Research Findings

Photo 1. Romaine lettuce grown on perlite mixed with standard polyhalite. Doses ascending from 0-37.5 g L^{-1}, from left to right. Photo by L. Peled-Lichter.

Effects of Polyhalite Fertilizers on Lettuce Development on a Soilless Culture

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Abstract

Lettuce production on a soilless culture served as a model system to test polyhalite as a potential sole donor of potassium (K) and calcium (Ca), separately. Polyhalite is available as a new commercial fertilizer marketed as Polysulphate® (ICL Fertilizers, Cleveland, UK). It is a natural hydrated sulfate of K, Ca, and magnesium (Mg) with the formula: $K_2Ca_2Mg(SO_4)_4{\cdot}2H_2O$. Two experiments were carried out, both using perlite 212 as a solid phase and final fertigation solutions as a liquid phase. The winter experiment (Eshel HaNassi, 11/11/19-14/01/20) tested standard Polysulphate (PSS) at 0, 12.5, 25, and 37.5 g L^{-1} perlite, while nitrogen (N), phosphorus (P) and micronutrients were provided via fertigation throughout the experiment, with no Ca or Mg donor other than PSS. The summer experiment (Hula farm, Northern R&D, 05/06/2019-09/07/2019) examined granular Polysulphate (PSG) at 0, 0.25, 0.50, and 0.75 g L^{-1} perlite, while N-P-K and $MgSO_4$ were supplied via fertigation with no Ca donor other than PSG. In the winter experiment, the rising PSS rate gave rise to enhanced root development and consequent increase in lettuce biomass. The elevated PSG rate in the summer experiment had a small positive effect on lettuce biomass. No symptoms of Ca deficiency (tip-burn) occurred, including in the control. The ability of polyhalite to provide all K requirements of a crop throughout the season was clearly demonstrated for lettuce; however, it largely depended on the crop duration and the amount of PSS embedded in the growth medium. Obviously, enrichment of the growth medium with PSG can ensure sufficient available Ca to satisfy lettuce requirements and guarantee high produce quality. Nevertheless, developing an accurate PSG application rate should be subject to thorough fine-tuning, taking local properties of the water and growth medium into consideration. Moving from a model to conventional cropping systems, economic evaluations of polyhalite application would always be necessary.

Keywords: Calcium; granular Polysulphate; *Lactuca sativa* L.; potassium; slow-release; standard Polysulphate.

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Introduction

Lettuce (*Lactuca sativa* L.) is a staple leafy vegetable for human consumption and an economically important food crop worldwide. In 2018, 1.27 million ha of lettuce and chicory (combined) were harvested worldwide, with a total production of more than 27 million tons (FAOSTAT, 2019). Although often regarded as being low in nutritional value, lettuce's nutrient composition, depending on type and growing conditions, can be equivalent to other 'nutritious' vegetables (Kim *et al.*, 2016b). Lettuce contains several minerals important for human health such as iron (Fe), zinc (Zn), calcium (Ca), phosphorus (P), magnesium (Mg), manganese (Mn), and potassium (K), in addition to other health-promoting bioactive compounds (Kim *et al.*, 2016a; b). Epidemiological studies have reported a correlation between fresh vegetable consumption and reduced risk of chronic diseases (Rodriguez-Casado, 2016).

Field production of lettuce is restricted to short seasons by a number of temperature-related physiological effects that include tip-burn, loose head, leaf discoloration, and bolting, as well as susceptibility to various diseases (Maynard and Hochmuth, 2007). Therefore, greenhouse production plays an increasing role in lettuce production, allowing the manipulation of environmental conditions such as temperature, light, and nutrients (Barbosa *et al.*, 2015).

Being a short-cycle leafy vegetable crop, lettuce displays a simple model for developing and testing innovative cultivation approaches. Among these, a large array of soilless culture technologies has been employed, given the advantage of fully controlled crop water status and mineral nutrition (Soundy *et al.*, 2001; Barbosa *et al.*, 2015; Mandizvidza, 2017; Ainun *et al.*, 2018; Djidonou and Leskovar, 2019). Hydroponic approaches are highly productive; however, challenged by very sophisticated technologies such as on-line control of temperature, pH, and balanced mineral nutrition, as well as water recycling and disinfection practices, they are significantly costly (Barbosa *et al.*, 2015).

