Research Findings

Photo 1. Experimental site. Photo by the authors.

Effect of Different Potassium and Sulfate Fertilizer Types on Cabbage Yield and Quality

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Abstract

Cabbage (*Brassica oleracea* var. *capitata* f. *alba*) is one of the most important vegetable crops in Turkey. The transition from traditional to modern agriculture includes revision of mineral nutrition practices. Beyond the common basal nitrogen (N) and phosphorus (P) application, potassium (K), which is usually ignored by Turkish farmers, is required to enhance yield and quality. There is also increasing awareness that sulfur (S) is an essential macronutrient, particularly for Brassicaceae crop species that produce highly appreciated secondary metabolites such as glucosinolates and antioxidants. Muriate of potash (MOP) and sulfate of potash (SOP) are very common fertilizers. Both are donors of soluble K, and the latter also supplies S. Polyhalite is a natural mineral, which occurs in sedimentary marine evaporates, and consists of a hydrated sulfate of K, calcium (Ca) and magnesium (Mg) with the composition of 14% K_2O, 48% SO_3, 6% MgO, and 17% CaO. The objective of this study was to compare the effects of three different K sources - polyhalite, SOP, and MOP - on cabbage

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yield, quality, and nutrient content and uptake. Standard N and P_2O_5 rates of 250 and 100 kg ha^{-1}, respectively, were employed throughout all five treatments included in the experiment. The control treatment was applied with N and P only, while the other four treatments received an equal dose of 300 kg K_2O ha^{-1} in the forms of MOP, SOP, polyhalite, or polyhalite+SOP. While MOP application significantly enhanced cabbage crop performance, the additional S, provided through SOP or polyhalite, obtained much higher yields and better quality. The best treatment was polyhalite+SOP, with a marketable yield of 81 Mg ha^{-1}, 60% higher than the control. While leaf S content and uptake did not differ among SOP, polyhalite, and polyhalite+SOP, polyhalite significantly raised leaf Ca and Mg contents, which may explain its advantage over SOP. Whereas polyhalite application as the sole K source is impractical, a suitable combination of polyhalite with SOP provides a promising solution for Turkish cabbage growers. The optimum rates for the two fertilizers should be determined considering crop requirements, soil nutrient status, and fertilizer cost vs. the expected benefits.

Keywords: Brassica oleracea var. *capitata* f. *alba*; MOP; polyhalite; SOP.

Introduction

Vegetables are very important in Turkish cuisine. In 2017, more than 0.8 million ha were used in Turkey to grow vegetables, with about 30 million tonnes of produce (www.dunyagida.com.tr). Among vegetables, cabbage (*Brassica oleracea* var. *capitata* f. *alba*) has gained special attention due to its culinary, as well as nutritional, significance (Avato and Argentieri, 2015; Šamec *et al.*, 2017; Ware, 2017). Cabbage is consumed in many different ways: raw, pickled, fermented, stewed, steamed, sautéed, braised, and stuffed. Over the last three decades, Brassicaceae crops have been the focus of intense research based on their human health benefits (Stoewsand, 1995; Björkman *et al.*, 2011; Šamec *et al.*, 2017; Ware, 2017). Sulfur (S) -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; Engel *et al.*, 2002). Glucosinolates contents largely depend on S availability and significantly varies with S fertilization (Falk *et al.*, 2007).

