Potassium mineral fertilizers from upgraded waste streams

As effective as traditional mineral fertilizer?

Hampus Edgardh

Kaliumgödsel från uppvärderat avfall - Lika effektivt som mineralgödselmedel?

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Abstract

Recirculating potassium from waste could limit our dependence on finite potash extraction. This study tested a potassium sulphate (SOP) made by EasyMining, in a pilot-scale process turning ashes into valuable fertilizer. The study tested SOP originating from the ash of incinerated poultry litter and straw, plus two other EasyMining products (glaserite and untreated ash), against a commercial SOP. This was done in a seven-week greenhouse pot trial with perennial ryegrass. Eleven treatments (including a control and several K rates) were applied with four replicates. Pots used coarse sand blended with peat and a full non-potassium (K) nutrient solution to isolate K effects. Measured parameters were dry matter yield, plant K concentration and uptake, cadmium (Cd), zinc (Zn) and copper (Cu) uptake. Mineral Fertilizer Equivalent (MFE) was calculated by comparing K uptake and DM yield between treatments.

Overall biomass did not differ significantly between treatments. No significant differences in K uptake could be determined between control, commercial SOP and the tested fertilizers in the lower K rates which were given to the tested fertilizers. MFE estimates were inconsistent and unreliable, particularly those based on uptake. The experiment failed to create a clear potassium limitation: controls and K fertilized pots showed similar growth, likely because the substrate released more K than anticipated. This undermined the ability to draw firm agronomic conclusions about fertilizer equivalence. Cadmium uptake was higher in ash-treated pots versus glaserite at the medium rate, indicating that EasyMining's processing can reduce Cd content. Zn and Cu uptakes showed no treatment effects.

The study offers indications that EasyMining's process can lower heavy metal risks. A repeat study using a lower K growing medium, refined dosing and pre-trial soil K testing, and ideally multiple harvests is recommended to get more accurate information about the agronomic performance of recycled potassium fertilizers.

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Abbreviations

Abbreviation	Description
EM	EasyMining
MFE	Mineral Fertilizer Equivalent
MKP	Mono Potassium Phosphate
MOP	Muriate of Potash
NOP	Nitrate of Potash
SLU	Swedish University of Agricultural Sciences
SOP	Sulphate of Potash

1. Introduction

There is a big need for potassium fertilizers in modern agriculture. This has traditionally been accommodated with the use of mineral fertilizers based on new raw materials, often from mines. These are however a finite resource, and with an increased focus on sustainability in the agricultural system, research is ongoing on how we can recirculate more nutrients.

Within the framework of a strategic innovation program, EasyMining - a company owned by recycling company Ragn-Sells, has developed a process for recycling potassium from ash. The aim of the technology is to upgrade ash that is traditionally seen as waste destined for landfill, into a valuable potassium fertilizer ready to be put back into circulation. The potassium recovery method is designed to integrate with their already existing technology for phosphorous recovery.

In collaboration with SLU, a fertilizer made by EasyMining in a small-scale pilot process, was evaluated in a pot trial and compared to commercial alternatives. The goal of the evaluation was to validate the efficiency of recirculated potassium products as fertilizers and thereby evaluate if the process is useful from an agronomic and environmental perspective. The evaluation also included analysis of heavy metal uptake, to draw conclusions about the processes capacity to remove contaminants from the fertilizers.

1.1 Objectives

The purpose of this study was to investigate the potential of a potassium sulphate fertilizer, developed by the company EasyMining.

The following research questions were examined in the study:

- Is the fertilizing effect, measured as crop yield and crop potassium uptake, equivalent between EasyMining's product and traditionally available alternatives of potassium sulphate?
- Does the recirculated fertilizer result in an increased uptake of heavy metals?

1.2 Delimitations

The extent of the study had the following delimitations: The studies production process can be applied to many different substrates with a wide range of contents and origins. Only one fertilizer, made from one substrate, was tested. Furthermore, the fertilizer was tested using only one crop and under a limited period and thereby showing only short-term effects.

2. Background

2.1 Potassium in the soil

In soils, potassium exist as a structural component of minerals, fixed in the lattice in clay minerals, adsorbed ions on surfaces of soil colloids, and as free cations in the soil solution (Bryson et al. 2014). The reserves of potassium in mineral soils consists to 99% of unavailable potassium as a part of the minerals. Chemical weathering is therefore a vital source of plant available potassium, especially for clay soils where a large specific area leads to an increase in these processes and its resulting nutrient release (Eriksson et al. 2011).

Adsorption of potassium cations to soil particles plays a large role in its behaviour as a plant nutrient. Potassium is subject to a chemical equilibrium between potassium in solute and potassium adsorbed to particles. Plant uptake of K, and the resulting lower concentration in the soil solution shifts the equilibrium and releases more of the adsorbed K as plant available cations. K-fertilization shifts the equilibrium the other way, increasing the amount of adsorbed potassium (Fogelfors et al. 2020). This adsorption mechanism decreases the risk of K leeching, although the extent depends largely on soil type (Eriksson et al. 2011).

Potassium can is susceptible to being fixed in the lattices of clay particles. This means that an excessive fertilisation with potassium on a clay soil will lead to an increase in the amount of unavailable potassium, and is to little direct advantage from an agronomic point of view (Bryson et al. 2014).

2.2 Potassium in the plant

Potassium is one of the six essential macronutrients essential for plant functions (Weidow 1998). It is absorbed by plants a cation, specifically K^+, through various transport mechanisms. Uptake of potassium is an active process, with selective channels of both high and low affinity transfer K^+ through the membrane. Uptake is stopped only if the potential difference between the cytosol and outer solution reaches equilibrium. This uptake can compete with the passive uptake of other positively charged nutrients, such as magnesium, calcium and sodium, in an process called cation competition. (Barker & Pilbeam 2007). This means that with an increased availability and uptake of potassium, increased levels of these nutrients are also needed to minimize the risk of deficiency of these nutrients (Båth n.d.). This potential issue is further exacerbated by the fact that plants are susceptible to luxury consumption of potassium. If the availability of potassium in the soil is abundant, plants may absorb 2-4 times the amount of potassium needed for its metabolic function (Bryson et al. 2014).

Potassium plays a vital role in numerous physiological processes, including water and nutrient movement within the plant, maintaining turgor pressure, opening of stomata and regulating osmotic potential. Potassium is also necessary for enzyme activation, membrane functions and for the formation of cellulose and protein (Bryson et al. 2014).

The first sign of potassium deficiency is growth retardation, something that could be the cause of many different factors, making it hard to identify. Potassium is highly mobile in the plant, which leads to translocalization of K in the case of deficiency. Older tissues are therefore the first part of the plant where clear deficiency symptoms can be observed (Barker & Pilbeam 2007). These symptoms begin with discolorations in the form of light green to yellow leaf tips and edges. Severe cases include susceptibility to lodging, and increased infections of plant disease due to thin cell walls (Bryson et al. 2014).

The role of potassium as an osmoticum is not inherently exclusive since K^+ partially can be substituted by sodium ions. The extent to which this is possible depends on the sodium uptake potential of the specific crop species, which can vary significantly. Sugar beet (*Beta Vulgaris*) and spinach (*Spinacia Oleracea*) both have a large uptake potential, and a big capacity for the substitution between sodium and potassium, but the effect has also been shown in Perennial Ryegrass (*Lolium Perenne*) (Barker & Pilbeam 2007).