An ideal growth medium should be highly porous, with a wide pore-size distribution range, providing maximum water retention and aeration, simultaneously. Additionally, it should be chemically inert, enabling full control of nutrient composition and balance in the liquid phase. Perlite, an inorganic, expanded alumino-silicate of volcanic origin, fulfills these prerequisites (Markoska *et al.*, 2018; Reka *et al.*, 2019) and, furthermore, it can be easily reused (Giuffrida and Consoli, 2016). Therefore, perlite is commonly used throughout the world for soil amendment and as a principal component of soilless growing mixtures. Crop mineral nutrition on perlite must be accurate and should include all essential macro- and micronutrients. Employing liquid composite fertilizers through fertigation seems an ultimate solution. In addition, this type of culture systems sets an ideal stage for the evaluation of new fertilizers and alternative sources of various nutrients.

Polyhalite is available as a new commercial fertilizer marketed as Polysulphate® by ICL Fertilizers, Cleveland, UK, is a natural hydrated sulfate of K, Ca, and Mg with the formula: $K_2Ca_2Mg(SO_4)_4{\cdot}2H_2O$. The purity of Polysulphate® is very high (95% polyhalite) with <5% sodium chloride (NaCl) and traces of boron (B) and iron (Fe) at 300 and 100 ppm, respectively. The typical analysis of polyhalite for S, K, Mg and Ca is 48% sulfur trioxide (SO_3), 14% potassium oxide (K_2O), 6% magnesium oxide (MgO), and 17% calcium oxide (CaO), respectively. Polyhalite, which may serve as a suitable fertilizer by supplying four nutrients, is less water soluble than the more conventional fertilizers and may conceivably provide a slower release of nutrients (Barbarick, 1991; Yermiyahu *et al.*, 2017; Yermiyahu *et al.*, 2019). A number of studies comparing polyhalite to other K and Mg fertilizers have shown that polyhalite is at least as effective as potassium sulfate (K_2SO_4) as a source of K, and at least as effective as potassium chloride (KCl) plus magnesium sulfate ($MgSO_4$) as a source of K and Mg (Barbarick, 1991). Calcium, the less soluble nutrient in polyhalite (Yermiyahu *et al.*, 2019), can provide available Ca at rates equivalent to those of gypsum (Bernardi *et al.*, 2018).

Lettuce crops require significant amounts of nitrogen (N) (Broadley *et al.*, 2000; Soundy *et al.*, 2001; Fu *et al.*, 2017; Conversa and Elia, 2019; Djidonou and Leskovar, 2019). Potassium is another macronutrient vital to plant growth, yield, and quality; it is involved in the regulation of stomatal conductance and photosynthesis, photophosphorylation, transport of photoassimilates from source to sink tissues via the phloem, enzyme activation, turgor maintenance, and stress tolerance (Marschner, 2012). Research associated with adequate and elevated levels of K on lettuce yield and quality is quite limited and inconclusive. Some studies found that K in a nutrient solution did not affect lettuce yield and quality (Bres and Weston, 1992; Fallovo *et al.*, 2009; Hoque *et al.*, 2010). In contrast, Soundy *et al.* (2001) demonstrated that increasing K concentration in a nutrient solution enhanced lettuce root growth. More recently, Barickman *et al.* (2016) showed that elevating K fertilizer levels resulted in an optimum pattern of lettuce biomass production and a linear increase in the leaf sucrose content. Maximum yield and produce quality were reached at K levels of about 200 kg ha^{-1}, presumably due to the consistent decline of Ca, Mg, and S uptake, as well as reduced micronutrient contents (Fe, B, Zn, Cu, and Mn) under further increasing K application rates.

Calcium is essential for cell membrane and cell wall construction (Marschner, 2012). In addition, this nutrient is an intracellular second messenger involved in the regulation of biosynthetic pathways and hormonal expression (de Freitas *et al.*, 2016).

Calcium application can alleviate postharvest disorders and enhance produce quality of many fruit and vegetable species (de Freitas *et al.*, 2016). In lettuce, lack of Ca in the youngest leaves causes membrane failure and cytoplasm leakage leading to tip-burn symptoms (Saure, 1998; Lim and White, 2005). Fallovo *et al.* (2009) concluded that in lettuce, marketable yield, shoot biomass and leaf area index were unaffected by nutrient solution composition; however, a high proportion of Ca in the nutrient solution increased the quality attributes, in particular Ca, chlorophyll, glucose and fructose concentrations. In contrast, excess Ca/cation ratios in the nutrient solution might be antagonistic to the uptake of P, K, and Mg (Mandizvidza, 2017).

