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Editorial

Dear readers,

To mathematicians, 70 is what is known as an abundant number, because the sum of its proper divisors (numbers that 70 can be divided) is 74, in other words greater than itself.

Why mention that here? In 2022, IPI celebrates our 70th anniversary. Perhaps you could say that if you measure IPI at 70 what we achieve together is greater than the work what we as individuals do.

Throughout the last seven decades, we have contributed to commissioning and sharing research into combinations, quantity, and availability of essential plant nutrients. The numbers of studies we have published now totals in the region of 2000.

IPI has worked in over 30 countries and with more than 45 crops.

This edition of *e-ifc* is no exception to our standards or style. Here you can read about the positive results of using potash to boost soybean productivity in two states of India where the crop is of great significance to the local agri-economy. We also include a report which reviews the evidence on how the use of polyhalite fertilizer, and the four key macronutrients it contains, consistently shows potential to improve yield, health, and quality of a wide range of crops.

All this work since 1952, all the findings, all the professionals we have shared with, all the farmers and growers reached, all the positive changes made, all the crop yields and quality improved and incomes and diets enhanced – this multiplies up to a remarkable legacy.

Like the abundant number seventy, IPI carries on with our work modestly and methodically to bring benefits in abundance to farming all around the world. That is certainly something to celebrate with you on our IPI 70th Anniversary.

Stay safe!

Dr. Patricia Imas
IPI Scientific and Communications Coordinator

Photo cover page: Vineyard in Israel. Photo by P. Imas.

Research Findings

Photo 1. Soybean production in India.

Assessing the Impact of Potash Fertilization on Soybean Production in India

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Abstract

Agriculture is the primary source of livelihood for nearly 60% of the India's population, a number that rises to 70% of the Indian population in rural areas. To meet the demand for food, farmers mostly engage in intensive cultivation which often results in nutrient mining which leads to a decline in the quality of soil. Declining quality of soil often results in reduced soil fertility and ultimately to poor production. Importantly, continuous nutrient exploitation without proper strategies for nutrient replenishment is a scenario that takes a long time to reverse.

This study aimed to assess the impact of potassium (K) depletion on soybean production by evaluating and demonstrating the important contribution of K application from K-inclusive fertilization regimes to increasing soybean yield and profitability. To evaluate soybean's K response when fertilizing with potash on K-depleted soils, a comprehensive experiment was carried out in Madhya Pradesh (M.P.) and Maharashtra states in India; 129 and 15 pairwise demonstration plot trials were set up in Madhya Pradesh and Maharashtra states, respectively. Two identical plots were laid side by side, one of which

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was fertilized with additional potash fertilizer. The results showed a significant yield increase from the potash application; the average yield increase was 244 kg ha^{-1} or 26% in M.P., and 105 kg ha^{-1} or 36% in Maharashtra. This produced an average additional net profit of 6,681 INR ha^{-1} and 2,544 INR ha^{-1} in M.P. and Maharashtra, respectively. It was concluded that the plant available K in the soil is significantly lower than the plant demand for soybean production in the two states. The K dose employed in the present study can be recommended to soybean farmers in the short-term as a transient means to obtain higher yields and profits. Further research is however recommended to determine appropriate K doses and application practices to ensure balanced crop nutrition and efficient fertilizer use for optimal yields.

Keywords: Soybean, potassium, nutrient mining, nutrient depletion, potash, MOP

Introduction

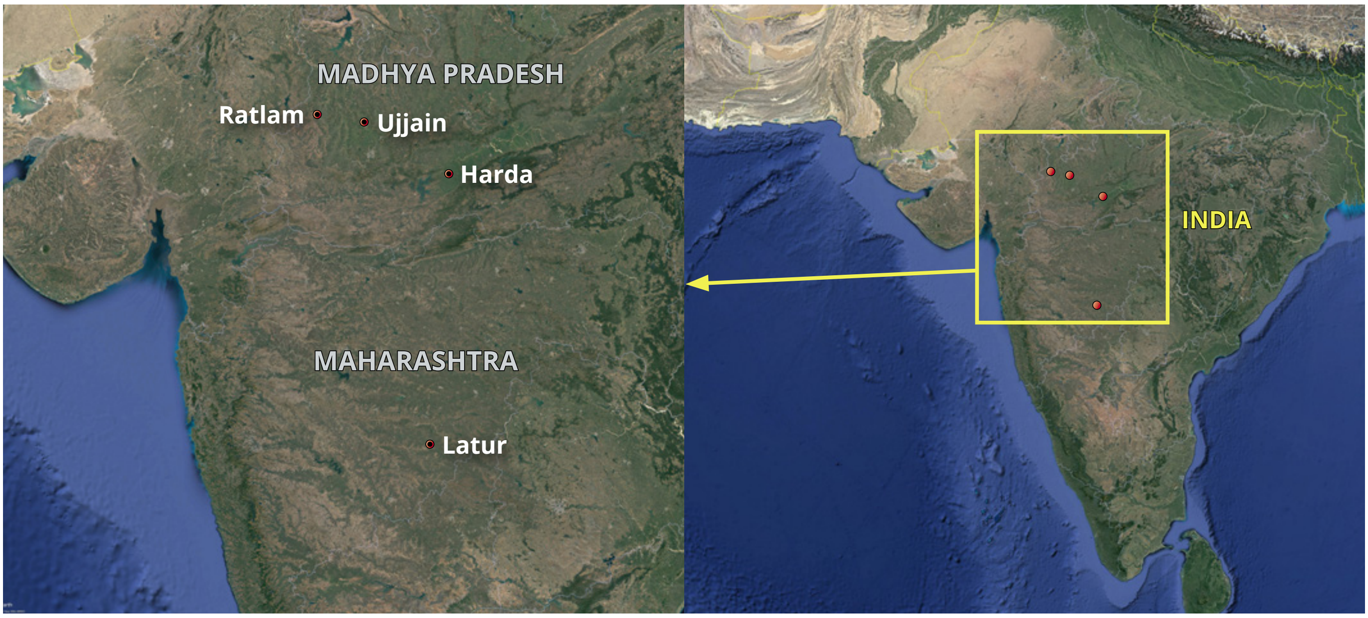
Soil forms the basis for any crop production activity. However, declining soil fertility is one of the primary factors that directly affect crop productivity. Management of soil fertility is important for the maintenance of sustainable productivity and nutritional security (Prasad and Power, 1997). Fertilizers are important in ensuring soil fertility, productivity, and long-term profitability if used accordingly (FAO, 2005). Imbalanced and incorrect use of fertilizers afflicts nutrient use efficiency and leads to deterioration in soil quality (Wallace, 2008).

Soybean (*Glycine max*) is a major source of vegetable oil, protein, and animal feed. Across India. It is a Kharif crop mostly grown in Madhya Pradesh and Maharashtra, but also in other states. India produces approximately 12 million metric tons of soybeans annually but unreliable rainfall, inadequate irrigation, outdated fertilizer practices, and imbalanced crop nutrition have, in specific instances, resulted in low yields (Chand, 2007; Sharma *et al.*, 1996; Tiwari, 2001).

Soybean requires considerable amounts of potassium for improved yields and quality. In India, soybean farmers use nitrogen and phosphorus fertilizers but not potassium and sulfur (Bhatnagar and Joshi, 1999). The practice of omitting K from the regular fertilization is common and has been a standard practice in the past few decades, especially in soils that are, by definition, classified as "K-rich soils". However, even K-rich soils can be depleted after years of intensive agricultural production. Many studies in the past have shown the importance of potassium in soybean production (Pettigrew, 2008; Yin and Vyn, 2003; Bhangoo and Albritton, 1972). However, it is well known that results from highly controlled studies do not necessarily translate into direct recommendations, especially in smallholder agriculture with sub-optimal practices overall, and where the producers have relatively low investment capacity. This study aims to report a positive soybean response to applied K in vertisols

Table 1. Soil conditions.

pH	5.1
$CaCO_3$	0%
Sand	58%
Clay	18%
Silt	24%



Map 1. Map of the study sites in India. Source: Google Earth.

in India, which are considered to be rich in potassium (Singh and Wanjari, 2012; Dwivedi *et al.*, 2007; Chen *et al.*, 2000).

The objective of this study is to evaluate the response of soybean to potash (MOP, KCl) application and to raise awareness among smallholder farmers of the importance of K fertilization in soybean production.

Materials and methods

The study was carried out in India in the states of Madhya Pradesh (M.P.) and Maharashtra. The trials were conducted in farmer fields in five different districts: Harda (9 plots), Mandsaur (47 plots), Ratlam (38 plots), Ujjain (35 plots), and Latur (15 plots) (Map 1).

Each study site consisted of two plots (0.4 ha each) laying side by side, one for each treatment. In Maharashtra, all plots were irrigated 1-3 times during the season, while in M.P. only plots in the district of Harda were irrigated. The improved soybean varieties recommended for each of the areas were used and all recommended agronomic practices were followed.

The study consisted of 2 treatments (Table 2) at each site:

- Treatment 1 (T1): common fertilizer practices where urea, DAP, and manure were applied, and
- Treatment 2 (T2): included MOP in addition to the common practice.

However, the local fertilizer practices varied between the districts as well as the states: the fertilizer regime was more extensive in M.P. compared to that of Maharashtra, not only in terms of NPK-dosage, but also in that farmyard manure (FYM) was only utilized in the state of Maharashtra. The dose of FYM was not researcher-managed in this study and was based on the availability of manure and farmers' usual practices. This way, the present study is able to evaluate if MOP application is beneficial without optimization of manure application, and regardless of farmer's current manure practices.

The statistical analysis was performed using pairwise T-tests (paired two samples for the mean). Additionally, ANOVA-test was used when comparing more than two groups or statistical populations. When comparing only two groups or statistical populations, another kind of T-test was used, as they had different sample sizes (two-sample assuming unequal variance). Linear regression was performed to understand the relationship between two variables. In all tests the confidence level of 0.95.

Results

The average yield of the plots which used MOP was higher than that of the plots which did not use MOP (Fig. 1). The average yield of the control plots with no MOP was 880.6 kg ha^{-1} with a standard error of 27.8. Soybean plants responded to the use of MOP with an average yield of 113.3 kg ha^{-1} and a standard error of 34.8. Through statistical tests, it was confirmed that the difference between the average control yield and average +K yield of 232.7 kg ha^{-1} was significant. It can therefore be concluded that use of MOP had a considerable and verifiable effect on average soybean yield.

Average soybean yields in the control and +K plots differed between the two states (Fig. 2). The average yield of the control plots in Maharashtra was 298.7 kg ha^{-1}, while in Madhya Pradesh it was 950.5 kg ha^{-1}. In the +K plots with MOP, these increased to 403.3 kg ha^{-1} and 1,198.5 kg ha^{-1} for Maharashtra and Madhya Pradesh, respectively.

Table 2. Fertilizer treatment in the soybean demo plot trials in Madhya Pradesh and Maharashtra.

District	Treatment	Fertilizer source			
		N from urea + DAP	P_2O_5 from DAP	K_2O from MOP	FYM [b]
		----------------------*kg ha^{-1}*----------------------			*t ha^{-1}*
Harda district	-K (T1)	50	60	0	
	+K (T2)	50	60	40	
Other districts [a]	-K (T1)	25	60	0	
	+K (T2)	25	60	75	
Maharashtra	-K (T1)	50	75	0	1-3
	+K (T2)	50	75	50	1-3

Comparison of the T1 and T2 treatments with regards to +K or -K in the fertilizer regime.
[a] The three districts of Mandsaur, Ratlam, and Ujjain.
[b] FYM (Farmyard manure) was derived from different kinds of domesticated animals depending on location and production. While the dose varied between the farms under this study, the dose and procedure were the same between each treatment and control plot.

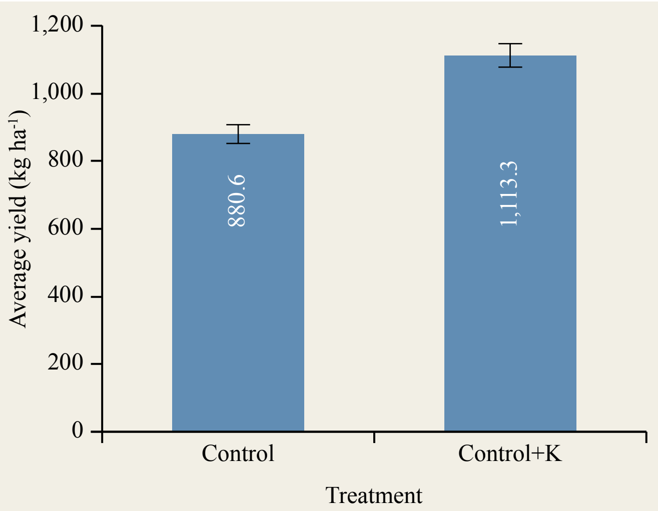


Fig. 1. Average soybean yield with and without MOP across all trials.

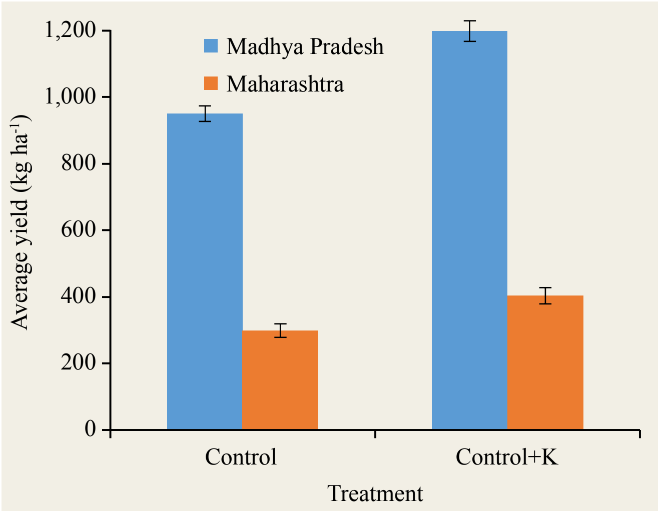


Fig. 2. Average soybean yield by treatment and state.