Potassium almost exclusively occurs in the plant in its ionic form, as K^+ dissolved in cellular tissues. K^+ concentrations do not differ dramatically between different plant tissue types, but the total amount in a tissue is closely varies with the amount of water in said tissue. Tissue water content can however vary between tissues and maturity of the plant. Potassium concentration expressed in wet weight can therefore clearly state the nutritional status of the plant, where as K concentration expressed per dry weight can give an understanding of total plant uptake (Barker & Pilbeam 2007).

2.3 Potassium as a fertilizer

Potassium fertilizers play a crucial role in modern agriculture, and a term commonly used for these is 'Potash', which includes both mined and manufactured salts containing water soluble potassium. Potash is primarily sourced from mining operations in Canada, Russia and Belarus (Somarin 2014). These countries stand for an estimated 74% of the world’s minable potassium reserves. These reserves consist of sedimentary rock deposits, both underground and surface deposits (International institute for Environment and Development 2025). In 2018, the world potash production reached 42 million tonnes. Over 90% of the potash extracted worldwide is used in the agriculture industry. Estimations show that "peak potash", the point potash extraction reaches its maximum, is set to take place around year 2057 (Al Rawashdeh 2020). Based on population growth and future nutrient demand, the world potassium reserves are predicted to deplete in 235-510 years (Sigurnjak et al. 2020). Potassium chloride (Muriate of Potash, MOP) is the most used potassium fertilizer world-wide, followed by potassium sulphate (Sulphate of Potash, SOP), potassium magnesium sulphate, potassium nitrate (Nitrate of Potash, NOP) and mono potassium phosphate (MKP) (International institute for Environment and Development 2025). The difference between these potassium containing salts is which anion accompanies the K cation. This affects the fertilizers agronomic properties where MOP contains a large amount of chloride, which is a problem for salt sensitive crops whereas SOP instead contains sulphate, a vital nutrient. The biggest drawback with SOP compared to MOP is its cost, being about twice as expensive, and thereby limiting the usage (Blaylock n.d.).

2.4 Potassium from a systemic perspective

Once mined and sold to farmers world-wide, the potassium enters circulation into the agricultural system. In Sweden, an average of 21 kg K/ha is spread yearly on farmland as fertilizers, and 70% of this potassium is lost, mainly as fixation in soils and leaching, on its way through the agricultural system. Every year 6 kg K/ha is taken out of the agricultural system in the form of produced agricultural products. The average annual turnover of potassium in animal manure is 30 kg K/ha, which makes animal manure an important factor in the turnover of potassium in Sweden, and most likely also in other similar combined livestock and arable farming systems (Granstedt 1999).

In recent decades, animal production systems have undergone structural changes. The localization of livestock production has become more geographically concentrated due to market access, feed resources, labour and the price of land making production more profitable in certain areas (Steinfeld et al. 2006).

One issue these areas with high concentration of livestock often have in common is that the high production of manure leads to problems. The capacity of surrounding farmland to absorb and utilize the manure is exceeded, leading to environmental damage and an inefficient nutrient use. This tendency is particularly prominent in areas where livestock, humans and agriculture share a limited area (Steinfeld et al. 2006).

Reserves of vital plant nutrients are finite, and subject to depletion. The current nutrient management within the food production system circulate part of the potassium, but more is needed for long term sustainability. This can be done by reducing losses, effectives use, and to recycle waste streams (Liu et al. 2020).

An answer to a high concentration of poultry litter in the Netherlands has been incineration, where the animal manure is incinerated, concentrating the nutrients in the ashes. From this process, the energy content in the litter can be utilized for producing heat and electricity. Two agronomically important components of the litter are lost, nitrogen and organic matter, but the potassium and phosphorous remains in the ashes together with high concentrations of minerals and heavy metals. The ashes can be used as a fertilizer as is, with a potassium fertilizing effect as good as conventional potassium sulphate (SOP). This was shown in a cultivation trail for both green bean (Phaseolus vulgaris L.) and Perennial Ryegrass (Lolium Perenne L.) (Ehlert 2020).

Combustion of the manure not only increases the proportion of potassium and phosphorous in the ashes, but also unwanted heavy metals that were already present in the manure. However, the ratios between the nutrients and heavy metals remain the same, and should therefore not lead to increased loading when used as a potassium or phosphorous fertilizer (Ehlert 2020). Copper, zinc and other heavy metals are added to livestock feed for animal health reasons or as growth promoters. This leads to elevated levels of heavy metals in the manure, which if accumulated in the soil or water, pose a serious threat to the environment (Steinfeld et al. 2006). Combustion of other waste material streams for energy recovery also concentrate heavy metals in the ashes(Rydegran n.d.). These waste streams can also be a possible application for new recirculation technologies and thus also need removal of these contaminants.

Recirculation of waste streams as fertilizers is an important step for increased sustainability. With the clustering of livestock agriculture and its negative effect on the utilization of animal manure, upcycling of the waste into more valuable and transportable compounds, with processes such as EasyMining’s, could be part of a more sustainable future.

2.5 EasyMining's process

This newly developed process focuses on the extraction of potassium and phosphorus fertilizers from waste. A key benefit of the technology is the ability to remove heavy metals, which otherwise could limit the usability of the ash as a fertilizer.

The process allows for a wide variety of substrates to be recycled. Tests are underway with substrates ranging from poultry litter fly ash and other byproducts from the agricultural sector to municipal solid waste ash and wastes originating from paper- and cement industries. This broad applicability shows the technology's potential for widespread implementation.

The waste undergoes several chemical treatment steps in which various potassium salts can be produced, which is shown in Figure 1. The process can be controlled to favour the formation of certain salts. Heavy metals are removed using chemical methods. Outputs from the process include salts like SOP, KCl or glaserite, sodium chloride and a phosphorous rich residue. (EasyMining 2025)

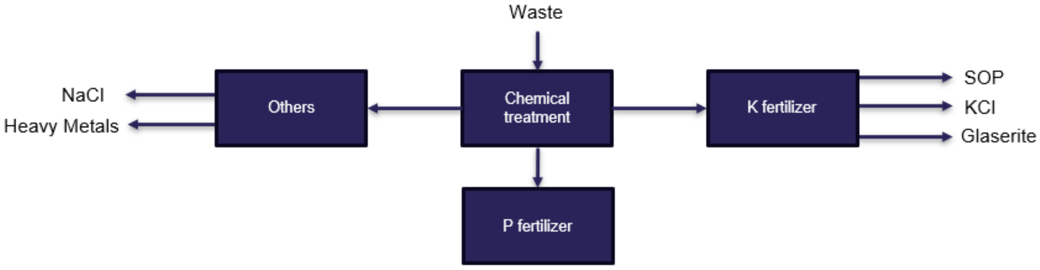


Figure 1: Simplified flowchart illustrating EasyMining's recycling process. (EasyMining 2025)

2.6 Methodology behind the pot trial

Evaluation of the fertilizers provided by EasyMining was done by a pot trial, where the experimental fertilizers were compared to a commercial alternative, in this case SOP, to examine their agronomic potential.