Sulfur is recognized as the fourth major plant nutrient after nitrogen (N), phosphorus (P) and potassium (K) (Khan *et al.*, 2005), and has been associated with high production goals (Zhao *et al.*, 1999; Hawkesford, 2000; Saito, 2004; Jamal *et al.*, 2010; Kovar and Grant, 2011; Steinfurth *et al.*, 2012). A good response to S application has been reported with respect to Brassica genera crop yields (McGrath and Zhao, 1996; Girondé *et al.*, 2014; Tiwari *et al.*, 2015), and particularly to cole crops (*Brassica oleracea*) (Susila and Locacsio, 2001). Nevertheless, crop responses to S application have been found to vary widely due to differences in location, soil type, various S-containing compounds in the soil and consequent S availability, crop genotype, environmental conditions and crop management (Björkman *et al.*, 2011). Cole crops have a significant S requirement; where the availability of this mineral is limited, crop yield and quality often decline (Haneklaus *et al.*, 2008). Over the last 25 years, due to strict regulations against industrial S emissions, the yearly global S atmospheric deposition has significantly declined (Kovar and Grant, 2011). During the same time, demands for food production have increased with the growing human population. Subsequently, requirements for S fertilizers have risen dramatically to meet annual crop demands.

In the last decade, the cabbage harvested area in Turkey was constant at 26,000 ha. During this period, cabbage production increased by 20% from 0.648 to 0.779 million tonnes, which resulted from an increasing annual average yield from 24.8 to 29.4 Mg ha^{-1} (FAOSTAT, 2017). These data reflect the dichotomy currently characterizing Turkish agriculture; while most farmers still stick to traditional practices (low input - low output), an increasing number have adopted and employ modern technologies, which has resulted in a significant rise in yields (Abukari *et al.*, 2016; Gökalp and Çakmak, 2016). Optimized mineral nutrition is essential to achieve consistently high-yield levels. Traditionally, Turkish cabbage growers apply complex fertilizer (N:P:K at 15:15:15 or 20:20:20) at planting, and ammonium nitrate (AN) or calcium ammonium nitrate (CAN) for later applications (side dressing). Additional K fertilizer is not applied very often due to economic considerations. In cabbage, carbohydrates stored in the cole during the vegetative phase are remobilized to furnish the reproductive phase. Potassium is vital to photosynthesis and to carbohydrate translocation and storage (Marschner, 1995; Zörb *et al.*, 2014). Therefore, an adequate K supply is necessary to guarantee the desired size and quality of cabbage heads.

Soil type and properties play a major role in determining nutrient availability for crops. Among the three major nutrients, K availability is greatly affected by the soil characteristics, especially under marginal K status (Zörb *et al.*, 2014). MOP (muriate of potash, known also as potassium chloride, KCl) is the most common K fertilizer. It is highly soluble and is immediately accessible to plant roots in the soil soluble phase. Nevertheless, as such, K^+ ions might be rapidly fixated to soil particles in certain soil types but, furthermore, they might be leached away from the rhizosphere under excess water supply (Zörb *et al.*, 2014). SOP (sulfate of potash, K_2SO_4), providing Cl-free K with the advantage of S supplement, is a suitable alternative to MOP. Nevertheless, the fate of K^+ ions is similar to that under MOP.

Polysulphate (Cleveland Potash Ltd., UK) is the trade mark of the natural mineral 'polyhalite', which occurs in sedimentary marine evaporates, and consists of a hydrated sulfate of K, calcium (Ca) and magnesium (Mg) with the formula: $K_2Ca_2Mg(SO_4)_4 \cdot 2(H_2O)$. The deposits found in Yorkshire in the UK typically consist of 14% K_2O, 48% SO_3, 6% MgO, and 17% CaO. In addition to being a natural, multi-nutrient fertilizer, polyhalite is much less soluble. Thus, with significantly slower nutrient release rates, base application of polyhalite at planting provides extended nutrient availability during cabbage crop development. In Turkey, polyhalite use might appear practical and beneficial compared to traditional practices.

The objective of this study was to compare the effects of three different K sources - polyhalite, SOP, and MOP - on cabbage yield, quality, and nutrient content and uptake.

Map. 1. The location of the experiment. Turkey, located at the northeast edge of the Mediterranean basin (above); Antalya region in the south of Turkey. *Sources:* https://c.tadst.com/gfx/citymap/tr-10.png?9; and, https://upload.wikimedia.org/wikipedia/commons/6/61/Antalya_in_Turkey.svg, respectively.