Fig. 3. All trial yield increases in order of magnitude and by state.

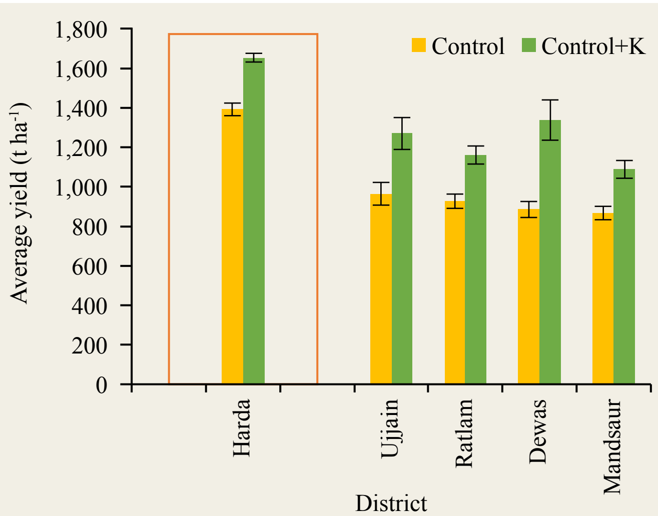


Fig. 4. Soybean average yield by treatment and district (Madhya Pradesh).

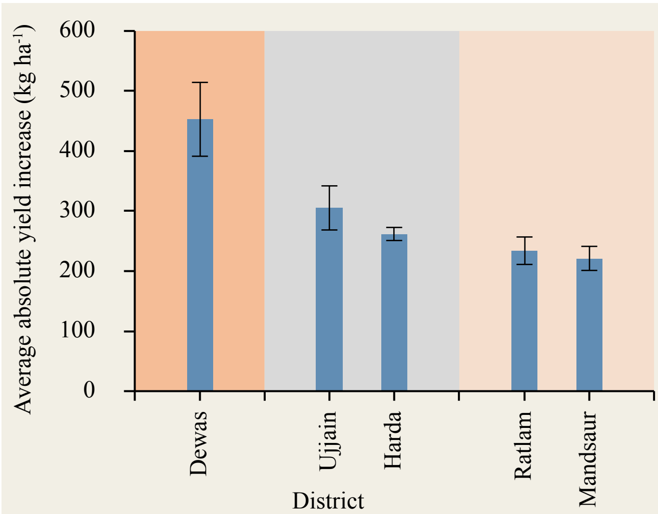


Fig. 5. Soybean average absolute yield increases by district (Madhya Pradesh).

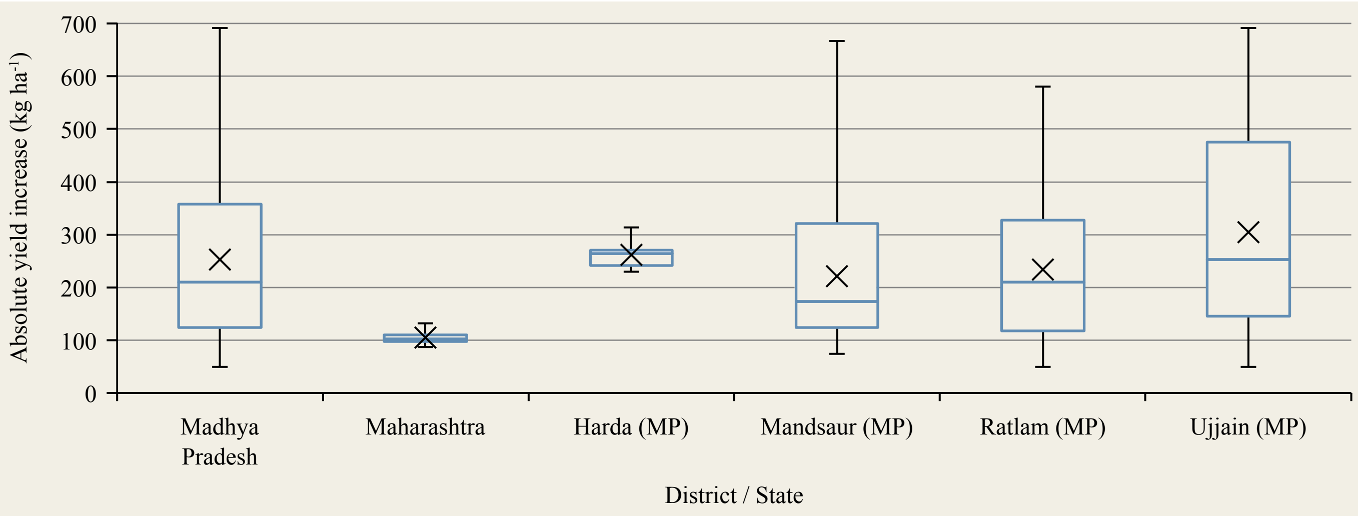


Fig. 6. Absolute yield increase distributions by district and state.

The differences in average yields by state extended to the average absolute yield increases in the two respective states (Fig. 3). The average absolute yield increase in Madhya Pradesh was 248.1 kg ha^{-1}, and in Maharashtra 104.7 kg ha^{-1}. The significance of this difference was confirmed with statistical tests leading to the conclusion that the effects of MOP were more profound in Madhya Pradesh than in Maharashtra. The trend in the difference between average absolute yield increase by state corresponded to the trend in the difference between average yield in the control plots, with a higher average absolute yield increase in Madhya Pradesh corresponding with a higher average yield in the control plots.

The average control and +K yields were highest in the district of Harda in Madhya Pradesh (Fig. 4). The average control yield in Harda was 1,392.0 kg ha^{-1}, and the average +K yield was 1,653.8 kg ha^{-1}. The differences between these average yields and their counterparts in other districts were statistically significant and were the only average yields to be so as a function of district.

Use of MOP had a beneficial impact on average yield across all districts of Madhya Pradesh, with statistical tests finding that the differences between average yields in control and +K treatments as a function of district were significant in all cases. Fig. 5 shows the range of average absolute yield increases as a function of district in Madhya Pradesh. The values ranged from 221.2 kg ha^{-1} in the district of Mandsaur up to 452.8 kg ha^{-1} in Dewas. The Dewas average was statistically higher than those of the two lowest average absolute yield increases (Ratlam and Mandsaur); the two lowest also being statistically the same.

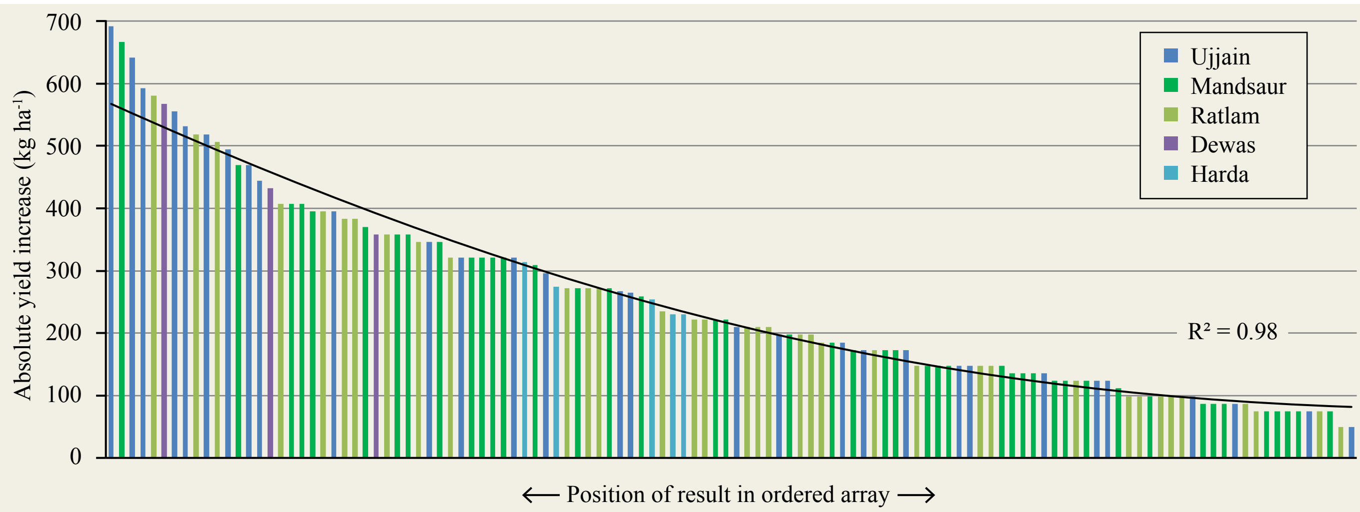


Fig. 7. Soybean absolute yield increase distribution by district in Madhya Pradesh.

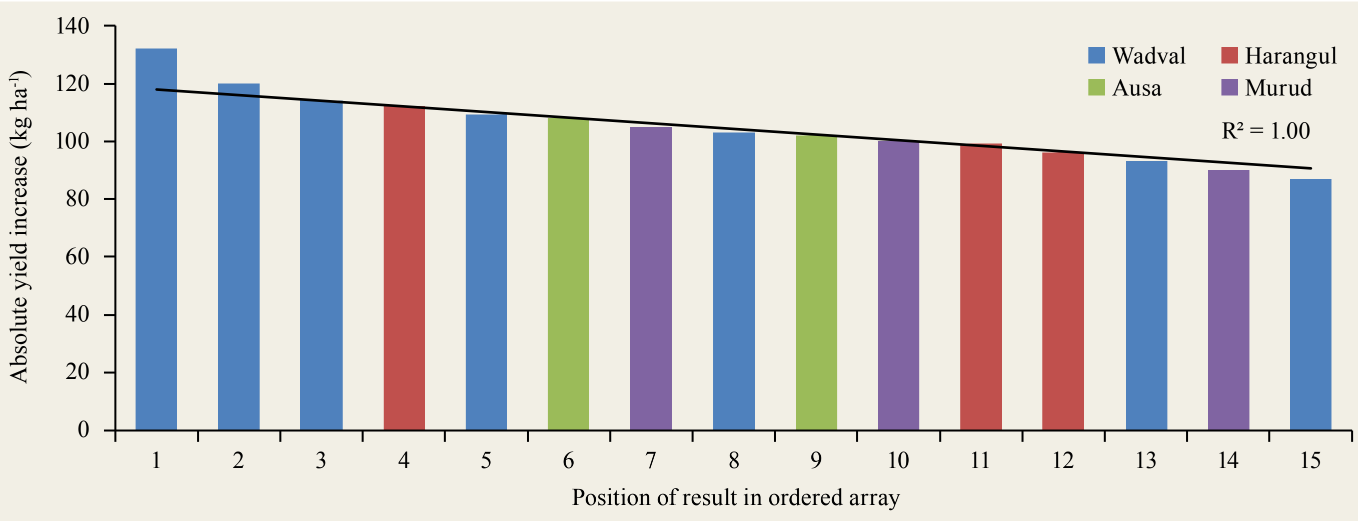


Fig. 8. Soybean absolute yield increase distribution by village in Maharashtra.

The distribution of absolute yield increases differed across the districts of Mandsaur, Ratlam, and Ujjain (Fig. 6). In Mandsaur, the minimum and maximum values were 74.1 kg ha^{-1} and 666.9 kg ha^{-1} respectively, giving a range of 592.8 kg ha^{-1}. In Ratlam and Ujjain, these ranges were 531.1 kg ha^{-1} and 642.2 kg ha^{-1}, respectively. In Harda, the range was much smaller (84.0 kg ha^{-1}). Ujjain had the highest maximum absolute yield increase, as well as the highest upper quartile, giving the district the highest mean and the highest response distribution.

There were differences in absolute yield increase data distributions between the states. In Madhya Pradesh, the data followed a linear distribution except for the highest and lowest responses (Fig. 7). Across the data set as a whole, the distribution followed a 2nd order polynomial, suggesting that two factors influenced the performance of MOP measured in absolute terms. In Maharashtra the distribution was different; it was uniform, with only a slight distribution slope (Fig. 8), which is also illustrated by the close proximity of the whole boxplot distribution to the average value, as well as the absence of outliers (Fig. 6). The distribution also followed a linear pattern suggestive of a single factor influencing MOP measured in absolute terms.

The average soybean control yield was highest in 2014 at 1,078.7 kg ha^{-1} and lowest in 2015 at 851.5 kg ha^{-1} (Fig. 9). The average control yields from 2015 and 2016 were statistically the same. The use of MOP had a beneficial impact on average yields across all years in Madhya Pradesh, with statistical tests finding that

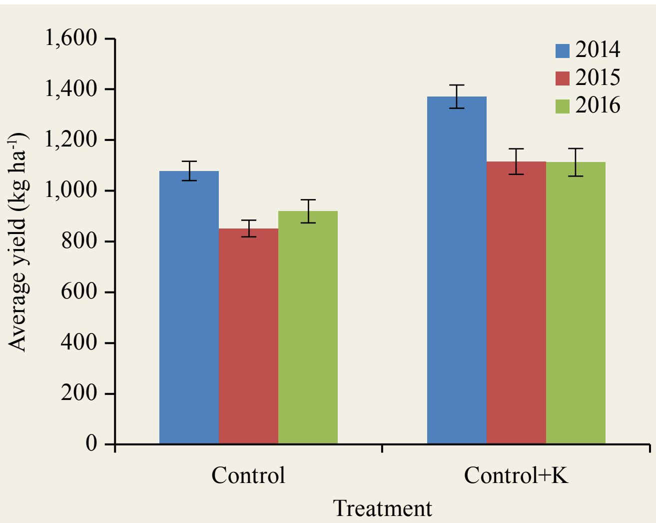


Fig. 9. Soybean average yield by treatment and year (Madhya Pradesh).