The main objective of the present study was to evaluate polyhalite as a possible supplemental solid fertilizer for lettuce, using a greenhouse soilless production as a principal model system. Polyhalite is available as both a powder (Polysulphate standard; PSS) and a granular (Polysulphate granular; PSG) product. Two experiments were carried out: the first was aimed to examine PSS as the sole K donor fertilizer, and the second tested the ability of very low PSG doses to provide lettuce with sufficient Ca.

Materials and methods

Two experiments were carried out. The first one took place at Eshel Hanassi Youth Village and high school, located in the Western Negev district of Israel, and the second at Hula Orchard Farm of Northern R&D in the Northern Galilee, Israel.

The first experiment was aimed at evaluating PSS as a sole K source. Romaine lettuce seedlings were planted on perlite 212 (Agrekal HaBonim Ltd., Israel) in 4-L pots on 11/11/2019. Plants were grown under controlled greenhouse conditions. Treatments included four levels of PSS: 0 (control), 12.5, 25, and 37.5 g L^{-1} that were thoroughly mixed with the perlite before planting. A final fertigation solution was prepared in a large container, using liquid ammonium nitrate 21% (ICL Haifa, Israel), phosphoric acid 85% (ICL Haifa, Israel), and Super Koretin (ICL Haifa, Israel) for micronutrients. All components were dissolved in water to produce 110, 30, and 3 ppm of N, P, and Fe, respectively, in the fertigation solution, used for all treatments throughout the growing season. Drip irrigation was exercised once a day until 30% drainage was reached. Harvest took place on 14/01/2020; plant length and weight were determined, as well as the number of leaves. Representative plants were photographed with the pots. Plants were then carefully rooted out; roots were washed and cleaned of perlite, measured, and photographed.

The second experiment aimed to evaluate PSG as a sole source of Ca. Romaine lettuce seedlings were planted on perlite 212 in 4-L pots, two seedlings per pot, on 05/06/2019. Plants were grown under controlled greenhouse conditions. Treatments included four levels of PSG: 0 (control), 0.25, 0.50, and 0.75 g L^{-1} that were thoroughly mixed with the perlite before planting. Water used for irrigation was desalinated using reverse osmosis at Zemach experimant station to a level of 0.6 meq Ca L^{-1}. Plants in all treatments were fertigated throughout the experiment with 'Shefer 5:3:8' (ICL Haifa, Israel) at 60 ppm N, and 200 ppm $MgSO_4$. Irrigation was scheduled three times a day, 10 minutes per irrigation (approx., 1 L day^{-1}). Harvest took place on 09/07/2019, 35 days after planting. At harvest, fresh above-ground biomass was determined. Plants were oven-dried at 70°C and dry biomass was determined. Leaf samples were taken, nutrient (Mg, Ca, K, and S) concentrations were determined at Zemach laboratories, and nutrient uptake was calculated.

Both experiments were designed in complete random blocks, with six replications consisting of five pots each.

Results

A significant response in lettuce growth to the perlite enrichment with PSS was recorded when the PSS dose was above 25 g L^{-1} (Fig. 1A), although a clear positive tendency could be observed throughout the scale of the application dose (Photo 2). The increment in the lettuce fresh weight was due to both greater numbers of leaves per plant (Fig. 1B) and leaf size, indicated by plant height (Fig. 1C). In contrast, the SPAD index, which measures chlorophyll density and, indirectly, indicates N content, was higher in the control leaves and consistently declined with the rising PSS dose (Fig. 1D).

Perlite enrichment with PSS significantly promoted the development of the lettuce root system (Fig. 2). Root length varied considerably and, therefore, displayed clear but statistically non-significant differences (Fig. 2A). Nevertheless, root biomass was obviously greater with the rising PSS dose (Fig. 2B).

In the second experiment, although smaller in two degrees of order than the PSS dosage in the first experiment, PSG displayed significant effects on lettuce fresh and dry biomass were recorded (Fig. 3). Yet, the effects were much weaker, adding no more than 25% to the fresh biomass, and even less to the dry plant biomass. Moreover, the influence of PSG seemed to decrease at the highest dose tested, 0.75 g PSG L^{-1}. While K, Mg, and S were supplied in fertigation via composite N-P-K fertilizer and $MgSO_4$, Ca was provided solely by PSG. Certainly, Ca concentration was significantly higher under PSG enrichment; however, no response was observed to the nutrient dose (Fig. 3C). Furthermore, control plants accumulated a considerable level of Ca, apparently in the absence of an available Ca source. Calcium uptake, a function of Ca concentration and plant biomass at harvest, followed the response pattern of fresh biomass to the PSG dose, but the differences between treatments were not significant (Fig. 3D).