Materials and methods

A field experiment was carried out in the Antalya region of Turkey (Map 1). Soil was sandy loam, calcareous, slightly alkaline, with poor P and K availability (Table 1). The experiment included five different fertilizer treatments: Control (standard N+P); SOP (N+P+K, with 100% K applied in the form of SOP); polyhalite+SOP (N+P+K, with K divided evenly between polyhalite and SOP); polyhalite (N+P+K, with K fully applied through polyhalite); and, MOP (N+P+K, with K fully applied through MOP). All fertilizers were applied pre-planting. Fertilizer doses were 250, 100, and 300 kg ha^{-1} of N, P_2O_5, and K_2O, respectively. A detailed description of nutrient and fertilizer quantities is provided in Table 2. The layout of the experiment was a randomized block design with four replications. Cabbage seedlings (cv. Oren 07) were transplanted at the end of September 2016, and harvested at the end of January (2017). Irrigation was practiced when necessary and all other agricultural practices were carried out on time according to recommendations.

Table 1. Physical and chemical properties of the experimental soil.

Soil properties		
pH (1:2.5)	8.2	Slightly alkaline
$CaCO_3$ (%)	19.9	High
EC micromhos cm^{-1} (25°C)	89	No salinity
Sand (%)	61	
Clay (%)	11	Sandy loam
Silt (%)	28	
Organic matter (%)	2.1	Medium
Available P (mg kg^{-1}) (Olsen)	5	Poor
Available K (mg kg^{-1})	58	Poor
Available Ca (mg kg^{-1})	2,631	Medium
Available Mg (mg kg^{-1})	102	Medium
Available Fe (mg kg^{-1})	7.6	High
Available Mn (mg kg^{-1})	5.8	Sufficient
Available Zn (mg kg^{-1})	0.2	Insufficient
Available Cu (mg kg^{-1})	0.8	Sufficient

Results

Total cabbage yield increased from 65 in the control to 103 Mg ha^{-1} under the combined polyhalite and SOP treatment (Fig. 1). The rate of marketable yield ranged from 70-80% of the total yield and was not influenced by the fertilizer treatments. Potassium application in the form of MOP in addition to the standard NP application tended to raise the marketable and total yields by 10 and 25% above the control, respectively; however, this response was statistically significant only for the total yield. SOP was much more efficient, contributing 28 and 16% marketable yield increases, compared to the control and MOP treatments,

Table 2. Detailed description of the fertilizer treatments according to nutrient supply under fertilizer type and dose.

Treatment	Nutrient						Fertilizer		
	N	P_2O_5	K_2O	CaO	MgO	SO_3	Polyhalite	SOP	MOP
	-- *kg ha^{-1}*								--
Control	250	100	-	-	-	-	-	-	-
SOP (K_2SO_4)	250	100	300	-	-	270	-	600	-
Polyhalite+SOP	250	100	300	182	64	649	1,071	300	-
Polyhalite	250	100	300	364	128	1,028	2,140	-	-
MOP (KCl)	250	100	300	-	-	-	-	-	500

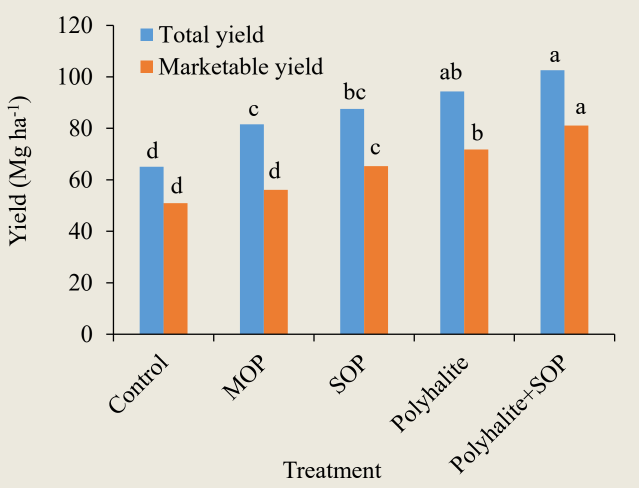

Fig. 1. Effect of fertilizer treatments on the total and marketable cabbage yields. *Note:* Identical letters indicate no significant difference (p<0.001) between treatments within each yield category. For further details of the treatments, refer to Table 2.