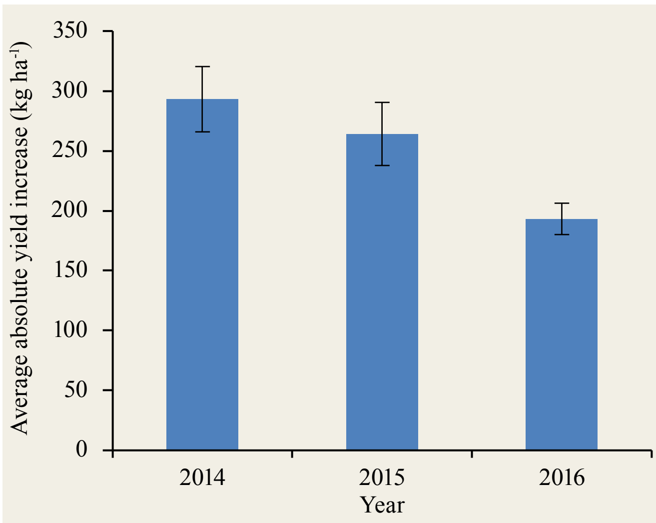


Fig. 10. Soybean average absolute yield increases by year (Madhya Pradesh).

Table 3. Cost benefit analysis.

	Madhya Pradesh	Maharashtra	Unit
Increase	26.5	36.4	%
Price of product	27.5-35.0	32	INR kg^{-1}
Yield increase	248.1	104.7	kg ha^{-1}
Profit increase	7,896.0	3,349.3	INR ha^{-1}
Cost of MOP	1,216.8	800.0	INR ha^{-1}
Net profit	6,679.3	2,549.3	INR ha^{-1}
B:C ratio	5.9:1	3.2	

the differences between average control and average +K yields as a function of year were significant in all cases. However, there was variation in the extent to which MOP increased average yields (Fig. 10). The average absolute yield increases of 2014 were statistically the same, but both were higher than that of 2016. This correlated, to some extent, with average control yields by year.

In Maharashtra, absolute yield increase was directly proportional to control yield in all trials, with an R^2 value of 1.00 where 1.00 equals a direct and exact correlation (Fig. 11). This meant that MOP performance measured in absolute terms was highest in trials where yields in control plots were highest. Conversely, relative yield increase was inversely correlated to control yield using a 2nd order polynomial fit. This meant that in relative terms, MOP performance was less pronounced in trials with higher control yields. The presence of a 2nd order fit corresponds to the role of both varying control yield and varying absolute yield increase in the calculation of relative yield increase. This also means that at very high control yields, use of MOP will reach a maximum in its effects when measured in relative terms (at 27.5%).

Additional net profit of 7,896.0 INR ha^{-1} and 3,349.3 INR ha^{-1} were recorded in Madhya Pradesh and Maharashtra, respectively (Table 3). This was as a function of average yield increases of 248.1 and 104.7 kg ha^{-1} respectively. This corresponded to an average benefit cost ratio of 5.9:1 and 3.2:1 as a function of local MOP input costs of 1,216.8 INR ha^{-1} and 800.0 INR ha^{-1} based on local and up-to-date market prices of crop product.

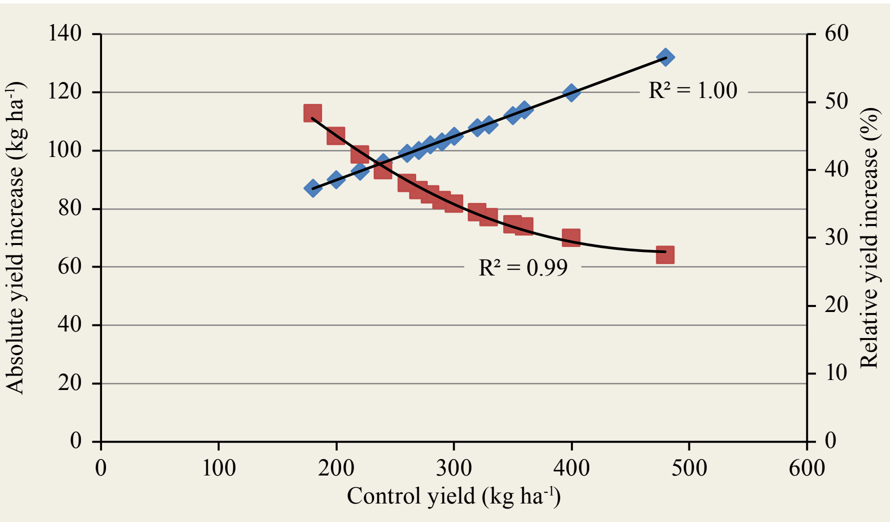


Fig. 11. Relationships between control yield and MOP performance (Maharashtra).

Discussion

The results unequivocally show that soybean yield was significantly increased by potassium application when compared to the control treatment. Results clearly demonstrate the potential for increasing soybean yields in this region by augmenting existing fertilizer regimes with MOP.

The results have also shown variability in the response to MOP by location. For example, the average MOP response in Maharashtra (104.7 kg ha^{-1}) was much lower than that of Madhya Pradesh (248.1 kg ha^{-1}), and the difference was statistically significant. Notably, the average control yield in Maharashtra (298.7 kg ha^{-1}) was also considerably lower than that of Madhya Pradesh (950.5 kg ha^{-1}), a difference which is statistically significant. The trend in the average MOP response by state therefore followed that of the average control yields.

Soil characteristics in the trial areas in the two states studied are very similar. The soil type is the same across the region, and as are other characteristics including sand:clay ratio and pH. The stark differences in average control yields and average MOP response cannot therefore be explained by examining the differences in these factors. The main notable difference, with respect to the conditions between the states, is growth period. All trials in Madhya Pradesh were planted and harvested between June and October respectively. This is the recommended growth period for soybean in this region, with the optimal sowing dates being the last two weeks of June and the ideal harvest date being before the end of October. It is also the period which receives the annual monsoon rains in July. In Maharashtra, trials were planted in mid-August and harvested in mid-November. As a result, rainfall was minimal to the extent that seven out of 10 trials were affected by drought. It is known that soybean yields fall the later in the season the plants are sown and harvested (Nath *et al.*, 2017). This is owing to the less favourable climatic conditions typical of the latter part of the season. This research has confirmed this and has also shown that this dynamic limits the extent to which MOP can increase soybean yields.

Average control yields and MOP performance also varied between districts within Madhya Pradesh. Spatial factors relating to soil did not vary between any of these districts. The statistical tests found that the average control yield of only one district (Harda) was different to those of the other districts. Two factors differed between the trials in Harda and those of all other districts except Hoshangabad. These factors were application of one irrigation, and nitrogen dosing rate. In Harda and Hoshangabad plots received one irrigation, whilst in all other districts plots were rainfed only. Likewise, in Harda and Hoshangabad the nitrogen dosing rate was 50 kg ha^{-1} in all trials whilst in all other districts in Madhya Pradesh the dosing rate was 25 kg ha^{-1}.

Climatic factors such as rainfall and temperature were comparable across the trials. Notably, the average control yields of the two trials in Hoshangabad were very high compared to the study average (1,470 kg ha^{-1} versus 950.5 kg ha^{-1}). These higher control yields in Harda and Hoshangabad could therefore be due either to irrigation, higher nitrogen dosing rate or both. It was confirmed through tests that the difference between the average control yield of the trials in Harda and Hoshangabad and that of other districts was significant.

It is possible to explore the effects of irrigation by examining the trials in Maharashtra. In these trials, all plots received irrigation. The number of irrigations in Maharashtra varied between one and three. Applying irrigation in crop production is expected to have a significant impact on crop yields (Adebayo *et al.*, 2018). However, the statistical tests found that the number of irrigations did not influence control yield (or MOP performance). Furthermore, the average yield in Maharashtra was sizably lower than that of Madhya Pradesh where only 7% of trials received irrigation. This leads to the conclusion that the higher average control yield in Harda (and Hoshangabad) was due to a doubling of the nitrogen dosing rate from 25 to 50 kg ha^{-1}. This same higher dosing rate was also used in all trials of Maharashtra. However, the later planting of the crops in Maharashtra may have precluded full use of the extra nitrogen applied.

Unlike the differences in MOP performance by state, the differences in MOP performance by district within Madhya Pradesh did not correspond with the differences in average control yields. The only average control yield by district in Madhya Pradesh shown to be statistically higher than those of other districts was that of Dewas. This shows that irrespective of factors such as nitrogen dosing rate and its influence on control yields, in certain instances there is an extremely high response to the use of MOP. This has not been linked to control yields within Madhya Pradesh. Given the similarity in conditions within Madhya Pradesh (i.e., soil type, growth period, rainfall, and temperature), it leads to the conclusion that another factor is behind the variability in MOP response within Madhya Pradesh. It is known that levels of K in soils in India vary considerably between different parts of the country (Hasan, 2002). Such variations in MOP response amidst similarity in other key factors leads to the conclusion that availability of K in the soils varies considerably between the parts of Madhya Pradesh included in this study.

In the year the trials took place in Dewas, very heavy rainfall preceded the planting season (rainfall departures of +1,500% in April of 2015). High rainfall preceding the planting season could therefore have provided the soil moisture necessary for better MOP performance, by lifting limits to growth and facilitating full use of K from the addition of MOP. Observing absolute yield increases as a function of both year and district, there is a clear correlation between heavy rainfall in excess of that expected (i.e., rainfall departures) and MOP performance. Soil condition – particularly soil moisture – may therefore also play a role in MOP performance, as well as natural availability of K in soils. The role of two factors in MOP performance would also align with the absolute yield increase distributions from Fig. 7. The distribution followed a 2nd order polynomial rather than a linear regression, indicating that more than one factor influenced MOP performance within Madhya Pradesh.

It was found that both average control yields and average absolute yield increases differed as a function of year. Observing rainfall patterns during the growing season (i.e., June to October) it is clear that the optimum control yields were achieved when average monthly rainfall was closest to the ideal amount of rainfall recommended for soybean growing in this region (80 cm of rainfall per month). This was also the year when MOP performance was highest (2014). This leads to the conclusion that MOP is most effective when rainfall is adequate but not excessive.

Average absolute yield increases as a function of cultivar were linearly proportional to average T1 (control) yields. This means that cultivars which offer higher T1 yields will result in greater yield increases for the same amount of MOP. Use of cultivar is a poignant topic within soybean production in India, with members of the sector asserting that the time for adopting new cultivars with higher yields is long overdue (Pushpendra *et al.*, 2017). It is frequently asserted that widely used cultivars such as JS-335 should be replaced by newer, better cultivars (Pathak, 2017). This work shows that the beneficial effects of MOP on yields will likely be higher on newer, higher yielding cultivars. This puts use of MOP in a unique position to ensure high yields are achieved if and when the industry transitions towards newer cultivars.

In conclusion, application of MOP increased yield and profitability. The positive response of potassium application to soybean yield is attributed mostly to the low potassium levels in the soils rather than the secondary factors such as manure and irrigation which had very minor effect in attaining increased yields. Fertilizers that are K inclusive are important in the optimization of yields and the maximization of profit. Therefore, K doses employed in this study should be recommended to farmers for use in these states. Further research is also recommended to determine appropriate MOP doses and application practices to ensure balanced crop nutrition, optimal fertilizer use, sufficient K availability whenever needed, and sustainable soil fertility.

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The paper "Assessing the Impact of Potash Fertilization on Soybean Production in India" also appears on the IPI website.

Research Findings

Photo 1. Polyhalite, mined at the Boulby mine, UK, is a natural mineral formed by evaporation from the seas, shown in its original composition. Photo: ICL, UK.

Fertilization Efficiency with Polyhalite Mineral: A Multi-Nutrient Fertilizer

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Abstract

As the world's population approaches eight billion people, there is an increasing demand for cereals, grains, vegetables, animal protein, as well as energy. At the same time, in the shadow of the COVID-19 pandemic, world hunger has increased. After remaining virtually unchanged for five years, the prevalence of malnutrition (PoU) increased from 8.4% to about 9.9% in just one year, further adding to the challenge of achieving the Zero Hunger target by 2030.

To sustainably increase agriculture productivity, the use of best plant nutrition practices is essential. The shortage of any one nutrient has the potential to limit the growth, productivity, and quality of crops,

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as stated in Justus von Liebig's "Law of the Minimum". In addition to nitrogen (N), phosphorus (P), and potassium (K), attention must be paid to other macronutrients including calcium (Ca), magnesium (Mg), and sulfur (S), and to the management of micronutrients as well. Balanced fertilization is essential to obtain the maximum potential for crop yield.

Since 2015 a new natural mineral fertilizer, polyhalite, has stood out as an alternative fertilizer. Polyhalite provides four macronutrients in a single granule: K, Ca, Mg, and S. Polyhalite has several differential characteristics, such as a low salt content and prolonged availability of nutrients. Polyhalite has a lower carbon footprint than similar fertilizers and can be used in organic production systems.

Reviewing the research into the use of polyhalite as a sustainable multi-nutrient fertilizer consistently reveals its potential to increase agricultural productivity, where it consistently and significantly improves the yield, health, and quality of a wide range of crops.