The experiment was designed under the the ceteris parabus assumption to allow valid conclusions: if all other factors are equal, the variable factor is the cause of the effect. This was combined with Liebig’s law of the minimum, which implies that plant growth is limited by the scarcest resource. In the case of this experiment, a limited nutrient, potassium. consequently, the level of growth can be attributed to the level of potassium that that is given to the specific plant or pot. To measure how the crop is affected by the fertilizers a yield response curve is commonly used. This showcases the relationship between input fertilizer and resulting yield. When an increase in fertilizer does not lead to an increased yield, it is no longer the limiting factor in growth. For Liebig’s law of the minimum to be applicable, crop yield must be within a region of the curve where increased fertilization leads to increased yield.

To induce potassium deficiency, the growing medium needed low plant available potassium. Most soils contain large amounts of potassium, but with a lower amount being available to the crop

The uptake amounts of specific nutrients differ between plant species, and in this context, a plant type with large uptake of potassium is needed. Crops with a high demand of potassium that are commonly grown in Sweden include lays, potato and sugar beets. For this experiment perennial ryegrass was chosen since it is a commonly used species which is easy to grow and have a high growth rate.

Several aspects are relevant to evaluate the pot trial:

The first aspect is the dry matter yield. This gives a good indication of the plant growth and uptake of nutrients. If all nutrients except potassium is available in abundance, yield differences can be attributed to potassium levels, and the potassium fertilizer effectiveness.

The second aspect that will be investigated is potassium content in the biomass, to calculate the uptake of potassium in the crop, as potassium levels can vary depending on availability.

Thirdly, the crops contents of heavy metals will be measured, and the uptake will be calculated to evaluate the potential effects from the fertilizers.

3. Methods and materials

3.1 Description of the pot trial

The pot trial was conducted in a greenhouse at SLU and was designed to evaluate the effects of various potassium fertilizers on plant growth and potassium uptake. A total of 44 pots were included in the study, divided into 11 different treatments with four replicates. Five different levels of commercial potassium fertilizer (potassium sulphate) were used (Table 1). Fertilization levels were decided using observed plant uptake amounts under field conditions (Andersson et al. 2025) and fertilization levels used in previous pot trials (Ehlert 2020). Fertilization levels per pot was calculated from amounts per hectare using the surface area of the pot.

Table 1: Fertilization levels used in the pot trial. Fertilizer doses in equivalent hectare doses and in mg/pot.

Fertilization level	Amount of Potassium (kgK/ha)	Amount of Potassium (mg/pot)	Comment
Control	0	0	Only used in the control treatment
Low	20	35	Used for all different fertilizers
Medium	40	71	Used for all different fertilizers
High	80	141	Only used to gauge yield response
Above optimum	120	212	Only used to gauge yield response

The experiment consists of four different potassium fertilizers with varying origin, as well as a control treatment without any potassium fertilization, relying solely on the potassium available from the growing medium. Treatments 2, 3, 4 and 5 was fertilized with commercial SOP sourced from a lab vendor, which was chemically identical to the SOP used in the agricultural industry. Fertilizer was added in all four levels. Treatments 6 and 7 was fertilized with SOP produced by EasyMining's new process. Treatments 8 and 9 was fertilized with glaserite from EasyMining's process. Glaserite is a double salt of potassium and sodium sulphate, which could potentially be used as a fertilizer. There is however limited research of this, which is why it was included in the trial.

Treatments10 and 11 was fertilized with ash from incinerated poultry litter and straw. This was the original substrate used to produce EasyMining's SOP and glaserite used in the trial. Treatments 6 to 11 was fertilized in levels low and medium. The experimental setup is summarized in Table 2.

Table 2: Summary of the different treatments included in the pot trial, the amount of potassium added to each treatment and ID assigned to each treatment.

Treatment	Fertilizer	Fertilization level	Amount of Potassium (kgK/ha)	Pot ID
1	Control	Control	0	1.1-1.4
2	Comm. SOP	Low	20	2.1-2.4
3	Comm. SOP	Medium	40	3.1-3.4
4	Comm. SOP	High	80	4.1-4.4
5	Comm. SOP	Above Optimum	120	5.1-5-4
6	EM SOP	Low	20	6.1-6.4
7	EM SOP	Medium	40	7.1-7.4
8	EM Glaserite	Low	20	8.1-8.4
9	EM Glaserite	Medium	40	9.1-9.4
10	EM Ash	Low	20	10.1-10.4
11	EM Ash	Medium	40	11.1-11.4

The trial was set up to produce a robust statistical basis for analysis, with four replicates per treatment ensuring reliability. The experiment was conducted over seven weeks to ensure a large plant growth and potassium uptake.

The pots were arranged in four groups of 11 pots, with one pot from each treatment in each group. This arrangement ensured to minimize environmental variability, in terms of light exposure and possible temperature gradient in the greenhouse. To further decrease the risk, the groups of pots were rearranged once a week, in a rotating schedule where the groups switched places on the table where they were placed.

During the first week of the experiment, the greenhouse temperature was maintained at 15 °C during the day and 10 °C at night. Artificial lighting was provided for 12 hours per day. After this initial period, the daytime temperature was increased to 20 °C and the nighttime temperature to 15 °C. The photoperiod was also extended to 16 hours per day.

To limit the amount of plant available K from the soil, coarse sand was chosen as the main constituent. The main drawback with this is its low water holding capacity. To counter this, peat was mixed with the sand, minimizing the risk of crop damage because of dry conditions.

To ensure good growing conditions the soil mixture was fertilized with large amounts of nutrients to ensure that no deficiencies occurred. Three nutrient solutions were prepared in the laboratory, which combined contained the nutrients presented in Table 3. Since the ash and glaserite products contained many other nutrients except K, the total amounts in these treatments were higher than the others.

Table 3: Levels of nutrients added to all treatments.

Nutrient	Dosage (kg/ha)	Reason for variance
N	150	
P	30-33	High level in ash.
Ca	38-45	High level in ash.
Mg	25-26	High level in ash.
S	34-83	Varying level due to different amounts of potassium sulphate added.
Fe	1.1-1.4	High level in ash.
Mn	1.1-1.3	High level in ash.
B	0.11	
Cu	0.21-0.25	High level in ash.
Zn	1.1-1.4	High level in ash.
Cl	78	
Mb	0.11	
Na	0.11-6	High levels in both glaserite and ash.

3.2 Carrying out the pot trial

Preparation of the experiment started with preparing a uniform soil mixture. In each of three large plastic containers, 40 kg of sand was mixed with 12.5 litres of peat, making three separate batches. These were thoroughly mixed with the use of shovels and 40 grams of crushed limestone were added to each container to increase the pH-value of the soil. The soils were again mixed to ensure homogeneity, and to eliminate any variability in nutrient availability across all pots.

Prior to filling the pots, all containers and tools were cleaned using dish soap and a brush. Equal parts soil from each large plastic container was again mixed in a smaller plastic container, before each pot was filled with 2300 ± 10 grams of soil. This ensured that all pots contained equal amounts of soil from all three batches. Uniform weight was paramount to ensure that equal nutrient availability.

Figure 2: Fertilization of each pot, by emptying into a plastic container and adding three different nutrient solutions.

The pots were then emptied, one by one, into a small plastic container, where the nutrient solutions were added by pipetting, before being mixed and put back into each respective pot. Each pot was marked with a plastic label containing each pots unique pot ID.

For the seeding process, a specific quantity of perennial ryegrass, variety Sirtaky, was used. A total of 0.1 ± 0.005 grams of seeds were weighed out for each pot. This corresponded to a dose of 566 kg per hectare. This is a large number of seed per hectare but aligns with doses used in other trials. (Delin et al. 2014) The seeds were spread evenly across the surface of the soil and lightly covered with 100 ml of the same soil mixture used before.