respectively. When polyhalite alone was the K donor, the marketable yield further increased by an additional 10% compared to MOP, and 40% above the control. The combination of polyhalite and SOP gave rise to the highest marketable yield, 81 Mg ha^{-1}, with significant increases of 13 and 59% more than polyhalite and the control, respectively (Fig. 1).

Corresponding to their effects on yield, fertilizer treatments produced a significant influence on the measures of the cabbage head. Marketable cabbage head weight increased from 2.68 kg under the control to 4.22 kg under the polyhalite+SOP treatment (Fig. 2A).

The content of total soluble solids (TSS) increased significantly in response to K application, with no further difference between the K sources (Fig. 2B). The content of phenolic compounds was significantly higher under S application, with the highest level under the combined polyhalite+SOP treatment (Fig. 2C). Antioxidant activity varied significantly among treatments, with the lowest values obtained under the control and SOP, and the highest under MOP, polyhalite, and polyhalite+SOP (Fig. 2D).

As may have been expected, no differences occurred between treatments in the leaf N and P contents, which were at the optimum range for cabbage according to Maynard and Hochmuth (2007) (Table 3). Potassium content was significantly lower and below the recommended optimum under the control. When K was applied at 300 kg K_2O ha^{-1},

Photos 2 and 3. Cabbage at harvest and at early stage. Photo by the authors.