The presence of PSG in the growth medium had no significant

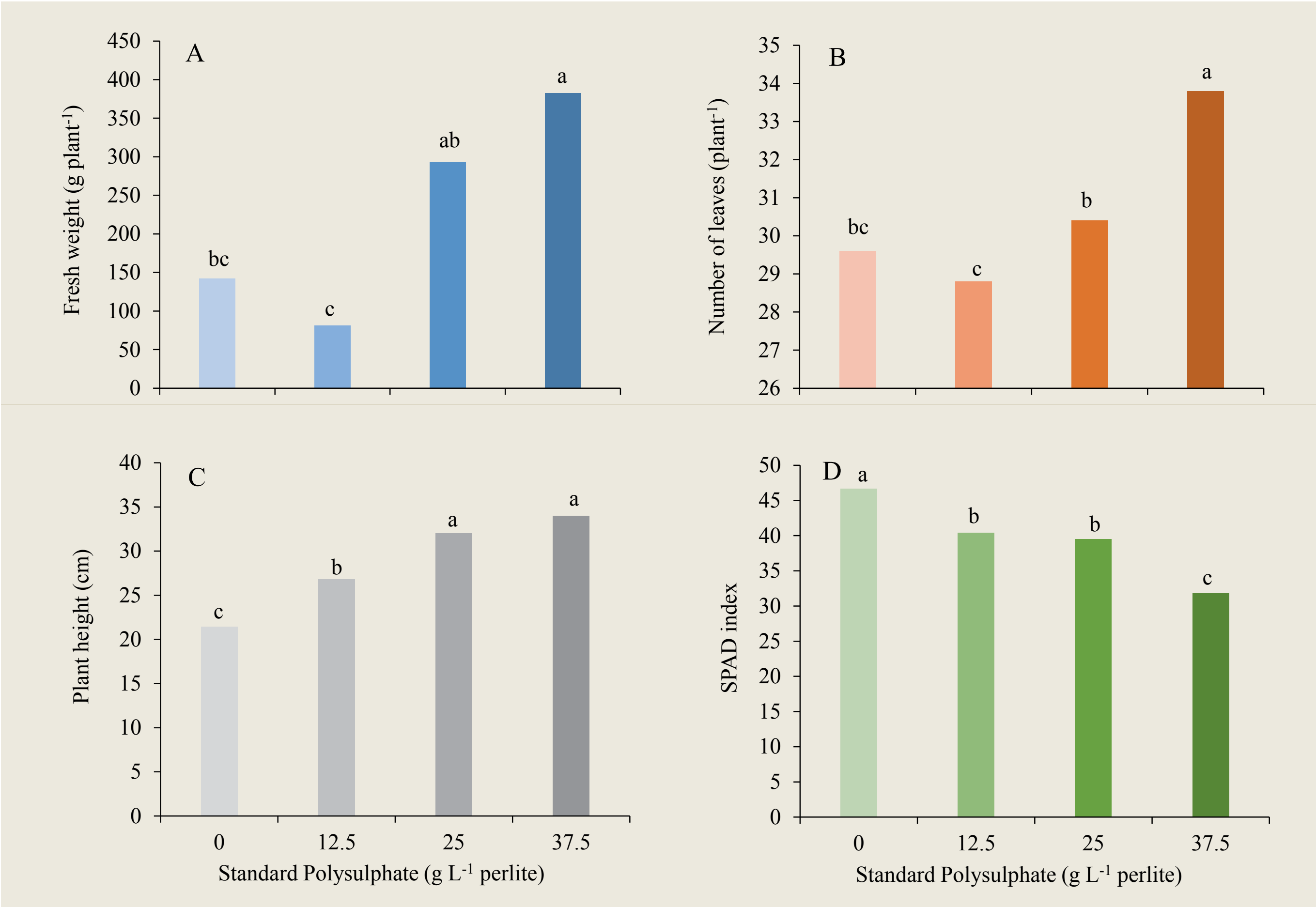

Fig. 1A-D. Effects of standard Polysulphate (PSS) concentration in the growth medium (perlite) on plant fresh biomass (A); number of leaves (B); plant height (C); and, SPAD index (D) at harvest. Similar letters indicate no significant differences between treatments at $p < 0.05$.