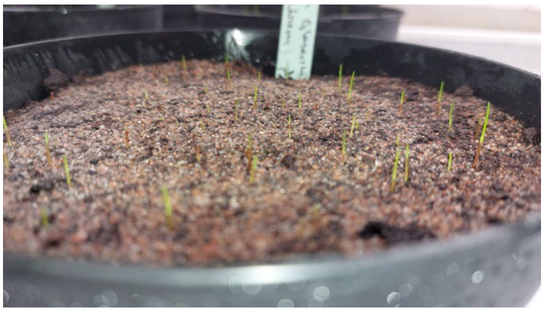


Figure 3: Emerging grass after careful watering.

Directly after seeding, each pot was carefully watered using a spray bottle. Care was needed as the sandy soil could easily erode when subjected to the water. Watering was carried out regularly, every to every second day to ensure adequate moisture level for plant growth. The time elapsed between waterings varied due to different levels of plant growth and evapotranspiration during the experiment period. Deionized water was used to ensure that no unknown sources of nutrients was added.

Sowing was missed in one pot, and even though this was sown one week later, the results from this pot was excluded from the analysis of the result.

The experiment was carefully monitored, and factors such as water need, deficiency symptoms, presence of pathogens, pests and weeds checked.

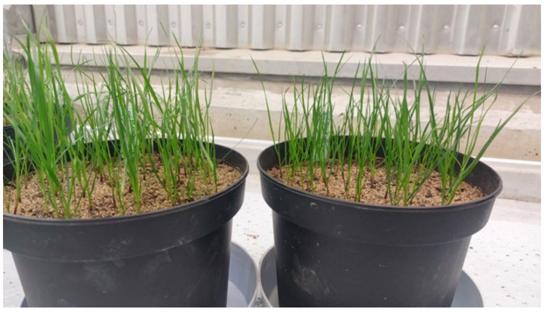


Figure 4: Pots 1.3 and 1.2 showing difference in growth.

After four weeks, it was possible to see that some pots had a decreased growth compared to the others. This could potentially be attributed to one of the liquid fertilizers added, containing calcium phosphate. This suspension had settled during the preparation of the pots, which could have led to a decreased dose of phosphorus. To evaluate this hypothesis, these four pots received an extra dose of the beforementioned nutrient solution and was returned to their respective placements in the experiment. The results from these pots were also excluded from the analysis of the result.

3.3 Harvesting and sample preparation

Due to noticeable signs of stress in the grass, the harvesting process commenced one week earlier than initially planned. This decision was made to ensure the collection of plant material before any decline in plant health could skew the results.

Figure 5: Noticeable signs of stress, yellow leaves, before harvest.

The grass was cut to a stubble height of approximately 1cm, and an example pot was used as a reference during the harvesting process. To minimize the risk of systematic errors, one replicate from each treatment was harvested at a time, allowing for a consistent sampling procedure.

Figure 6: Harvesting under way.

The samples were dried in 50 degrees for 48 hours. After drying, the samples were weighed while still in the bags. A random selection of empty bags was weighed, and the average weight of the bags were subsequently subtracted to obtain the net dry weight of the samples. Following the weighing process, the samples were ground to a fine powder to ensure homogeneity before being sent for analysis to ALS Scandinavia in Luleå. The samples were analysed for concentrations of potassium, copper, zinc and cadmium.

Figure 7: Root mass being broken apart and soil shaken loose.

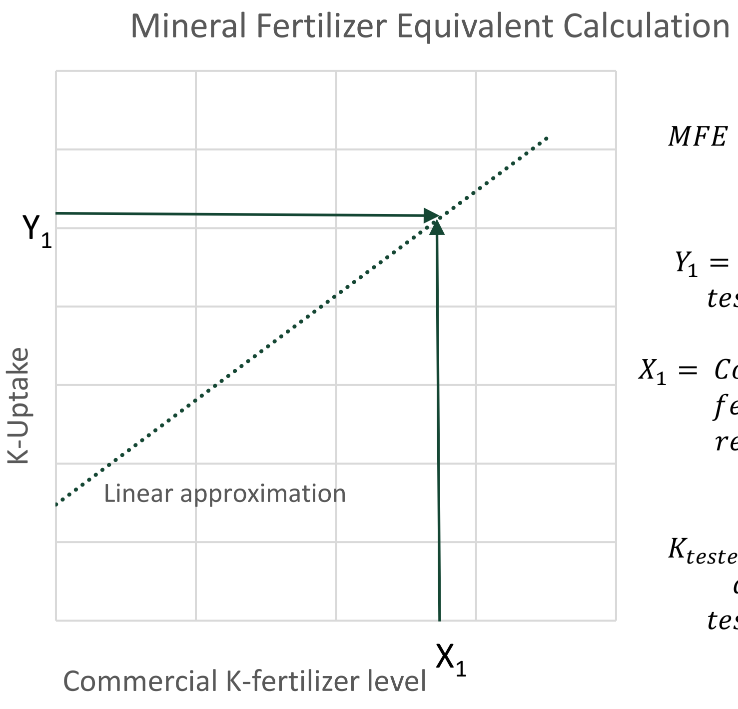
In addition to plant samples, soil sampling was also conducted. The pots were allowed to completely dry before beginning this process. Each pot was carefully removed from the grown together mixture of roots and soil, before the roots were broken apart with the help of a spade. The soil was shaken free from the root mass. Careful attention was required throughout this process to ensure that all soil particles were thoroughly separated, resulting in a representative soil sample. pH measurements were taken from a selection of the soil samples to assess acidity levels, providing insight into the soil conditions during the experiment. These were found to be in the interval 5,8-6,0. Finally, the soil samples were handed over to EasyMining where they were screened to remove any root material, before they underwent a leech test to evaluate the different fertilizers effect on soil conditions and environmental impact.

3.4 Calculations

The analysed concentrations of potassium, cadmium, zinc and copper was processed in Excel. Uptake was calculated using the following formula:

$$Uptake = \frac{Concentration\ in\ drymass * Sample\ weight}{\%Drymass}$$

Mineral Fertilizer Equivalent (MFE) was calculated based on potassium uptake and harvested biomass. MFE quantifies the effectiveness of a tested fertilizer (typically organic) relative to a standard mineral fertilizer. Although EM SOP and glaserite are also mineral fertilizers in this case, the comparison remains valid and provides insight into their relative potencies. Calculations followed the methodology described by Delin et al. 2014. This was done by plotting the potassium uptake or biomass against the potassium fertilization for the control and commercial fertilizer treatments. A linear regression was made, and from this the correspondent level of commercial fertilizer for each of the tested fertilizers and fertilization levels was calculated.



$$MFE = \frac{x_1}{K_{tested}} \times 100\%$$

$$Y_1 = K - Uptake\ for\ tested\ fertilizer$$

$$X_1 = Commercial\ mineral\ fertilizer\ needed\ to\ reach\ the\ same\ K - uptake$$

$$K_{tested} = Amount\ of\ K\ applied\ with\ tested\ fertilizer$$

Figure 8: Calculation of MFE using a linear approximation (dotted line) of K-Uptake as a function of commercial K-fertilizer level. Revised schematic figure from Delin et al. 2014 : 6.