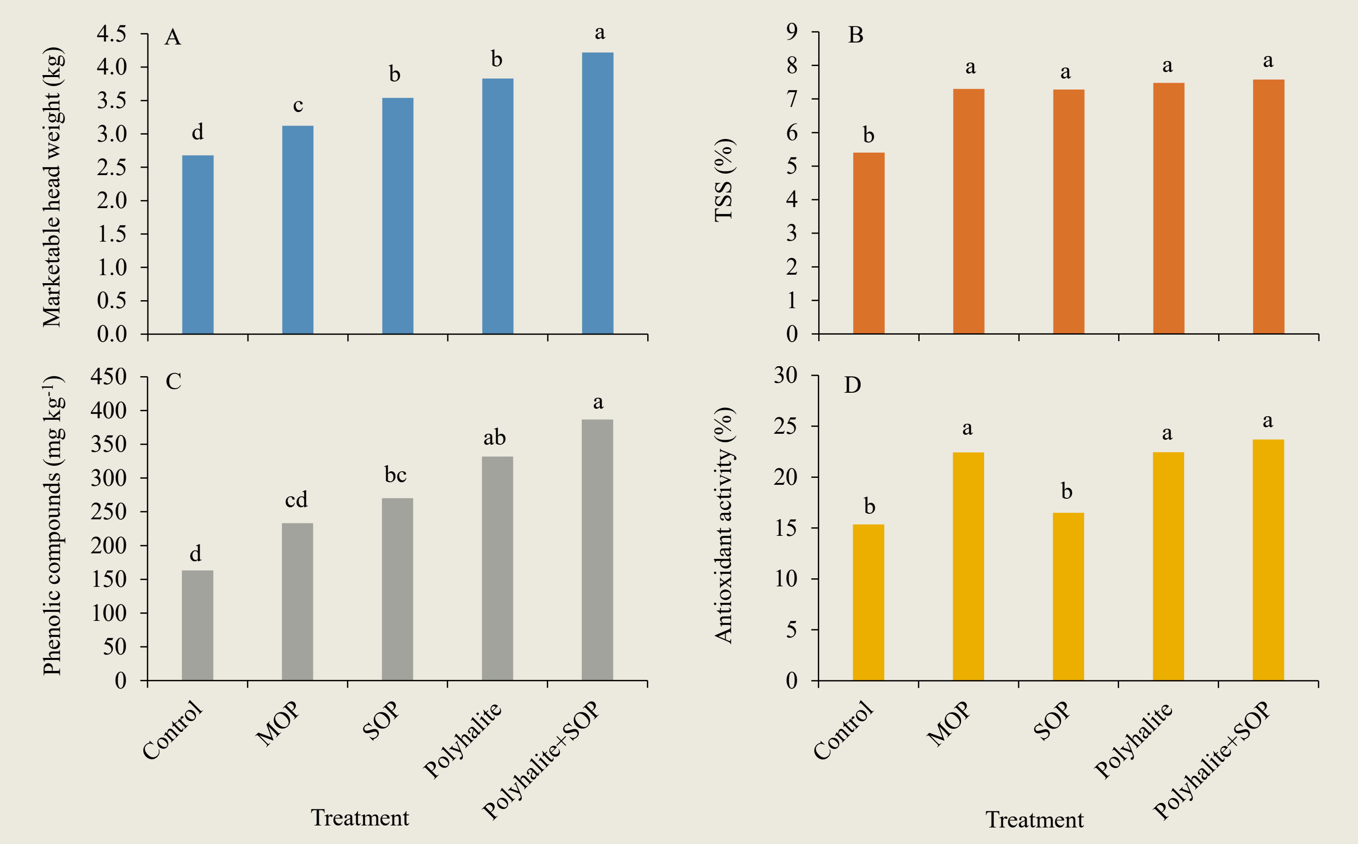

Fig. 2. Effect of fertilizer treatments on cabbage quality parameters. *Note:* Identical letters indicate no significant difference (p<0.01) between treatments. For further details of the treatments, refer to Table 2.

leaf K contents ranged from 2.8-3.1%, within the optimum range, and with little differences among the various K sources (Table 3). With no external Ca source, this nutrient was at the minimum edge of the recommended optimum range. Polyhalite application raised Ca leaf content above 2%, slightly beyond the recommended range (Table 3). On the other hand, leaf Mg content, which was also delivered through polyhalite, did not differ among treatments. Leaf S content was much higher than the lower threshold of 0.3% (Maynard and Hochmuth, 2007), but was significantly higher under the S-donor fertilizers (Table 3). No significant differences occurred in leaf S content between SOP, polyhalite+SOP, and polyhalite, in spite of the huge differences in SO_3 doses (Table 2).

Table 3. Macro-element contents of cabbage leaves.

	N	P	K	Ca	Mg	S
			%			
Control	3.58	0.38	1.89c	1.69b	0.27	0.59b
MOP (KCl)	3.50	0.36	2.82b	1.63b	0.25	0.56b
SOP (K_2SO_4)	3.73	0.37	3.10a	1.50b	0.24	0.76a
Polyhalite	3.64	0.36	2.93ab	2.19a	0.28	0.69a
Polyhalite+SOP	3.47	0.35	2.87b	2.01a	0.27	0.73a
	ns	ns	***	***	ns	***
References values[1]	3.0-4.0	0.3-0.5	2.3-4.0	1.5-2.0	0.25-0.45	>0.30

***: p≥0.001; ns: non-significant; [1]Maynard and Hochmuth, 2007.

Micro element application was not included in the different fertilizer treatments. Leaf iron (Fe) content was far beyond the optimum range and differed substantially, although inconsistently, among treatments (Table 4). In contrast, leaf contents of manganese (Mn), zinc (Zn), and copper (Cu) were below or at the lower threshold of the optimum range, and were not affected by the fertilizer treatments.

Nutrient uptake corresponded to crop biomass and nutrient content. Nitrogen uptake responded to K application by a significant increase compared to the control. Furthermore, S application, in addition to K, gave rise to considerably greater N uptake (Fig. 3), which did not necessarily correlate with the various S doses (Table 2). A similar response pattern was observed with P and K uptake (Fig. 3). Naturally, Ca and Mg uptake was

Table 4. Micro-element contents of cabbage leaves.