Keywords: polyhalite, fertilizer, balanced nutrition, multi-nutrient, macronutrient, micronutrient, organic

Introduction

The world population is expected to reach eight billion people later this year, increasing demand for food, including cereals, grains, vegetables, and animal protein, as well as increasing demand for energy. World hunger increased in 2020 under the shadow of the COVID-19 pandemic. After remaining virtually unchanged for five years, the prevalence of malnutrition (PoU) grew from 8.4% to about 9.9% in just one year, further increasing the challenge of achieving the Zero Hunger target by 2030 (FAO, 2021).

Food production is basically dependent on agriculture, so the need to adopt correct management within production systems is gaining in importance, as producers aim at increasing agricultural production, without threatening environmental sustainability. The challenge is to increase productivity, producing more food while only minimally altering with the size of the cultivated area. Within this scenario, the use of best practices aimed at adequate plant nutrition is essential for success, and care must be taken to ensure plants have access to adequate amounts of all the nutrients required by each cultivated species. Individual nutrient's requirements are related to each other, and the shortage of any one of them has the potential to limit the growth, productivity, and quality of crops, as stated in Justus von Liebig's "Law of the Minimum" (Browne, 1942). This means that, in addition to nitrogen (N), phosphorus (P), and potassium (K), attention should be paid to other macronutrients including calcium (Ca), magnesium (Mg), and sulfur (S), and to the management of micronutrients as well. Balanced fertilization is essential to obtain the maximum potential for crop yield.

Despite the existence of K in most rocks and soils, the economic sources of K are associated with sedimentary evaporitic deposits in chloride and sulfate forms. Few K minerals are used in the production of potassium fertilizers, with sylvinite and carnallite being the most common in the production of the most abundant source of the potassium, muriate of potash (KCl). Deposits of these minerals were formed millions of years ago by the evaporation of saline waters in restricted basins which generated minerals concentrated at depths ranging from 300 m to more than 2,500 m in some parts of the world. Fertilizers can also be extracted from deposits in lakes with high saline concentration. Israel and Jordan produce KCl through evaporation of water from the Dead Sea (Roberts, 2005).

In addition to KCl, other sources of the nutrient have been used in recent decades, mainly potassium sulfate (K_2SO_4), double potassium, and magnesium sulfate obtained from the mineral langbeinite ($K_2SO_4 \cdot 2MgSO_4$) and potassium nitrate (KNO_3) (Table 1, adapted from Agrolink, 2022).

Brazil is the fourth largest consumer of fertilizers in the world, accounting for 7% of the volume, behind China, USA, and India (Saab and Paula, 2008). It is estimated that Brazil's consumption of fertilizers exceeded 42 million tons in 2021, with more than 11 million tons being KCl making Brazil the second largest consumer of potassium, third of phosphorus and fourth of nitrogen (Oliveira *et al.*, 2019).

Since 2015 a new mineral, polyhalite, has stood out as an alternative and complementary source for potassium fertilization providing four macronutrients in a single granule: K, Ca, Mg, and S. Polyhalite has several differential characteristics, such as a low salt content and the nutrients' prolonged availability. It has proven to be a source with high potential for sustainable management of the main crops' nutritional balance, allowing higher yield, health, and quality (Vale and Sério, 2017).

Table 1. Potassium mineral fertilizers.

Fertilizer	N	K_2O	S	Mg	Cl
Muriate of potash		58-62%			47%
Potassium sulfate		48-53%	15-19%		
Langbeinite		21-22%	20-22%	10-11%	
Potassium nitrate	12%	44-46%			

Adapted from Agrolink, 2022

Photo 2. Boulby mine, located in Yorkshire, UK is the only commercial polyhalite mine currently in operation. Photo: ICL, UK.

Map 1. Location of the ICL mine at Boulby, UK. Source: Google Earth.

Formation and extraction of the polyhalite mineral

Polyhalite is a dihydrated potassium, calcium, and magnesium sulfate ($K_2Ca_2Mg(SO_4)_4 \cdot 2H_2O$). It is a natural mineral produced by successive marine evaporation events throughout history (Kemp *et al.*, 2016) and it has great potential as a potassium fertilizer with low chlorine (Cl) content, while being rich in K, Ca, Mg, and S (Ogorodova *et al.*, 2016; Albadarin *et al.*, 2017). Polyhalite is widely formed as a constituent of marine evaporates, associated with halite (NaCl) and anhydrite ($CaSO_4$) (Barbier *et al.*, 2017).

Polyhalite deposits exist in several places in the world, being initially found in Austria and described by Stromeyer (1818), and later found in other areas of Europe. The main deposits of the mineral were recorded decades later in Texas and New Mexico, USA (Schaller and Henderson, 1932), then in Russia (Kurnakov *et al.*, 1937), and finally in Zechstein Basin in Yorkshire, UK (Stewart, 1949).

In the 1930s, the USA showed strong interest in this mineral due to its abundance in western Texas and New Mexico, about 106,800 km^2 of deposit (Mansfield and Lang, 1929). But with the discovery of KCl in large quantities in Saskatchewan, Canada, interest in polyhalite waned as the industry turned to this mining area instead.

Historically, the mineral has attracted reduced interest from companies due to its lower K content and prolonged availability compared to other sources. However, in recent years, polyhalite has increasingly been seen as a potential source of fertilizer due, in part, to the increase in the price of KCl which enabled incentives for the use of alternative potassium fertilizers. Polyhalite is also a source of S, helping meet crops' demand for S to optimize the productivity and quality of crops. It is currently extracted in small volumes, compared to other fertilizers, but this has increased significantly in recent years. The industry continues to evolve, with the UK subsidiary of Israel Chemicals Limited (ICL UK) currently extracting the mineral from a depth of 1,200 m at their Boulby Mine, in Yorkshire, UK (Map 1), distributing around 800,000 t/year of polyhalite worldwide, as a fertilizer for

Photo 3. Polyhalite extraction from 1,200 m below ground at Boulby Mine, Yorkshire, UK. Photo: ICL, UK.

direct application or to complement NPK blends (Imas, 2017) (Photos 2 and 3).

This natural mineral, with its unique characteristics, is used as a multi-nutrient fertilizer. In addition, it is one of the few sources of K suitable for chloride-sensitive crops. The first use of polyhalite as a fertilizer was reported when Fraps (1932) published results of experiments carried out in pots with corn and sorghum in Texas, USA, and showed that polyhalite would be suitable for use as a potassium fertilizer, providing equivalence of 96% K availability compared to KCl and K_2SO_4 fertilizers (Photo 4).

Several experiments have compared the use of polyhalite as a fertilizer to the use of equivalent commercial soluble salts. At the University of Colorado, USA, Barbarick (1991) found a better yield response of forage sorghum with increasing levels of polyhalite, when compared to soluble salts at the same application rate (Fig. 1) and associated this response with the slower solubility of polyhalite. Tiwari *et al.* (2015) found an advantage regarding oil production in mustard and sesame when applying polyhalite compared to using equivalent amounts of soluble fertilizers. In cabbage and cauliflower, higher quality and higher yields were obtained when polyhalite was used as a source of Ca, Mg, and S compared to fertilization with the equivalent soluble salts (Satisha and Ganeshamurthy, 2016).

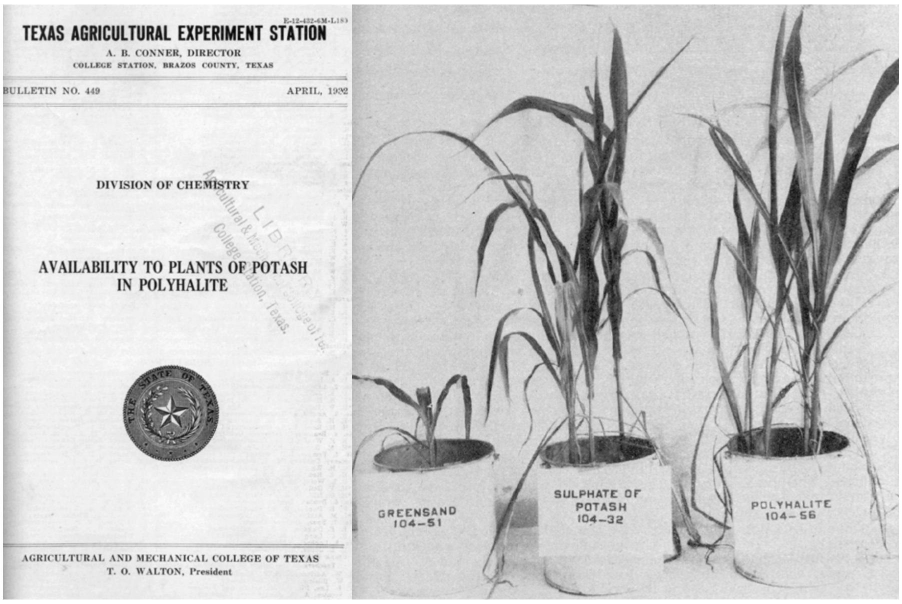

Photo 4. First recorded work to evaluate plant nutrition with polyhalite. Cover of the publication and images of pots showing the comparison between corn grown with polyhalite and potassium sulfate. Fraps, 1932.

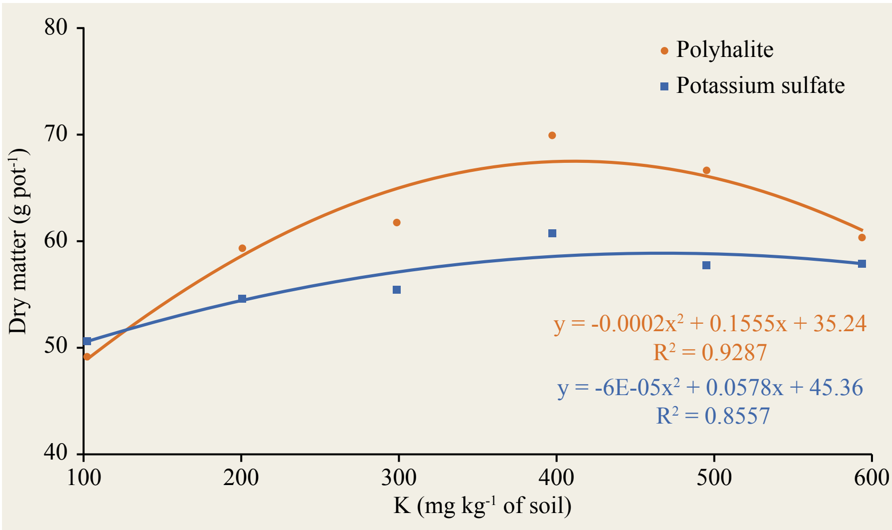

Fig. 1. Forage sorghum dry matter productivity as a function of K application through polyhalite and potassium sulfate. Barbick, 1991.

Polyhalite characteristics and properties

Polyhalite is a mineral with unique characteristics, making it a fertilizer with a high potential for main crops, bringing several benefits related to quality and yield.

Mineralogical composition

Polyhalite is an evaporitic mineral, hydrated sulfate of potassium, calcium, and magnesium. It crystallizes in the pseudo-orthorhombic triclinic system, although crystals are very rare. The normal habit is massive to fibrous. It is white to gray in color, like the mineral mined at the Boulby mine in the UK (Photo 1), although it can be red in some regions due to iron oxide inclusions. It is transparent, fluorescent, and non-magnetic in nature. Its fractures are brittle, similar to glass and non-metallic minerals (Bindi, 2005).

Chemical composition

Polyhalite is a naturally occurring mineral containing four macronutrients, K, Ca, Mg, and S. The mineral mined at the UK's Boulby mine has a very high purity (95% polyhalite) with a concentration of less than 5% sodium chloride (NaCl). There are traces of boron (B) and iron (Fe) at 300 and 100 mg kg^{-1}, respectively. Polyhalite has 48% SO_3 (19.2% S), 14% K_2O (11.6% K), 6% MgO (3.6% Mg) and 17% CaO (12.2% Ca), all available for plant uptake. Although it has a lower water solubility limit than other K sources,

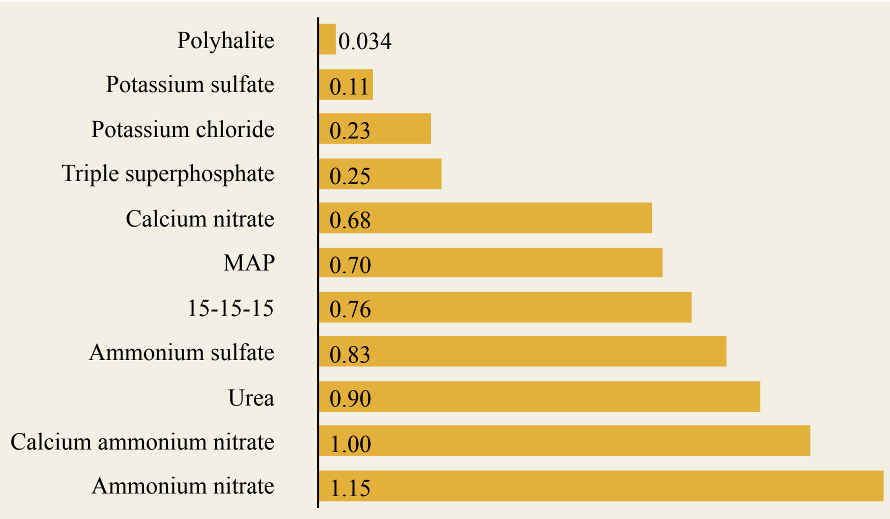

Fig. 2. Carbon footprint measurement of products used as fertilizers in agriculture. Source: ICL.

when applied at rates below its solubility limit, it provides more than enough K, Ca, Mg, and S for plant growth (Yermiyahu *et al.*, 2017).