3.5 Statistical analysis

Statistical analysis of all gathered and calculated data was made in Minitab using a one-way ANOVA test for every measured variable. A p-value of 0.05 was considered statistically significant. Pairwise considerations were made using Tukey's method.

All averages and standard deviations shown in diagrams was calculated and visualized in Excel. The cadmium concentrations are very low, and some pots were under the lower limit of detection for the equipment used by the laboratory. Values reported by the laboratory as being below a detection limit (e.g., <0.007 mg/kg) were assigned half the detection limit in the calculations, to avoid skewing the results.

4. Results

4.1 Biomass yield

Results of the biomass yield showed no significant differences between any of the treatments (p=0.228).

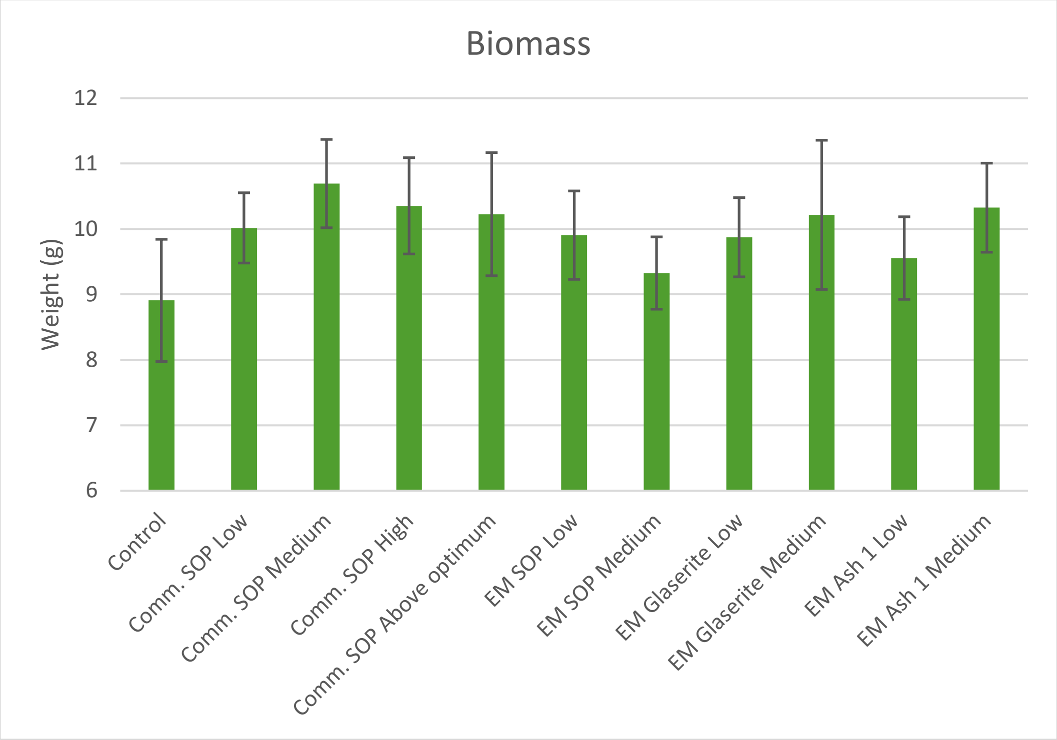


Figure 9: Dry weight of harvested biomass from the different fertilization treatments. Error bars indicating standard deviation. The p-value is 0.228.

4.2 Potassium

4.2.1 Potassium uptake

The Comm. SOP Above optimum leads to a higher uptake of potassium than all other treatments except for Comm. SOP High, and EM SOP Medium. The p-value for the potassium uptake is 0.00048, indicating a statistical significance between A and B groupings, as shown in Figure 10. No other statistically significant differences can be determined from the results.

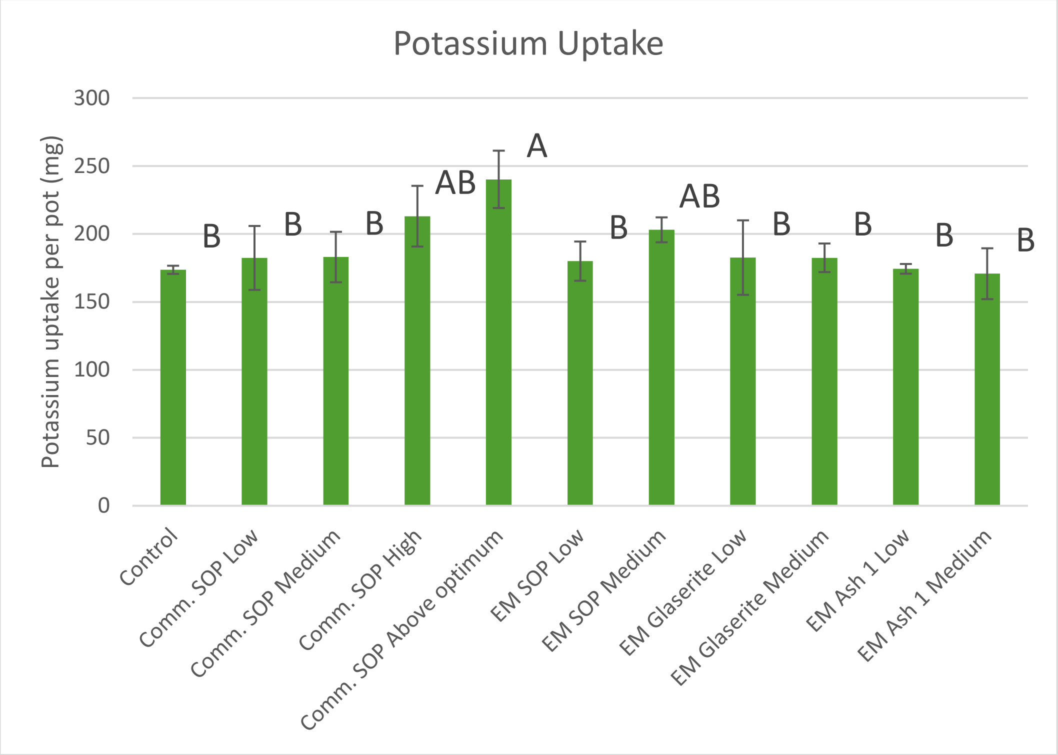


Figure 10: Potassium uptake for the different fertilization treatments. Error bars indicate standard deviation. Different letters indicate statistical significance between treatments. The p-value is 0.00048.

4.2.2 Potassium concentration

No treatments have a significant difference from the control in terms of potassium concentration. The Comm. SOP Above optimum did lead to a higher concentration than all other treatments except for Comm. SOP high, EM SOP medium, and the control. EM Glaserite Low and EM Ash Medium both have lower potassium concentrations than Comm. SOP Above optimum and EM SOP Medium. The p-value for the potassium concentration is 0.00047, indicating a statistical significance between A, B and C groupings, as shown in Figure 11.

