combination of polyhalite and MOP would result in a profit of 46,000 kVND ha^{-1}, almost 18,000 more than with MOP alone at 150 kg K_2O ha^{-1} (Fig. 5C). The marginal balance point between the additional fertilizer cost and the expected profit occurred at about 100 kg K_2O ha^{-1}, using the combined fertilizers. These results support earlier studies that demonstrated the advantages of utilizing polyhalite fertilizers for cabbage and other crucifer crops grown on various soil types in other countries (Satisha and Ganeshamurthy, 2016; Anac *et al.*, 2019; Terrones *et al.*, 2020).

Conclusions

Polyhalite, in 1:1 combination with MOP, was used to fertilize cabbage grown on a degraded grey soil in northern Vietnam. The combined fertilizer significantly enhanced cabbage crop performance and consequently gave rise to substantial increases in the total and marketable yields, compared to the common farmers' practice which used solely MOP. Using a combination of polyhalite and MOP, K application dose was reduced from 150 to 100 kg K_2O ha^{-1}, while the profit grew by 64%, from 28,000 to 46,000 kVND ha^{-1}. These results indicate the advantage of polyhalite as a supplemental fertilizer contributing K as well as other essential macronutrients.

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The paper "Effects of Polyhalite Application on Yield and Quality of Cabbage Grown on Degraded Soils in Northern Vietnam" also appears on the IPI website.