Natural mineral for direct use in agriculture

As it is a mineral practically free of contaminants and with nutrients present in the form of soluble salts, polyhalite is simply extracted, crushed, and sieved, with no chemical processes in its production. Due to this simplified production, polyhalite fertilizer has a low carbon footprint (Fig. 2), which is an increasingly important factor for food producers and processors globally.

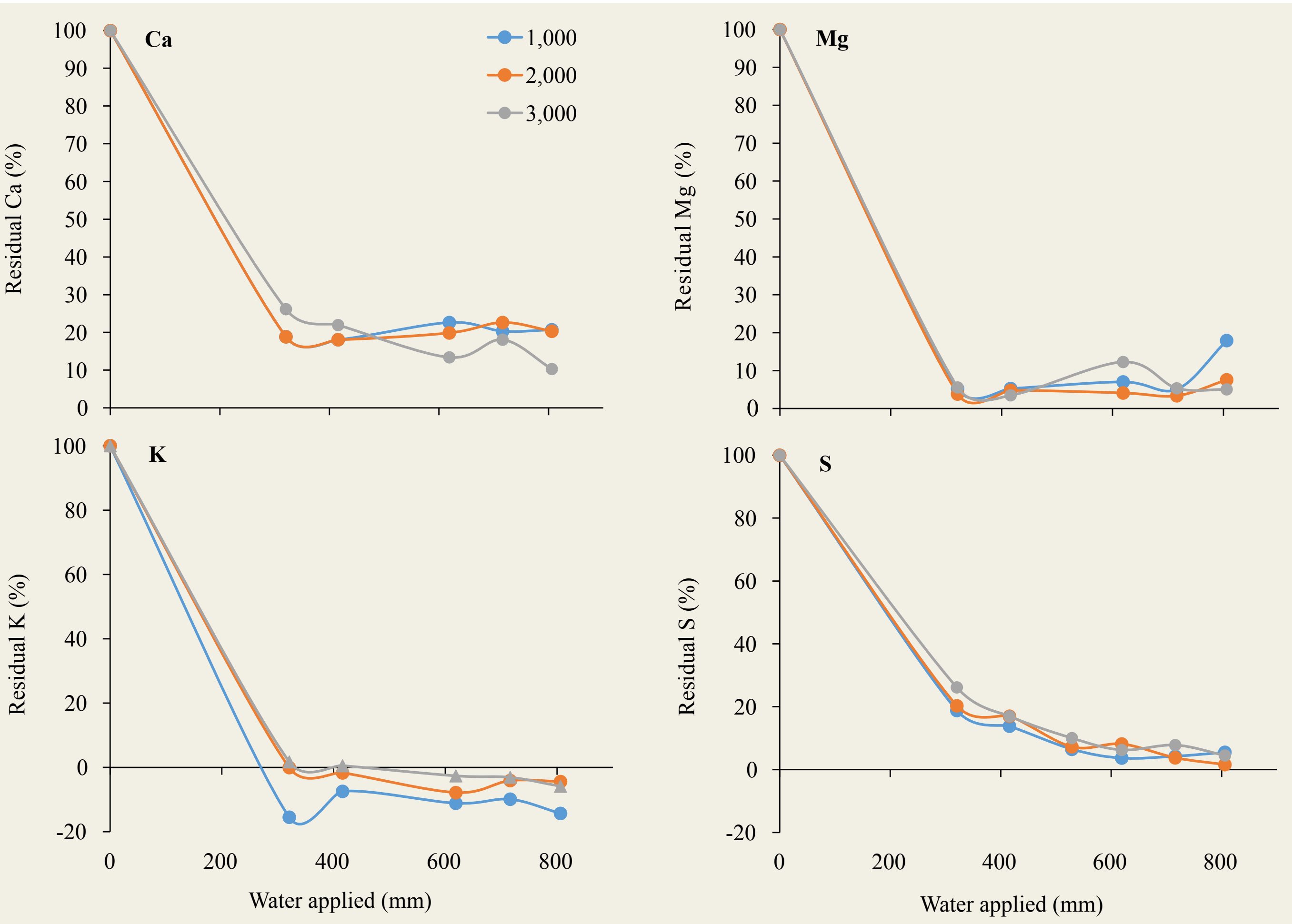

Fig. 3. Residual percentage of polyhalite elements Ca, Mg, K, and S from the field experiment. Polyhalite was applied at doses equivalent to 1,000, 2,000, and 3,000 kg ha^{-1}. The measurements took place at accumulated water applications of between 300 and 800 mm. Yermiyahu *et al.*, 2019.

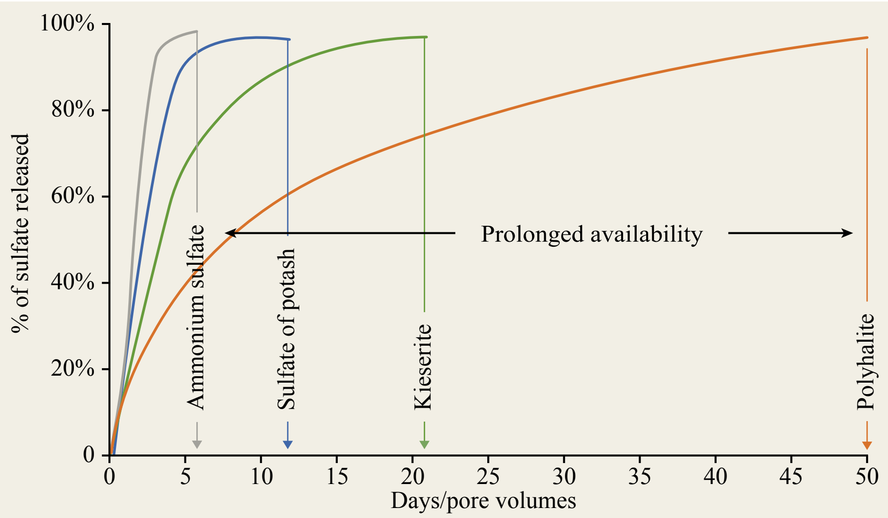

Fig. 4. Study in leach columns showing that polyhalite has prolonged availability (up to 50 days under laboratory conditions), in relation to other S sources. Jiang *et al.*, 2017.

Photo 5. Leach columns used in experiment at University of Nottingham.

Solubility with prolonged availability

Solubility is an important factor for fertilizers. Solubility varies considerably between sources affecting nutrient release rates and therefore their availability to plants, in addition to the potential for losses due to leaching, runoff and volatilization. Solubility also determines the potential for use in liquid fertilizer production. Barbarick (1991) stated that polyhalite was less soluble in water than conventional fertilizer sources and could provide a gradual release of nutrients. This prolonged availability of nutrients can guarantee nutrition at different stages of crop development, while also significantly reducing leaching losses.

Experiments evaluating the use of polyhalite have shown significant advantages for many crops (PVFCCo, 2016a, 2016b; Tam *et al.*, 2016; Melgar *et al.*, 2018; Tien *et al.*, 2018; Eryuce *et al.*, 2019). Polyhalite solubility and the potential availability of its various constituent minerals have been studied in both laboratory tests and field experiments (Yermiyahu *et al.*, 2019). In the laboratory test, the K and Mg salts were completely dissolved, while the Ca salts showed slower solubility. In the field experiment, carried out on a sandy soil in the Negev desert, Israel, under repeated wetting cycles that simulated successive rainfall events, all polyhalite constituents were dissolved between 75-100% after 300 mm of accumulated water application, in the order of K > Mg > S > Ca (Fig. 3). Significant differences in solubility occurred with application of increasing amounts of water, up to 800 mm. While K and Mg presented negligible or null residues, the dissolution of S was more gradual, and the Ca residues remained constant. Dissolving polyhalite in water takes longer and requires larger volumes of water compared to other soluble fertilizers. Any residual granules present on the surface after the evaluations did not show significant amounts of the nutrients. This indicates the safety of considering the guaranteed levels of the product, whilst reducing possible risks of fertilizer overuse and allowing the application of polyhalite as a fertilizer with slower release than most of soluble sources.

Research carried out in leach columns at the University of Nottingham, UK confirmed that polyhalite has a more prolonged release of S (Fig. 4) compared to other sources. Complete solubilization of S from polyhalite took 50 days, with about 50% of the nutrient already available after the first 10 days, which would allow adequate plant nutrition at that time. On the other hand, ammonium sulfate, the most soluble S source tested in the evaluation, made all S available within the first 5 days, indicating it was susceptible to leaching losses from the soil (Jiang *et al.*, 2017).

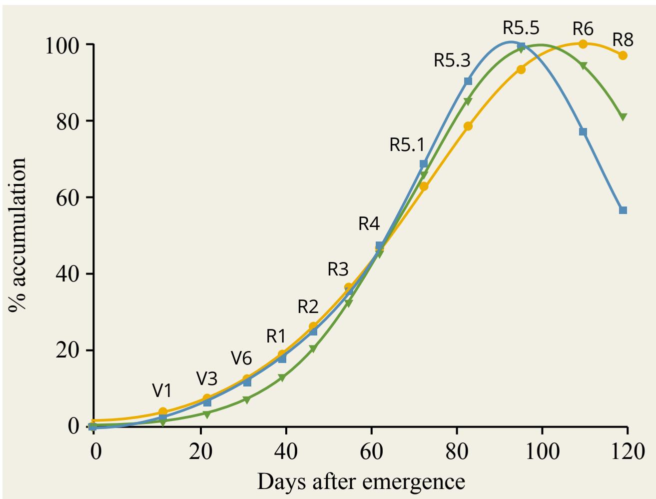

Fig. 5. Rate of sulfur absorption by different soybean cultivars: BRS 184, SYN 1059, DM 6563 - Intacta RR2 PRO. Oliveira Jr. *et al.*, 2016.

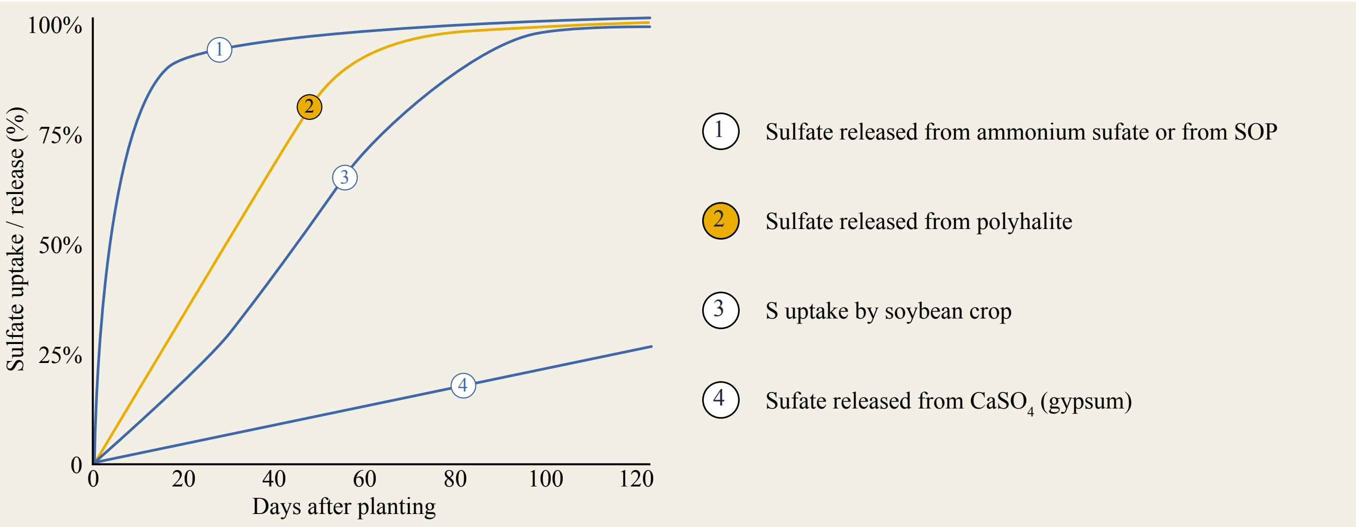

Fig. 6. Availability of sulfate from different sources and demand for sulfur by the soybean crop. Source: ICL.

This characteristic of prolonged availability of polyhalite nutrients, in addition to providing nutrition at the appropriate stages of crop development, also contributes to less leaching of the nutrients, especially S. Unlike other nutrient sources, polyhalite continues to supply sulfate to plants even after heavy rains, making it an adequate source for fertilization throughout the growing period. It also has the advantage of being recommended as the only source of S which requires just a single early dressing.

EMBRAPA studies with three soybean cultivars (Oliveira Jr. *et al.*, 2016) show that during the vegetative stage, S absorption remains low, accumulating less than 20% of the crop's needs, increasing during the reproductive stage when the accumulated values reached 20%, 50%, 70%, and 100% in stages R1, R4, R5.1, and R5.5, respectively (Fig. 5). Thus, it can be suggested that a single application of polyhalite as the source of S could meet the demand for the nutrient right from the initial vegetative stage to the beginning of the reproductive stage (Fig. 6).

Several studies carried out under laboratory and field conditions made it possible to define the average solubilization curves for polyhalite (Fig. 7). For K and Mg, complete solubilization is fastest, with nutrients completely available in the soil solution within 10 to 20 days. Within the first 15 days, between 70 and 80% of the S is solubilized with the remainder between 45 and 50 days after application. Ca has the slowest availability among the four guaranteed macronutrients, close to 60% at 10 days and finalizing complete dissolution after approximately 50 days. This shows the difference in solubility between the chemical forms present in the product: potassium sulfate and magnesium sulfate are more soluble, while calcium sulfate has a slightly slower solubility (Yermiyahu *et al.*, 2019).