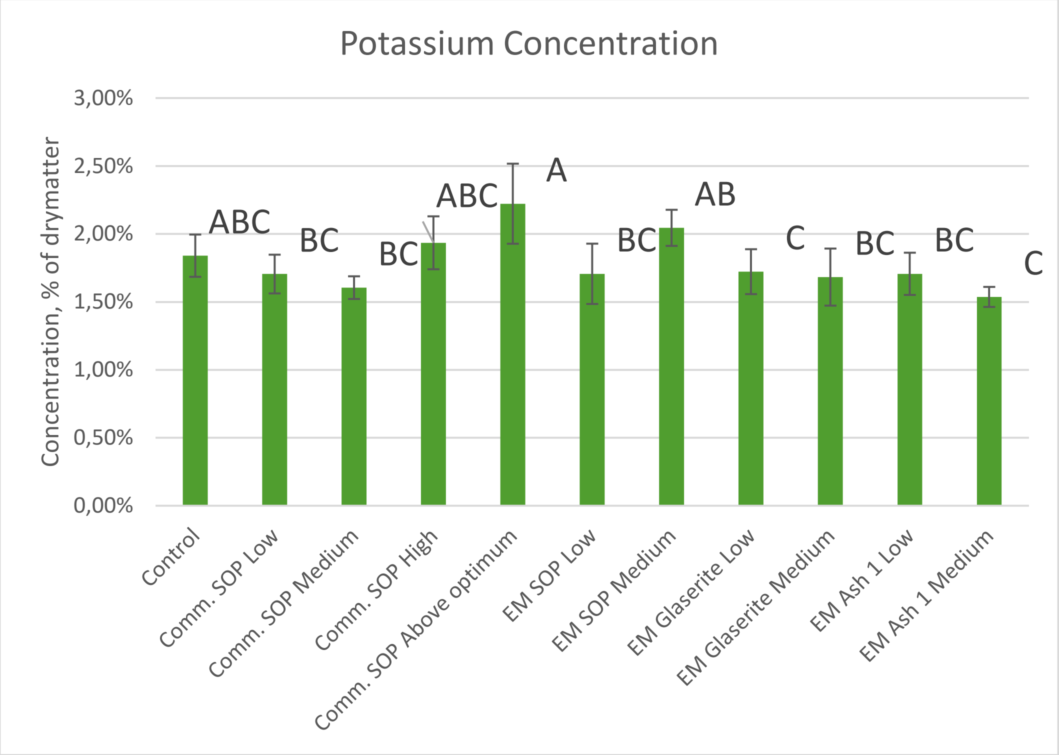


Figure 11:Measured potassium concentration for the different fertilization treatments. Error bars indicate standard deviation. Different letters indicate statistical significance between treatments. The p-value is 0.00047.

4.2.3 Mineral Fertilizer Equivalent

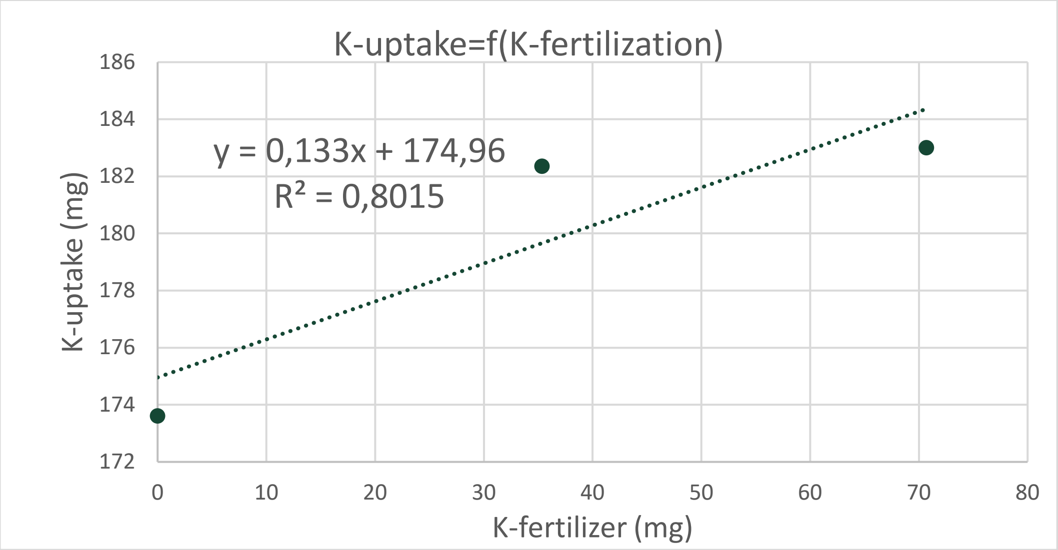


Figure 12: Plant K-uptake (mg) as a function of added K-fertilizer (mg) for the control, low and medium commercial SOP treatments. The dotted line is a linear regression.

MFE was calculated for all treatments using the methodology explained in section 3.4, its resulting linear approximation is shown in Figure 12. Calculated MFE values are shown in Table 1.

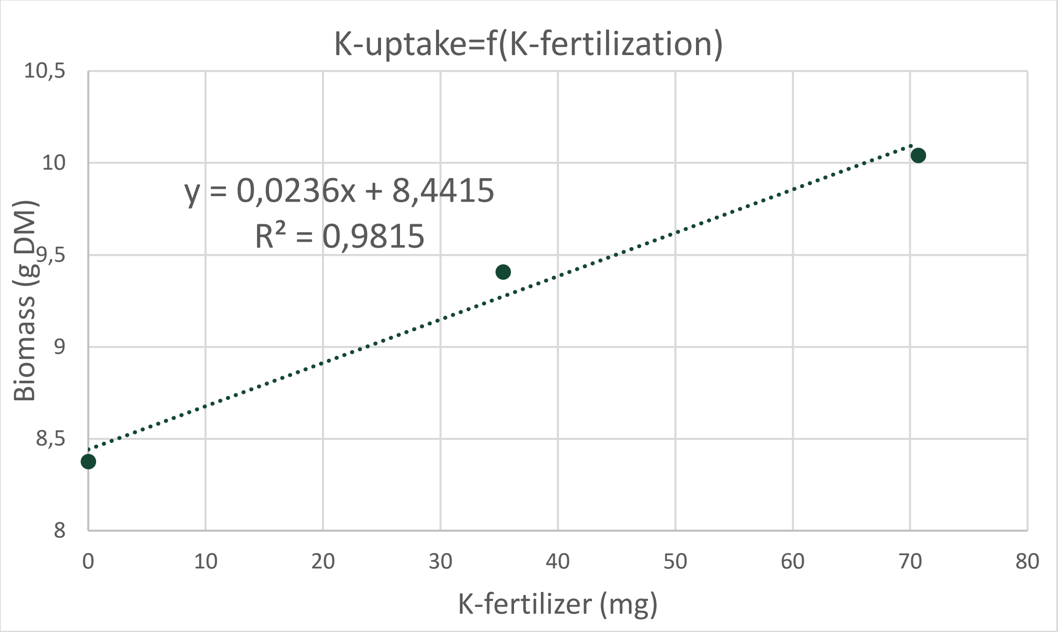


Figure 13: Plant biomass (g DM) as a function of added K-fertilizer (mg) for the control, low and medium commercial SOP treatments. The dotted line is a linear regression.

MFE was also calculated from biomass instead of uptake for all treatments using the same methodology, its resulting linear approximation is shown in Figure 12. Calculated MFE values are shown in Table 4.

Table 4: Calculated MFE values for each of the experimental treatments and fertilization levels.