Treatment	Fe	Mn	Zn	Cu
	--*mg kg⁻¹*	--		
Control	69.3abc	18.9	21.7	4.83
MOP (KCl)	48.5bc	19.0	20.5	4.32
SOP (K_2SO_4)	81.9a	20.1	22.1	4.75
Polyhalite	43.8c	18.5	21.7	4.35
Polyhalite+SOP	70.3ab	18.9	20.9	4.44
	*	ns	ns	ns
References values[1]	20-40	20-40	20-30	4-8

*: p≥0.05; ns: non-significant; [1]Maynard and Hochmuth, 2007.

the highest under polyhalite application, although smaller increases occurred also under MOP or SOP treatments. Consequently, S uptake was very high in treatments with S-donor fertilizers. Interestingly, uptake rates provided an empiric perception of the differences in SO_3 dose between treatments but with no direct quantitative correlation (Fig. 3).

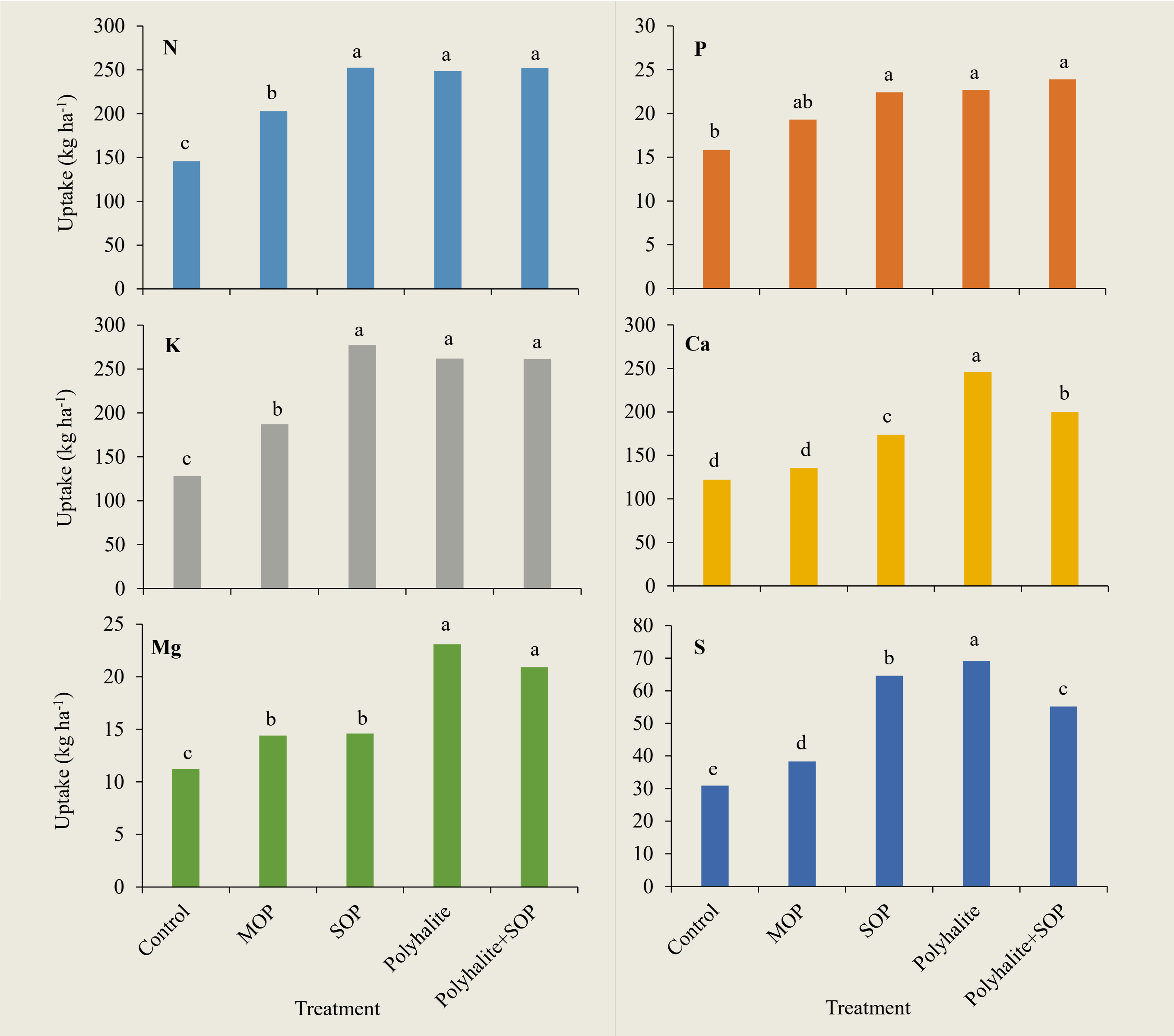

Fig. 3. Effect of fertilizer treatments on cabbage macronutrient uptake. *Note:* Identical letters indicate no significant difference (p<0.01) between treatments. For further details of the treatments, refer to Table 2.

Discussion

Photo 4. A view of the experimental field. Photo by the authors.

Cabbage yield and quality displayed a significant positive response to K application, as was directly indicated by the MOP treatment. Total yield increased by 25% (Fig. 1) due to a larger head weight (Fig. 2A). The contents of TSS and phenolic compounds considerably increased, as well as the rate of antioxidant activity (Fig. 2). Quite often, improved plant K status brings about increases in the content of other nutrients, such as N or P (Marschner, 1995; Jamal *et al*., 2010). This was not the case in the present study (Table 3); however, the better K status resulted in significant biomass growth, which, in turn, increased the overall uptake of N, and to a lesser extent - P (Fig. 3). The improvement of crop K status was similar also under SOP, polyhalite, and the combined treatment, as indicated by the increased leaf K contents (Table 3). Nevertheless, the direct effects of K contribution in these cases was masked by the additional S influences.