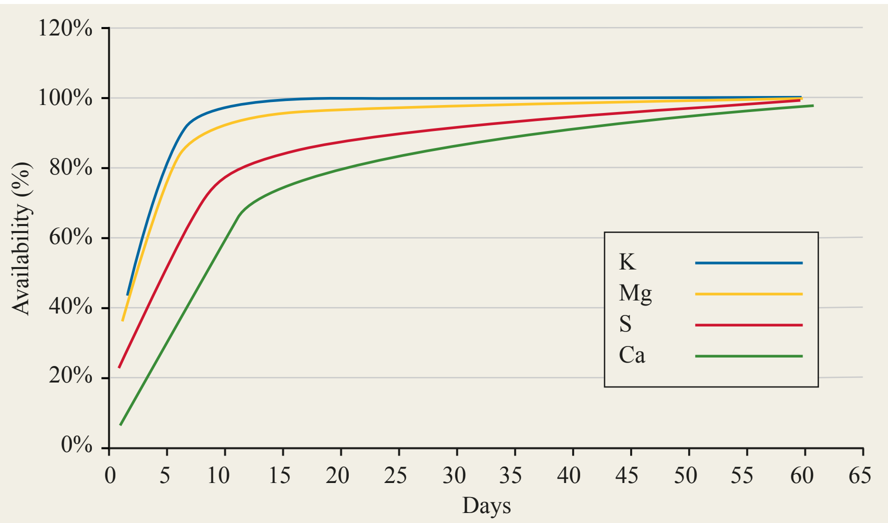

Fig. 7. Prolonged availability of polyhalite nutrients for 40-50 days under field conditions. *Source:* ICL.

Salt index

Fertilizer application is a pre-condition for sustainable agriculture, especially on weathered soils, such as those in tropical regions. When practiced correctly, fertilization must meet the nutritional demands of crops with minimal influence on the environment. Practically all fertilizing materials are salts; they dissolve in water, which transports nutrients through the soil, and is the medium where they are accessible to plant roots. However, increasing salt concentrations above certain levels can

Table 2. Salt index for different fertilizers (suppliers of K, Mg, Ca, or S) by calculation method (CPH, 2006) or by electrical conductivity determination (Jackson, 1958), at the IMI TAMI R&D Institute, Haifa, Israel. Fried *et al.* (2019).

Fertilizer	Salt index	
	CPH	Jackson
Polyhalite	32.3	52.0
KCl	116.2	138.0
Gypsum ($CaSO_4$)	8.1	42.0
K_2SO_4	42.6	100.0
$MgSO_4$	44.0	76.0
Langbeinite ($K_2SO_4 \cdot MgSO_4$)	-	26.6
KNO_3	69.5	85.0

adversely affect the crop, usually described as salt stress. To avoid fertilizer-induced salinity problems, it is essential to recognize the chemical nature of the products in use, not only as nutrient providers but also as salts, and to establish rules and limits for reasonable application methods.

Salinity has two major impacts on plants: toxic and osmotic stress (Munns and Tester, 2008). Toxic effects occur when the concentration of sodium (Na) or Cl ions in the leaf cells' cytosol increases above a certain threshold, usually 150-200 µmol, damaging the enzymes and sensitive photosynthetic structures. Several plant species activate compartmentalization mechanisms, storing saline ions in vacuoles and organs, trying to avoid their harmful influence. However, as these abilities differ greatly between crop species, a toxicity test seems useless to assess and compare the effect of fertilizer salinity. In addition, most fertilizers do not contain Na, while fertilizers without Cl are gaining more and more value.

In contrast, the osmotic component of salt stress has similar effects on all plant species. As the ions, or soluble compound concentration in the liquid phase of the soil increases, the availability of water to the plant roots decreases. This phenomenon is expressed as the osmotic potential of the soil extract, whose strength also depends on the chemical properties of the soluble compounds. Consequently, fertilizers can differ significantly in their effect on soil osmotic potential. Thus, to evaluate the osmotic effect of fertilizers, the parameter known as salt index (SI) was established in the 1940s (Rader *et al.*, 1943). The salt index expresses the proportion of the increase in the osmotic pressure of the saline solution produced by a given fertilizer compared to the osmotic pressure of the same weight of sodium nitrate ($NaNO_3$). Sodium nitrate was selected as the standard to measure the salt content against because it is completely soluble in water ($NaNO_3$ SI is equal to 100). For example, the SI value for KCl considered by the authors was 116, that is the salinity of this fertilizer would be 16% higher than that of $NaNO_3$ when the products were applied at the same rate.

However, the Rader method often seemed impractical, and furthermore, their SI tables did not include many fertilizers developed later. Jackson (1958) published a simpler laboratory method, where the SI of the fertilizer was measured by the electrical conductivity in relation to $NaNO_3$. Several laboratories have used this method to evaluate new materials. More recently, many references, such as the Crop Protection Handbook (CPH, 2006), have adopted and published SI tables based on calculations that make use of values from both methods (Mortvedt, 2001). In comparison between four methods, Murray and Clapp (2004) showed that SI values obtained for different K fertilizers can differ significantly (Table 2) and therefore in fertilizer SI assessments more than one approach should be considered. For KCl, the authors presented an SI value close to 150 by the Jackson method, well above the standard defined in the initial research on the subject. When calculating by the CPH method they found a result similar to the Rader parameter, indicating the possibility of using the CPH method in practice. Barbier *et al.* (2017) also found considerable differences in SI values for the same fertilizer between laboratories, determining an SI value of 128 for KCl using the Jackson method.

Working at the IMI TAMI R&D Institute, Haifa, Israel, Fried *et al.* (2019) performed validations of the SI of polyhalite and other sources containing K, Ca, Mg and S, using both the calculated method described by CPH (2006) and the determined value according to Jackson (1958), with results shown in Table 2. The theoretical calculation of polyhalite's SI presented a value of 32.3 (Table 2), significantly lower than the standard 100 for $NaNO_3$. However, there were major differences between the theoretical calculation and the Jackson method, with the latter's values being much higher for all sources. Differences between fertilizers within each method, however, were consistent. Among K-supplying fertilizers, SI values decreased in the order of: KCl > K_2SO_4 > KNO_3 > polyhalite > langbeinite.

Polyhalite has low salt index values compared to more common and equivalent fertilizers and this can be attributed to the dominant

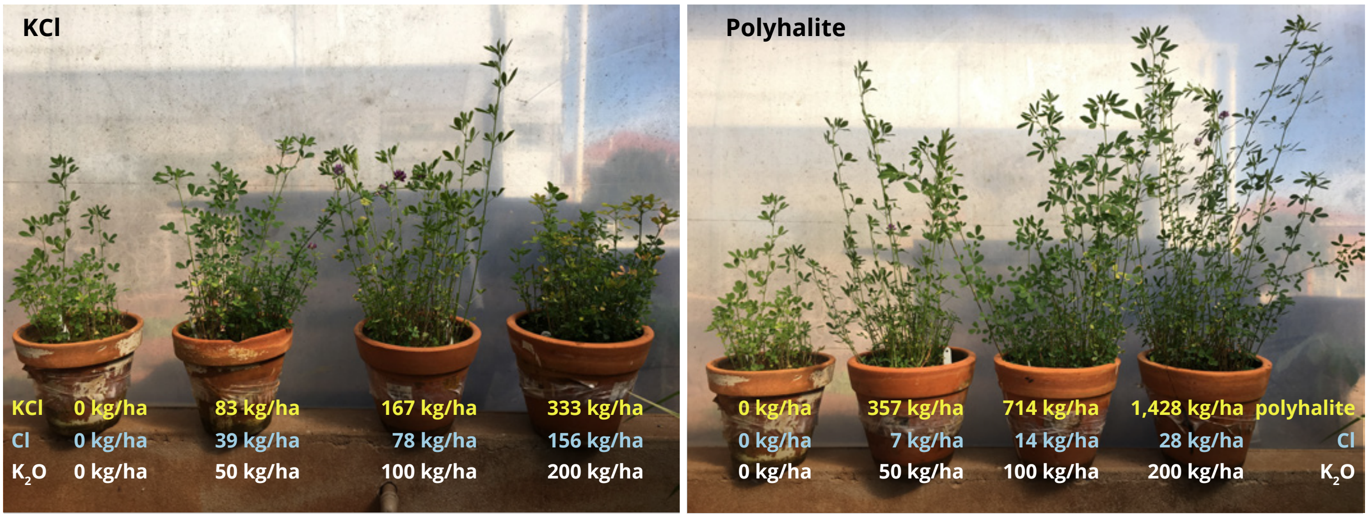

Photo 6. Performance of alfalfa grown in pots under four levels of K application (0, 50, 100, and 200 K_2O kg ha^{-1}) using KCl (left) and polyhalite (right). Photos: A.C.C. Bernardi.

portion of $CaSO_4$ in the fertilizer. This is one of polyhalite's significant advantages, reducing risk of salinity during the sensitive early stages of many crops (Havlin *et al.*, 1999). Another advantage of polyhalite, referring to the salt index, is related to the chloride levels, which are very low in the mineral, thus avoiding risks of ion accumulation at depth, and reducing impacts related to the root system development.

Bernardi *et al.* (2018) compared the supply of potassium fertilization from two sources, KCl and polyhalite for alfalfa crop (*Medicago sativa*) under controlled conditions. Fertilizer rates ranging from 0 to 200 kg K_2O ha^{-1} were evaluated, using single fertilizer sources or blends. The results showed the benefit of replacing KCl with polyhalite, which led to an increase in biomass, resulting in higher yield. Comparing the increasing rates of polyhalite and KCl, there is a greater risk when using KCl. Plants show less development due to the higher SI; at the same rate of K_2O, KCl applies approximately 5.5 times more Cl than polyhalite (Photo 6).

Ways of use and application

Another advantage of polyhalite relates to its versatility. Polyhalite can be used as a simple fertilizer or in NPK blends, providing S, K, Mg, and Ca with prolonged availability. In physical blends with other fertilizers available on the market, polyhalite is shown to be fully compatible, not affecting the chemical and physical-chemical characteristics of the formulations, thanks to its neutrality and low hygroscopicity characteristics (Fig. 8). Available in granular and powder forms, polyhalite can be applied to all crops, if it is managed according to nutritional demand, both in quantity and at the right time

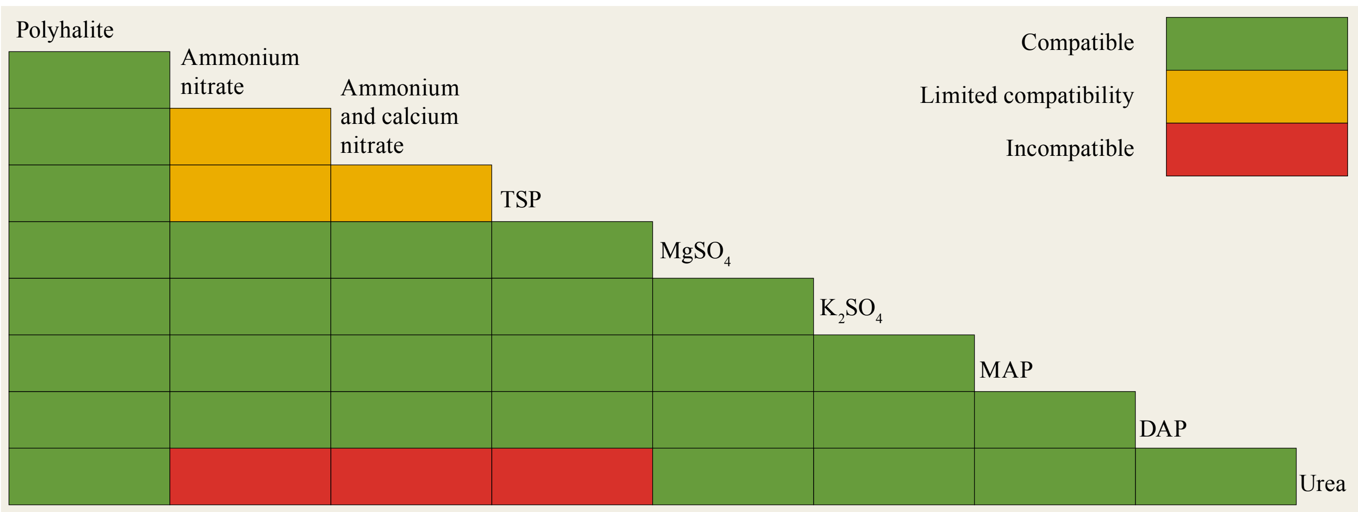

Fig. 8. Compatibility between raw materials to produce formulated fertilizers, based on the IFDC method. Source: ICL.

Photo 7. Polyhalite fertilizer available in granular (left) and powder (right) forms. Photos: ICL.

due to its gradual release. It can be applied in the planting furrow or incorporated, because of its low salt content, or applied to the surface, meeting the application ranges of the most used fertilizers in agriculture (Fig. 8).

Mobile calcium and magnesium in the soil profile

Due to the increasing use of potassium fertilizers in Brazilian soils, Ca and Mg availability have become a challenge in arable areas. Thanks to the chemical characteristics of limestones, which have low mobility in the soil profile, it has been observed that the practice of liming alone cannot correct the levels of both nutrients. At greater depths the situation worsens, especially in no-tillage areas and also in those with perennial crops, where limestone is applied superficially and without incorporation leaving the nutrients concentrated in the surface layer (Freiria *et al.*, 2018; Martinez *et al.*, 2000). Thus, the management of Ca and Mg, also included in fertilization, becomes a tool to reach greater agricultural sustainability.