Photo 2. Effect of PSS concentration in the growth medium (perlite) on lettuce plant size and appearance before harvest. Photos by the authors.

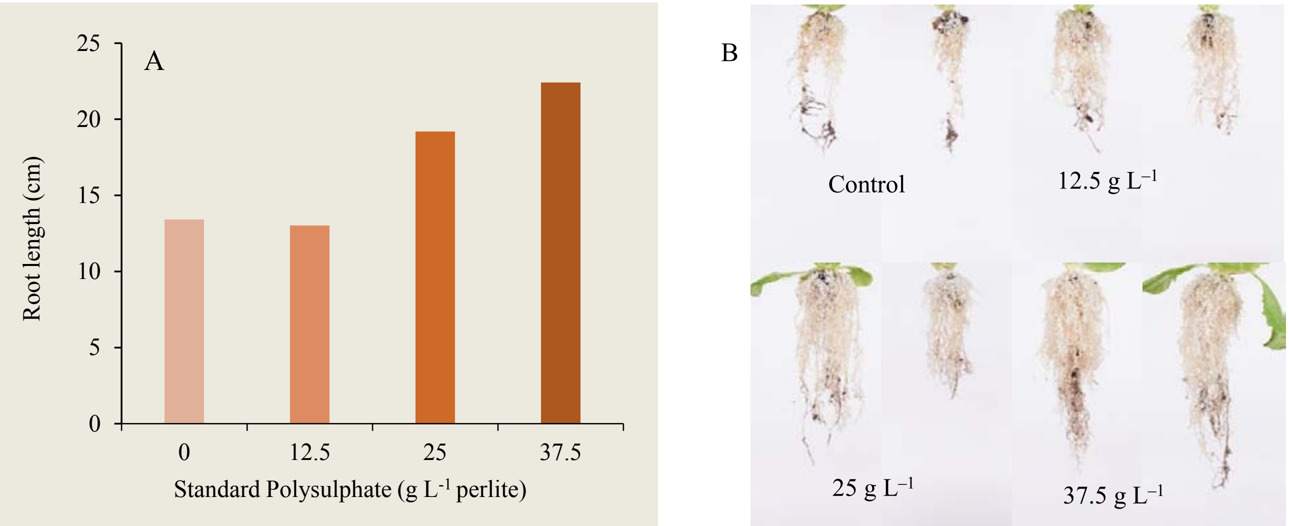

Fig. 2A,B. Effects of standard Polysulphate concentration in the growth medium (perlite) on the root length (A), and overall appearance (B) at harvest.