Treatment	MFE (K-uptake)	MFE (biomass)
EM SOP Low	107%	98%
EM SOP Medium	299%	18%
EM Glaserite Low	163%	95%
EM Glaserite Medium	80%	66%
EM Ash Low	-13%	55%
EM Ash Medium	-45%	70%

4.4 Heavy metal uptake

4.4.1 Cadmium

EM Glaserite Medium shows a lower cadmium uptake than EM Ash Low and EM Ash Medium. The p-value for the cadmium uptake is 0.016, indicating a statistical significance between A and B groupings, as shown in Figure 14. No more statistically significant differences can be determined from the results.

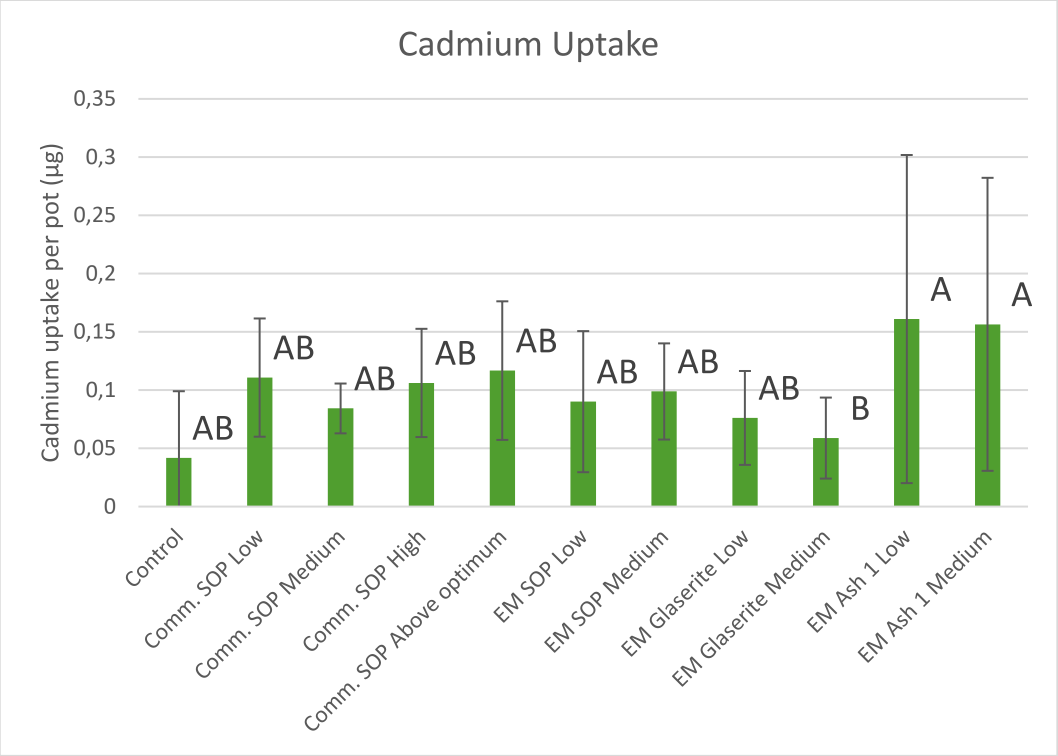


Figure 14: Calculated cadmium uptake for each treatment. Error bars indicating standard deviation. Different letters indicate statistical significance between treatments. The p-value is 0.016.

4.4.2 Zinc

Results of the zinc uptake showed no significant differences between any of the treatments (p=0.430).

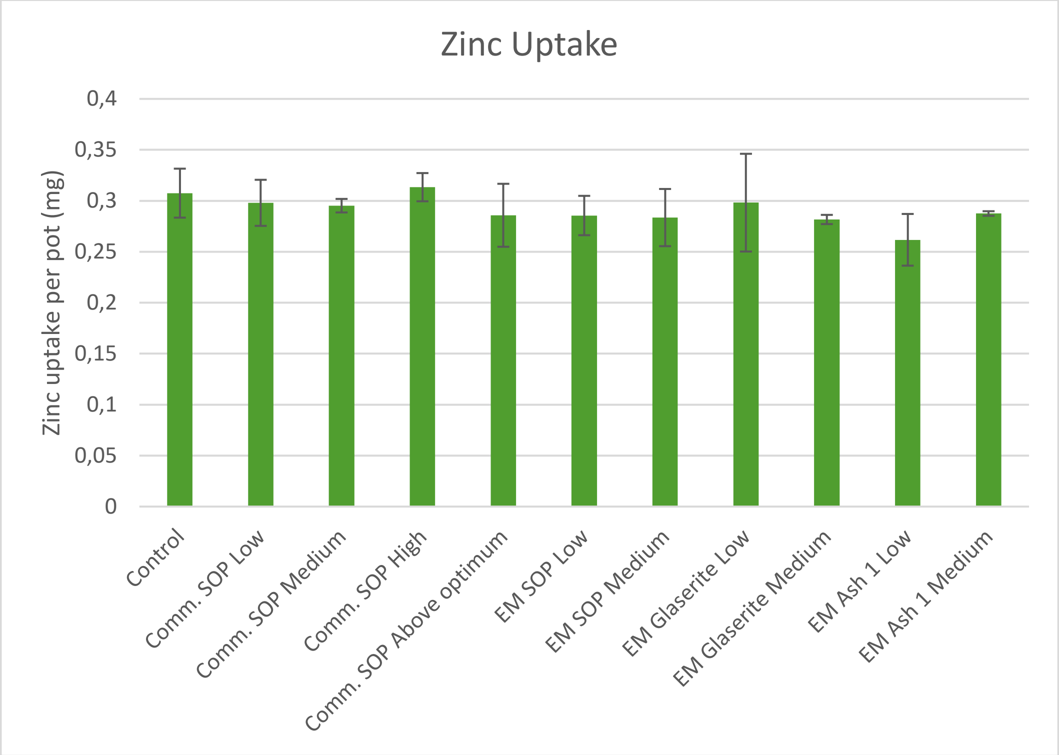


Figure 15: Calculated zinc uptake for each treatment. Error bars indicating standard deviation. The p-value is 0.430.

4.4.3 Copper

Results of the copper uptake showed no significant differences between any of the treatments (p=0.530).