Calcium is responsible for the structural and physiological stability of plant tissue, generating phytates and pectates, which make it important for maintenance of the integrity of the cell wall. Calcium activates multiple growth regulatory enzyme systems, helps convert nitrate into forms necessary for protein formation, and contributes to improved disease resistance. Since calcium is immobile within the plant, deficiency symptoms appear on younger leaves. New leaves are usually smaller than normal, are distorted, curled or hook-shaped, and the growing tip may die (Marschner, 2012).

Magnesium has an important role in plant metabolism, including photosynthesis and carbon incorporation, being the central atom of the chlorophyll molecule (Marschner, 2012). It also plays a key role in defense mechanisms under abiotic stress conditions (Senbayram *et al.*, 2015), and light intensity has a strong influence on it. Plants grown in environments with intense light show a greater need for Mg than plants grown in conditions of lower intensity. As Mg is mobile within the plant, deficiency symptoms appear first on the lowest and oldest leaves. The first visible symptoms are pale leaves, which develop interveinal chlorosis. On some plants, reddish and/or purple spots will appear on the leaves. Several publications have shown the increasing extent of Mg deficiency in agricultural areas of different parts of the world. Plant Mg nutrition is often neglected, and scarcity negatively affects plant growth, with hidden hunger for this nutrient being one of the biggest nutritional problems of cultivated plants (Cakmak and Yazici, 2010; Guo *et al.*, 2016; Castro *et al.*, 2020).

In polyhalite, Ca and Mg are present in sulfate forms and so have greater mobility than when supplied as carbonates, causing them to occupy deeper layers of the soil allowing the root system to grow in depth and volume. Vale (2016) compared the effect of polyhalite with that of KCl as a source of K for soybean cultivation in Sapezal, Mato Grosso, an area that had received 2.5 Mg ha^{-1} of dolomitic limestone, incorporated with a harrow. At planting, 100 kg ha^{-1} of P_2O_5 was applied via MAP. Potassium sources were applied at a rate of 140 kg ha^{-1} of K_2O without incorporation, divided into two applications, 50% in V1 phase and the remainder in V6. The plots that received polyhalite showed a 10.2% increase in yield compared to KCl fertilization. After harvesting, soil samples were collected at depths 0-5, 5-10, 10-15, 15-20, 20-30, and 30-40 cm to determine levels of K, Ca, Mg, and S throughout the soil profile. Limestone application only influenced the availability of Ca and Mg in the 0-10 cm layer, proportional to its mechanical incorporation. The application of polyhalite increased the Ca and Mg contents throughout the profile, increasing Ca by 23% and 8%, respectively in the 0-20 and 20-40 cm layers. For Mg this increase was 25% and 17% for the same layers. This movement of the bases followed the sulfate movement, with an increase in the S content in the profile, mainly in the 20-40 cm layer (Fig. 9).

Organic certification

Polyhalite mining does not involve chemical processes, so the mineral is available in its natural form. This makes it appropriate as a fertilizer for use in organic agriculture, meeting certification criteria worldwide. Polysulphate, the polyhalite fertilizer from ICL, has certification in countries such as the US, Canada, Italy, Brazil, the Netherlands, as well as the European Union and the UK.

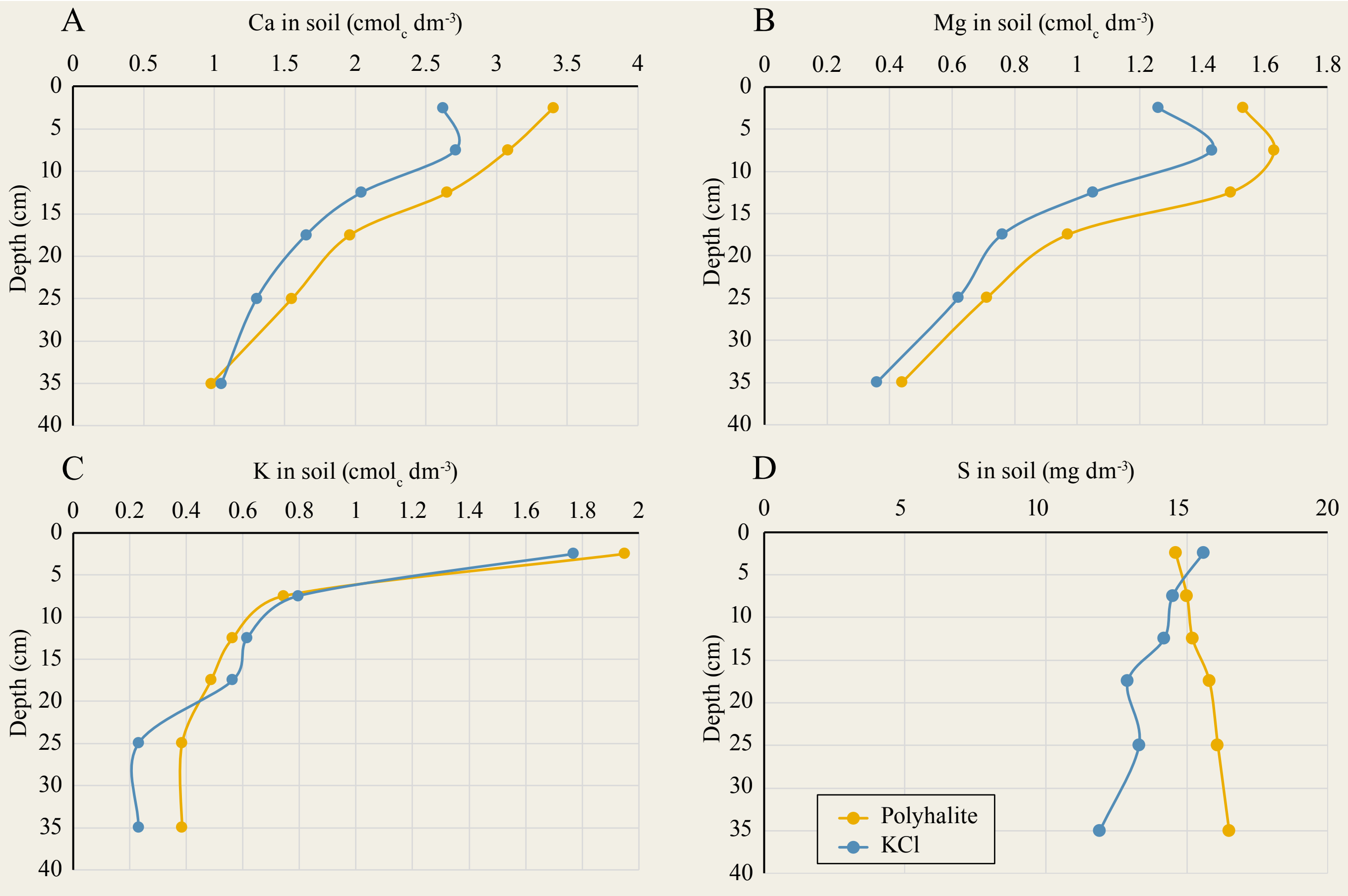

Fig. 9. Contents of Ca, Mg, K, and S in the soybean soil profile after treatments with liming and fertilization with KCl or polyhalite in Latosols. Vale, 2016.

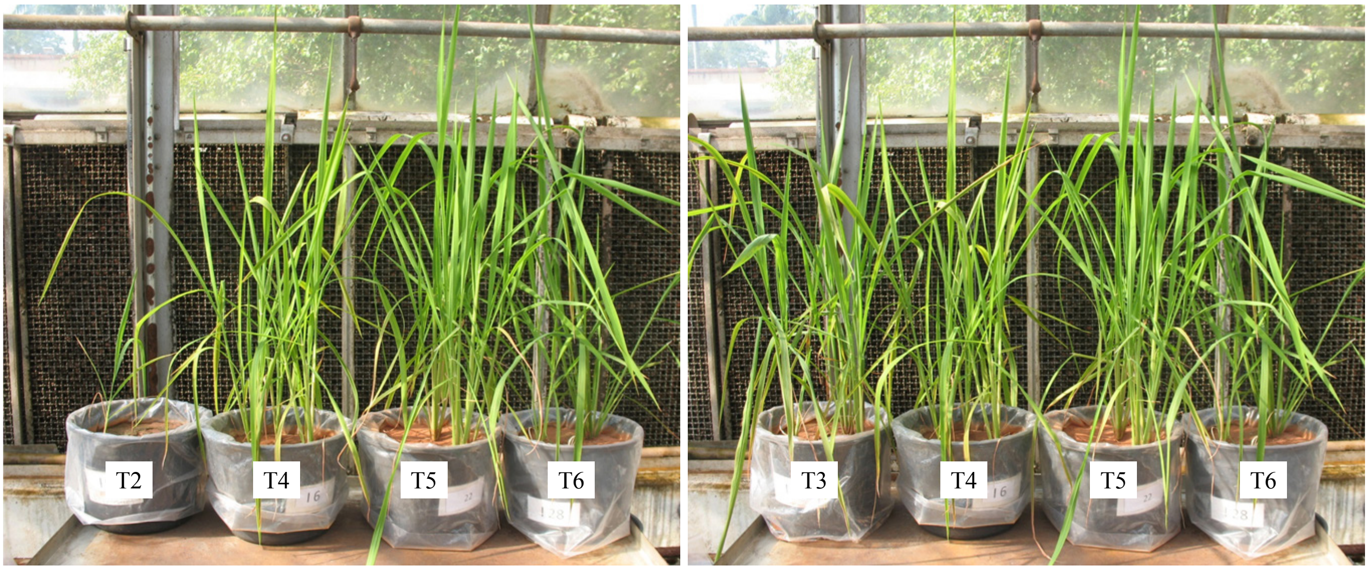

Photo 8. Rice grown in pots as part of the process to register polyhalite as a fertilizer in Brazil. Treatments: T2 control without K, Ca, Mg, or S; T3 Soluble salts of K, S, Ca, and Mg; T4 granular polyhalite; T5 granular polyhalite (double dose); T6 crushed polyhalite. Vitti (2013), referenced by Vale and Sério (2017).

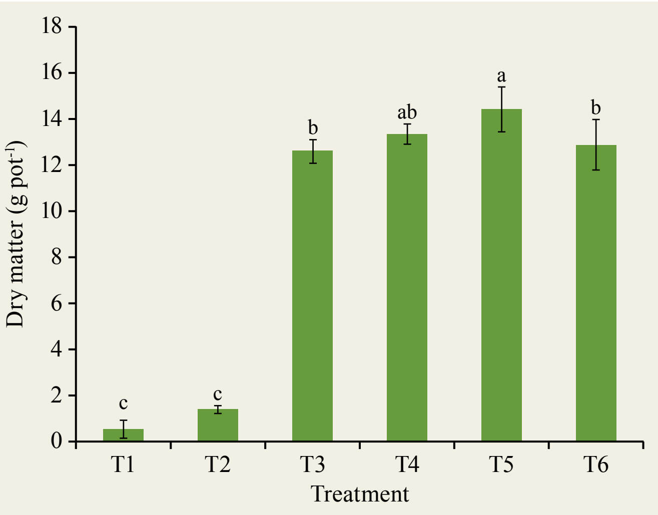

Fig. 10. Effect of fertilizer treatments on rice dry matter production. Treatments: T1. Absolute control; T2. No addition of K, S, Ca, and Mg; T3. Granular polyhalite; T4. Soluble salts of K, S, Ca, and Mg; T5. Granular polyhalite (double dose); T6. Crushed polyhalite. Different letters indicate statistically significant differences at P=0.05 (Duncan's test). Vale and Sério, 2017.

Agronomic efficiency of polyhalite use in Brazil

Agronomic research has proven the efficiency of polyhalite as a fertilizer. Polyhalite is registered with the Ministry of Agriculture (MAPA) and is included in Annex I of Normative Instruction No. 39 (Brasil, 2018).