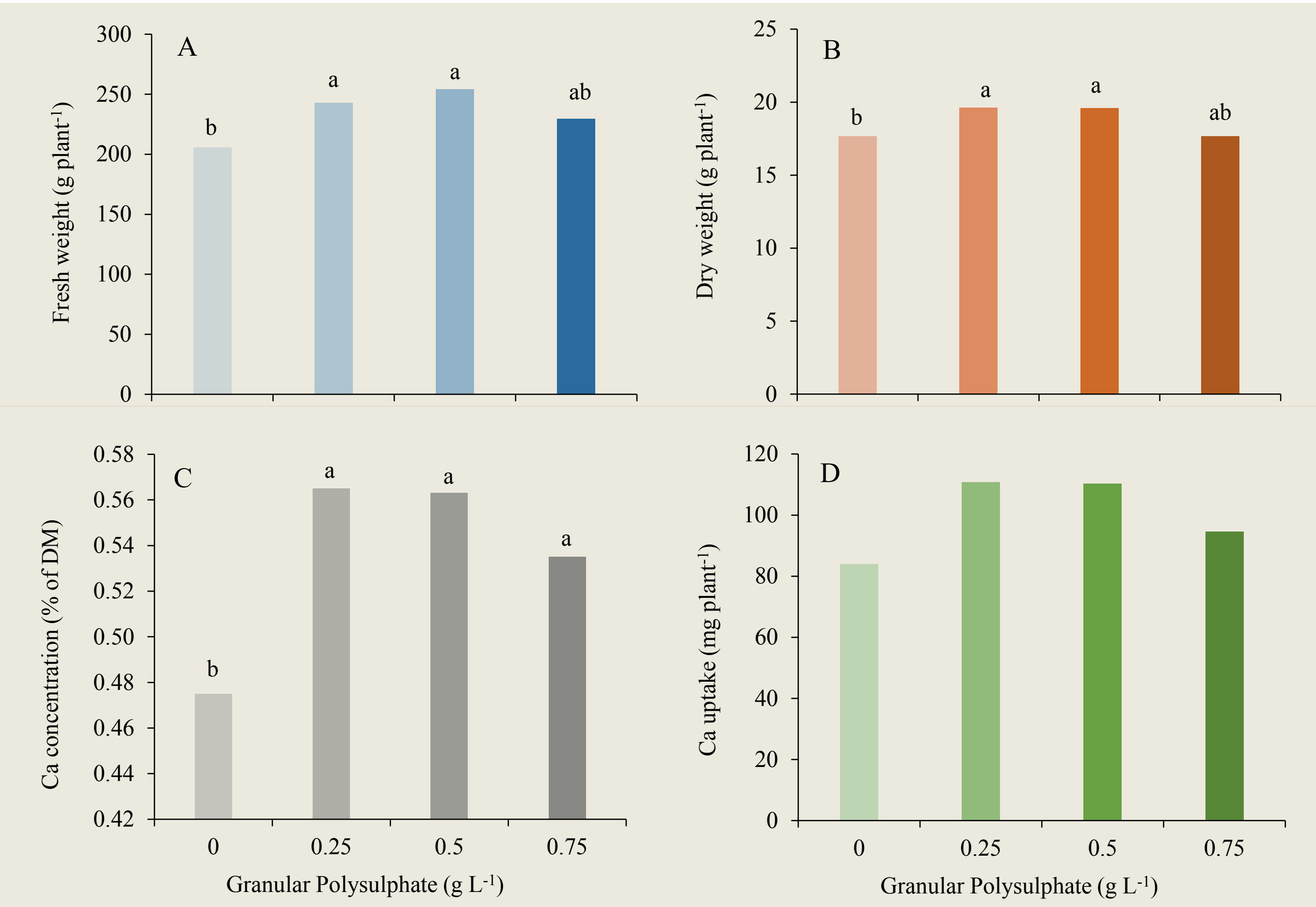

Fig. 3A-D. Effects of granular Polysulphate (PSG) concentration in the growth medium (perlite) on plant fresh weight (A); plant dry weight (B); calcium concentration (C); and calcium uptake (D). Similar letters indicate no significant differences between treatments at $p < 0.05$.

Table 1. Effects of PSG concentration in the growth medium on nutrient (S, Mg, and K) concentration in leaves and uptake, determined at harvest.

PSG	Nutrient concentration			Nutrient uptake		
	S	Mg	K	S	Mg	K
g L^{-1} perlite	---------------------%---------------------			---------------*mg plant^{-1}*----------------		
0	0.133b	0.525	4.33	111.5b	92.8	766
0.25	0.165a	0.498	4.17	183.1a	97.7	818
0.50	0.161a	0.423	4.24	177.8a	82.8	830
0.75	0.160a	0.465	4.37	151.6ab	82.2	772

Similar letters indicate no significant differences between treatments at $p < 0.05$.

effect on leaf K and Mg concentrations, or on the uptake of the nutrients (Table 1) that were supplied through fertigation. In contrast, leaf S content and uptake significantly increased under PSG treatments, but similar to Ca, with no correlation with the PSG dose (Table 1).

Discussion

Significant progress has been made recently in understanding the role of K^+ in root growth, development of root system architecture, cellular functions, and specific plant responses to K^+ shortage. There is evidence linking K^+ transport with cell expansion, membrane trafficking, auxin homeostasis, cell signaling, and phloem transport, all of which place K^+ among the important general regulatory factors of root growth (Sustr *et al.*, 2019). In general, when plant roots encounter a low K^+ region they often stop growth (Gruber *et al.* 2013; Kellermeier *et al.* 2013). Li *et al.* (2017) suggested that under low K^+ conditions, the auxin transport towards the root tip is blocked, and root growth subsequently stops. It is not surprising, therefore, that in the present study the most straightforward response of lettuce to a lack of K^+ was a significantly poorer root system (Fig. 2B). Polyhalite, applied as PSS at 25-37.5 g L^{-1} perlite, gave rise to a remarkable increase in root biomass. The enhanced size and, presumably, the consequent boosted function of the greater root system promoted an increase in the number and size of the leaves (Fig. 1), realizing commercially equivalent levels of lettuce yield and quality. The declining SPAD value recorded in response to increasing PSS dose (Fig. 1D) can be associated with excess N, which accumulated in the leaves under growth inhibition due to the K deficiency.