The effect of S alone on cabbage performance was not examined in the present study. Unequivocally, S had a significant additive effect on cabbage yield (Fig. 1). The rate at which cabbage S requirements are fulfilled is difficult to determine, since the differences in S content (Table 3) and S uptake (Fig. 3) between the relevant treatments are relatively much smaller and inconsistent with the dissimilarities in S rates (Table 2). Considering K and S uptake, SOP application alone seemed to meet cabbage requirements for these nutrients. Yet, polyhalite, and moreover polyhalite+SOP, obtained significantly higher yields (Fig. 1) and better produce quality (Fig. 2C and D). Enhanced Ca and Mg uptake, the main donor of which was polyhalite, provides an explanation for the advantage of treatments with polyhalite. Without polyhalite, the leaf contents of these two nutrients were at or below the minimum edge of the optimum range (Maynard and Hochmuth, 2007).

In conclusion, application of K, S, Ca, and Mg significantly enhanced cabbage yield and quality in agreement with some previous studies (Susila and Locascio, 2001; Satisha and Ganeshamurthy, 2016). While SOP contributes only K and S, polyhalite provides significant amounts of Ca and Mg, in addition to K and a substantial rate of S. The advantage of polyhalite obtaining significantly higher yields is obvious. Nevertheless, since K_2O content in polyhalite is low (14%) compared to MOP and SOP, a large quantity of this fertilizer would be required to provide sufficient crop K requirement, whereas the accompanying SO_3 rates would be far beyond crop needs. Therefore, applying polyhalite alone as the K, S, Ca, and Mg fertilizer seems impractical. On the other hand, a suitable combination of polyhalite with SOP (or with MOP, a combination that was not tested in the present study) appears much more practical for Turkish cabbage growers. The optimum rates of the two fertilizers was not determined here, and should therefore be determined in future experiments, considering crop requirements, soil nutrient status, and fertilizer cost vs. the expected benefits.

Acknowledgement

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