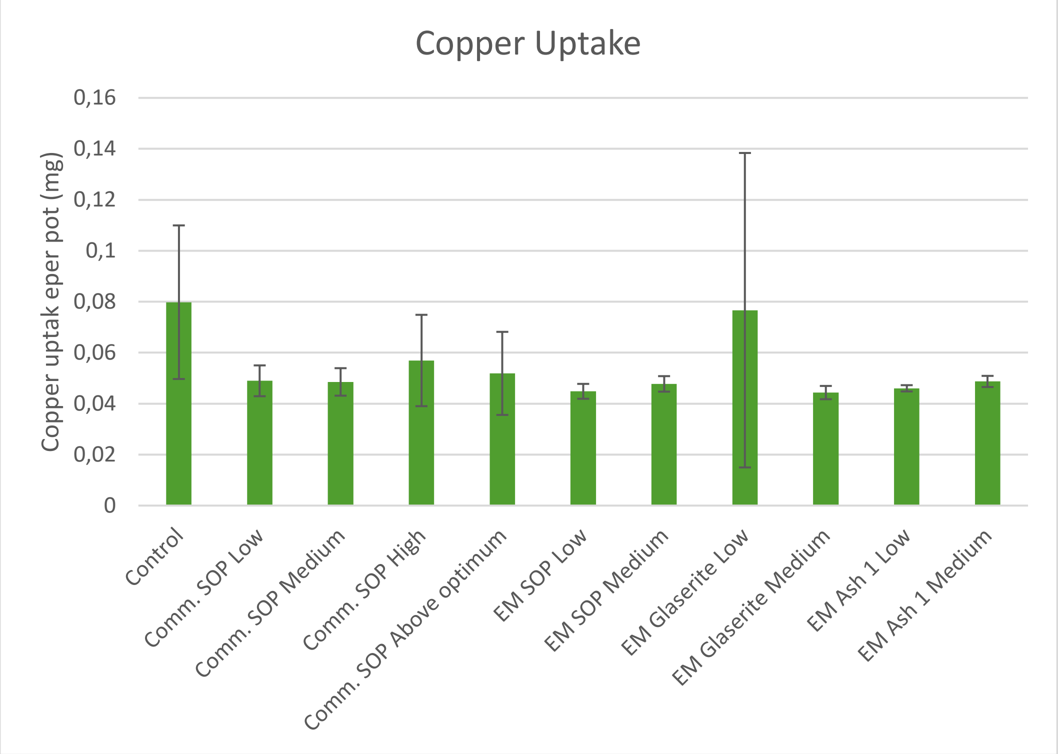


Figure 16: Calculated copper uptake for each treatment. Error bars indicating standard deviation. The p-value is 0.530.

4.5 Excluded pots

Five pots were excluded from the experiment due to mistakes when preparing the pots, as described in Table 5. All five pots remained in the experiment after a remedy to the suspected problem had been applied and was excluded when processing the data collected. This was to be able to evaluate the cause of the problem and its distribution in the experiment.

The four pots that received extra phosphorous fertilization after having shown growth impairment responded well to the fertilization and continued to grow for the entire period without showing any signs of deficiency. The growth impairment can therefore, with high probability, be attributed to missed phosphorous fertilizations. The cause of this was most likely settling of the fertilizer suspension, leading to lower levels of phosphorous in the top levels of the fluid, which were extracted with the pipette and mixed into the soil.

Figure 17: Pots 1.3 (left) and 1.2 (right). The right pot received extra potassium after a deficiency was suspected. The left pot received no special treatments.

Exclusion of these pots decreased the statistical foundation from the experiment, and therefore the potential to draw relevant conclusions. This was especially evident for the control treatments, where two of the four replicates were excluded.

Table 5: Excluded pots and explanation for exclusion.

Pot ID	Reason for exclusion	Cause of exclusion
1.2	Impaired growth	Missed P-fertilization
1.4	Impaired growth	Missed P-fertilization
6.1	Impaired growth	Missed P-fertilization
10.4	Impaired growth	Missed P-fertilization
11.1	Decreased growth period	Late seeding

5. Discussion

Adequate range of K-concentration in plant dry matter of fully developed leaves is 1.5-4% according to Bryson et al. 2014. Pinkerton et al. 2008 claim that the critical deficiency range (critical for 90% of maximum yield, without visible symptoms) is around 1.0–1.5%, and that the adequate range is around 2.5–3.5%. The results from the experiment shown in Figure 11indicate that the potassium concentration in the shoots are adequate (>1.5%), but on the lower side depending on the treatment. For the higher fertilization levels, K concentration is still in, or slightly below the adequate range, depending on source. This contradicts, albeit with some uncertainty, the potential that luxury consumption of K could have decreased uptake of other nutrients and thus limiting growth.

The results concerning the potassium uptake show that the highest level of fertilization used in this trial resulted in a slightly increased uptake, compared to all other treatments except for two. This mechanism is expected for all fertilization levels, although the results show no statistical evidence of this.

The calculated MFE values (Table 4) show varying results, for both the biomass and uptake-based calculations. Values show large variations for the same fertilizer in different doses, which indicate that the values are not reliable. The expected values of EM SOP are around 100%, as the SOP is chemically almost identical to the commercial alternative. The uptake-based calculations show big variance because of the weak correlation between fertilizer dose and uptake. The same applies for the biomass-based calculations, although these values have a smaller variance.

Part of the study was to examine the fertilizer effect on the uptake of heavy metals. In this perspective it's interesting to compare the ash to the EM SOP and the glaserite. This gives and insight into how well EasyMining's process removes heavy metals. For cadmium, we have a significant difference in uptake between both ashes and the medium glaserite treatments. This is reasonable, as the high cadmium content in the ash is removed in the process before the formation of glaserite. It is safe to assume that with better data, the same conclusion could be drawn for the low glaserite, as well as for both levels of EM SOP.

Zinc and copper uptake shown no significant differences between the treatments. There are several potential reasons behind this. The zinc and copper contents could be the same in both fertilizers and the ashes, but in that case a difference in uptake should be visible for the different fertilization levels. The uptake could also be limited due to low concentrations in the soil, or high specificity in the plant uptake. From the gathered data, the only conclusion that can be drawn is that the none of the fertilizers or level of fertilization tested affects the uptake of zinc or copper in the tested crop.

The main purpose of this study was to, from an agronomic viewpoint, investigate EasyMining's potassium sulphate that was created in their new process. The pot trial resulted in data that is ambiguous and difficult to draw any statistically significant conclusions from regarding the fertilizers efficacy. Of the three tested fertilizers, not one differed from the control in terms of biomass yield, potassium uptake or potassium concentration This leads to the conclusion that there was a fundamental flaw in the experiment setup, or execution.

The data showed quite large standard deviations, with many treatments having data outliers. This could originate in in uneven growing conditions, fertilization, soil heterogeneity or plant stress. The exact cause is difficult to decide, and numerous factors acting individually or in combination could be the cause.

A main problem the data is that the control treatments show no difference in growth or uptake compared to the treatments that was fertilized. This means that potassium has not been the limiting factor for growths in any of the treatments. This is probably caused by the potassium delivery from the growing substrate used. The sand is an unlikely culprit, but the biological breakdown of the peat that was added for water retention purposes have probably delivered higher amounts of potassium than expected. Potassium uptake varied from 171-203 mg/kg for the tested fertilizer treatments (treatments 7-11). Comparison with the amount of potassium that was added with the experimental fertilizers (35-71 mg, from Table 3), indicates that the fertilizer levels are reasonable and that the experiment would probably have given an improved outcome if the soil delivery of potassium was lowered significantly. A wider interval in fertilizer levels could potentially have been beneficial, as this increased the chance of seeing differences in yield and uptake levels. Expanding the scope of the experiment to include several harvests could have been beneficial, as this could remove some potassium from the pots.

To further evaluate the efficacy of the tested fertilizers, a new pot trial is recommended. A valuable lesson learned from this experiment is to use a growing substrate with lower potassium delivery potential than what was used. Determination of soil K-availability using soil testing would also have been beneficial, although time consuming. Fertilizing and seeding should also be done following a stricter procedure to eliminate the risk of mistakes, leading to exclusion of pots.

6. Conclusion

The pot trial failed to provide insight into the study's primary purpose, to evaluate the EM SOP's agronomic performance compared to a commercial alternative. This was due to too high levels of potassium being available in the soil, which lead to inconclusive results. The study provided some insight into the secondary purpose, to evaluate if the fertilizers had any unwanted effect on the plant's uptake of heavy metals. A significant increase in cadmium uptake was measured for the treatments fertilized with ash compared to the treatments fertilized with 40 kg K/ha of glaserite. A follow up study is recommended, to be able to properly evaluate the fertilisers from all the initially stated perspectives.

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