In this experiment, polyhalite served as the sole K donor, while N, P, and micronutrients were supplied through the fertigation system. PSS competence to fulfill lettuce K requirement was demonstrated, with no observable negative side effects on produce quality. In addition, PSS was the sole supplier of Mg and S, two essential nutrients; no deficiency symptoms occurred for these nutrients, indicating the potential role of PSS as an Mg and S donor. Nevertheless, the majority of vegetable or leafy species have much longer crop cycles compared to lettuce. Thus, and in spite of the relatively slower nutrient release rate of polyhalite (Yermiyahu *et al.*, 2017), significantly larger PSS doses might be required for conventional cropping systems.

In the second experiment, the ability of PSG to supply lettuce Ca requirements was examined while the other macro- and micronutrients were supplied through fertigation. Usually, excess Ca application would not promote significantly greater biomass (Maynard and Hochmuth, 2007; Pinto *et al.*, 2014; Ainun *et al.*, 2018); however Ca deficiency might cause tip-burn, browning of the younger leaves, which is a substantial quality drawback that particularly occurs under high temperature and evaporative demands (Bres and Weston, 1992; Saure, 1998; Mandizvidza, 2017; Sublett *et al.*, 2018). In the present study, a slight increase in lettuce fresh and dry biomass did occur, but this was not proportional with the PSG dose (Figs. 3A, 3B). No tip-burn problems occurred; however, bolting, quite natural in the warm conditions that prevailed during the experiment, necessitated an early harvest. The results of a successive experiment, where the PSG dose was raised and the irrigation water was further purified, were very similar, although Ca uptake was lower (data not shown). These results suggest that in the lettuce production system described, Ca is not a limiting factor. It may be questionable whether similar conclusions would prevail under elevated N application rates and a more favorable temperature range. Under such conditions, lettuce growth rates are expected to increase significantly (Broadley *et al.*, 2000; Fu *et al.*, 2017; Conversa and Elia, 2019; Djidonou and Leskovar, 2019), increasing Ca demand, and consequently, for the required Ca availability in the growth medium. Another question may be raised due to the Ca content and uptake values in the control of the second experiment (Figs. 3C, 3D), where apparently no Ca donor was applied; what was the exact Ca source in that system?

A possible candidate is the irrigation water used; although desalinated, it contained Ca at 0.6 meq L^{-1}. Unfortunately, no direct measurements of water uptake were carried out during the experiment. Roughly calculated, the irrigation water delivered a total of 175 mg Ca plant^{-1}, much greater than actually taken up by the plants (Fig. 3D). It is well known that nutrient uptake in hydroponic systems is substantially more efficient than in conventional soil cultures and, hence, much lower nutrient concentrations are required (Soundy *et al.*, 2001; Barbosa *et al.*, 2015; Ainun *et al.*, 2018). Conversely, the recently estimated water uptake rates of lettuce (Barbosa *et al.*, 2015) do not support the uptake of the complete amount of Ca provided solely by the irrigation water. In addition, the greater Ca uptake demonstrated by plants treated with PSG clearly indicate that this supplementary fertilizer took part in the Ca supply to these plants. Theoretically, PSG potentially held a reservoir of 60-180 mg Ca $plant^{-1}$; nevertheless, Ca occurs in polyhalite in the form of gypsum, and its solubility is very slow (Yermiyahu, 2019). It would be more realistic, then, to assume that only a small portion of the Ca held in PSG became available during the experiment.

In conclusion, the ability of polyhalite to provide all the K requirements of a crop throughout the season, which was clearly demonstrated for lettuce, largely depends on the crop duration and the amount of PSS embedded in the growth medium. Obviously, enrichment of the growth medium with PSG can ensure sufficient available Ca to satisfy lettuce requirements and guarantee high produce quality. Nevertheless, developing an accurate PSG application rate should be subject to thorough fine-tuning, taking local properties of the water and growth media into consideration. Economic evaluations will always be necessary when moving from the soilless model presented here to conventional cropping systems.

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The paper "Effects of Polyhalite Fertilizers on Lettuce Development on a Soilless Culture" also appears on the IPI website.