The first study proving the availability of nutrients in comparison with supply from other recognized nutrient sources was carried out by Vitti (2013), referenced by Vale and Sério (2017), with rice grown in pots in greenhouse conditions. Polyhalite was applied in two physical forms, granular and powder. Two control treatments were used, the first one without the addition of any nutrients, and the second without the addition of the four macronutrients present in polyhalite (K, Ca, Mg, and S). One treatment received all nutrients in the form of recognized soluble fertilizers salts (calcium sulfate, magnesium sulfate, potassium sulfate, and KCl) at an equivalent level to the polyhalite treatment. To evaluate any possible toxicity of the product, one treatment was conducted with a double dose of polyhalite. Results found that rice plants lacking the macronutrients K, Ca, Mg, and S showed much lower development, while soluble

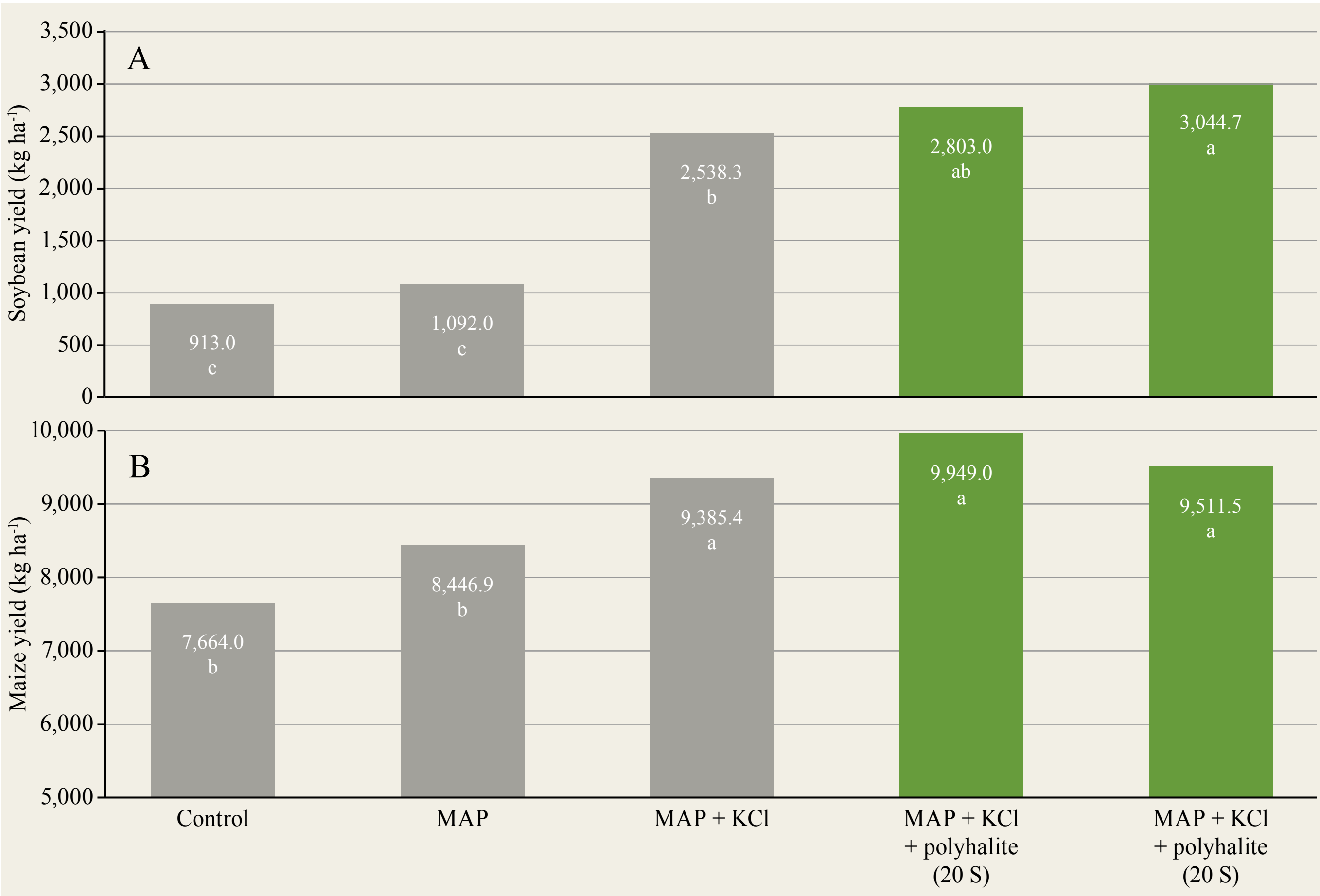

Fig. 11. Soybean yield as a function of partial replacement of KCl by polyhalite (A), and residual effect on corn (B), in Luis Eduardo Magalhães, Bahia state. Vale and Dowich, 2017.

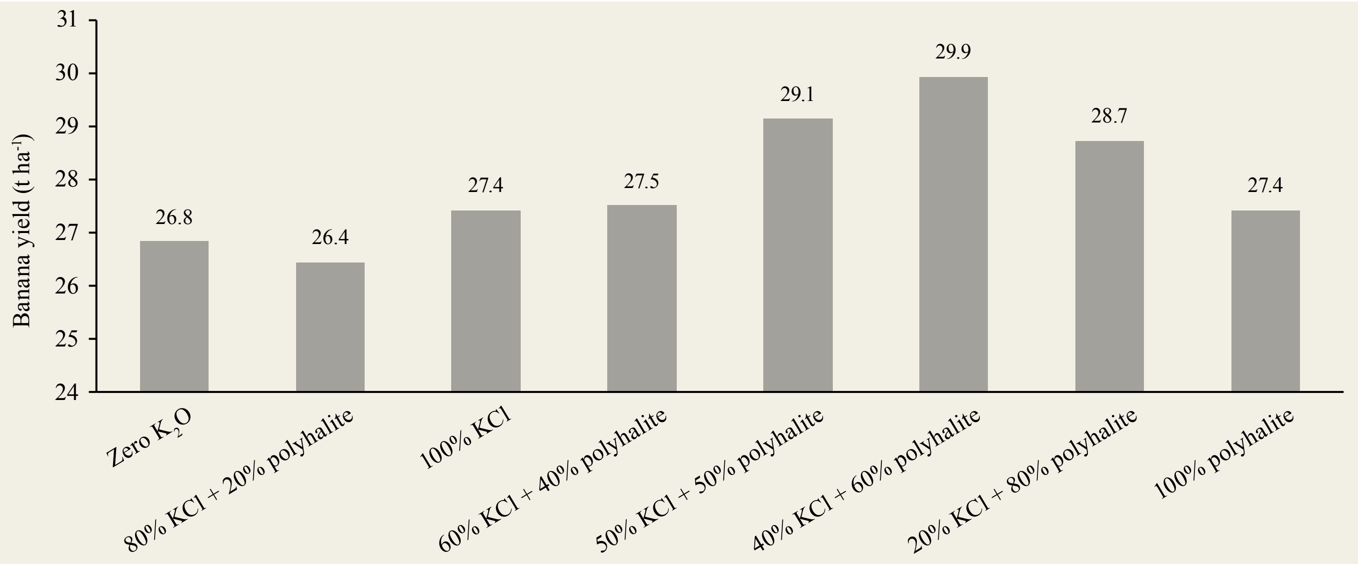

Fig. 12. Yield of banana in response to fertilization with different K sources, at a dose of 360 kg ha^{-1} of K_2O in Juquiá, Sao Paulo state. Silva *et al.*, 2018.

sources, including the application of granular or powdered polyhalite, allowed for normal plant development (Photo 8). Both granular and powdered polyhalite showed similar efficacy when compared to soluble sources (Fig. 10). There were no toxicity or salinity problems after applying the double dose of polyhalite.

Since 2016 polyhalite research in Brazil has continued, seeking to adjust the fertilization recommendations for the region's main crops. Several areas with soybean, corn, coffee, vegetables, sugarcane, cotton, among others, have already been fertilized with polyhalite, demonstrating its productive potential and superior quality compared to conventional nutrient sources.

The use of polyhalite in soybean fertilization, and its residual effect in the subsequent cultivation of corn was evaluated in an experiment in the Luis Eduardo Magalhaes region, west of Bahia (Vale and Dowich, 2017). Although soybean cultivation was influenced by the El Niño weather phenomenon that occurred in the 2015-16 season, with prolonged droughts and late rains, potassium fertilization had a high influence due to the reduction in rainfall. Combining MAP and KCl increased production by 36% in relation to fertilization with MAP alone. Introducing polyhalite to the MAP and KCl fertilizer strategy increased the yield by up to 19.9% compared to KCl treatment (Fig. 11A). After the soybean harvest and subsequent fallow period, corn was sown in October 2016, and all treatments received the same fertilization of 150 kg ha^{-1} N as urea, 100 kg ha^{-1} P_2O_5 as MAP and 60 kg ha^{-1} K_2O as KCl, to evaluate the residual effect of the sources applied in the previous soybean fertilization. Corn yield was 6% higher due to the residual effect of polyhalite compared to KCl fertilization, showing the importance of S, Ca, and Mg and the viability of polyhalite in the management of these crops (Fig. 11B).

Two trials were carried out at the Fundação Rio Verde experimental station, in Lucas do Rio Verde, Mato Grosso state, Brazil. A soybean trial compared polyhalite with simple superphosphate and pastilled elemental sulfur as sources of S, in both broadcast and furrow application. Polyhalite proved to be a viable soybean fertilizer using either application method, producing superior yields to the other treatments. The application of polyhalite in the furrow increased yield by 16.7% compared to KCl, 14.1% compared to elemental S, and 9.7% compared to simple superphosphate. The second trial, with cotton, compared polyhalite and ammonium sulfate as sources of S in broadcast application, when applied at different stages. Better yields were achieved with ammonium sulfate applied 20 days after sowing, polyhalite applied 5 days after sowing, and when polyhalite was applied at 5 and 20 days after sowing. This third way to apply the product was interesting as it produced the greatest average yield of cotton bolls per plant, which may be indicative of the effect of applying fertilizer with Mg (Pittelkow *et al.*, 2018).

Several experiments were carried out in fruit crops, including evaluation of the use of polyhalite for banana fertilization in Juquia, Sao Paulo state (Silva *et al.*, 2018). Typical crop management involves high doses of KCl, leaving soils with a high concentration of K and generally with high salinity. This can influence plant development and nutrition, mainly due to competitive inhibition from Ca and Mg. The treatments were blends of KCl and polyhalite tailored to provide 360 kg ha^{-1} of K_2O, and a control treatment with no nutrient application. As the soil had a high saturation of K, there was no significant effect of the application of KCl in relation to the control, with a 1.5% reduction in fruit production due to fertilization with K_2O alone. The best result was obtained with the 60:40 polyhalite:KCl blend, which increased the yield by 13.2% in relation to fertilization with KCl (Fig. 12). The plots that received polyhalite

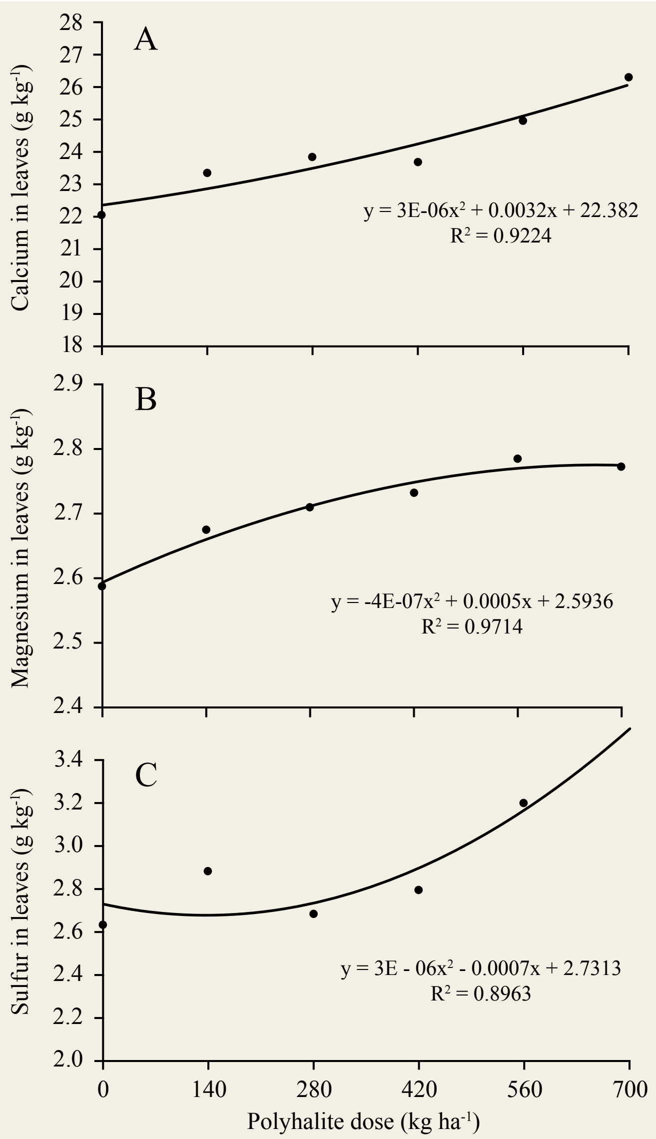

Fig. 13. Effects of polyhalite dose on foliar calcium (A), magnesium (B), and sulfur (C) concentration in Natal orange trees, expressed through binomial regression curves. * and ** indicate significance of the regression curve at $P < 0.05$ and $P < 0.01$, respectively. Silva and Vale, 2021.

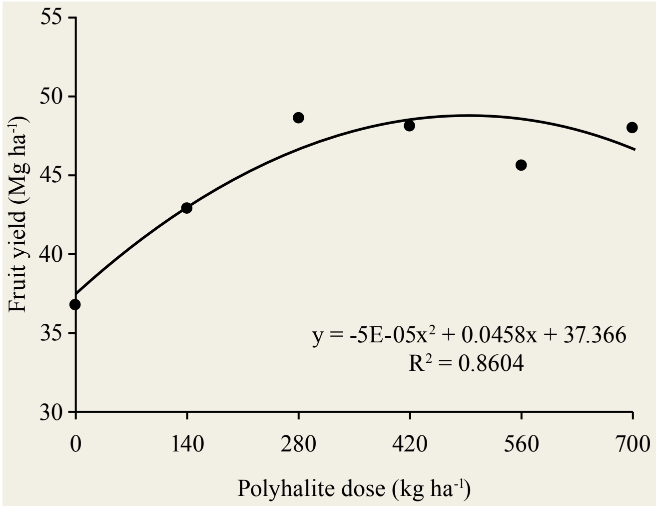

Fig. 14. Effects of polyhalite dose on fruit yield in Natal orange trees, expressed through binomial regression curves. * and ** indicate significance of the regression curve at $P < 0.05$ and $P < 0.01$, respectively. Silva and Vale, 2021.

showed bunches with greater vigor, and the plants with the largest stem diameter. Polyhalite is a viable alternative for use in banana fertilization, as it improves the nutritional balance with the supply of Ca, Mg, and S, in addition to reducing salinity and increasing yield potential.

In order to evaluate the effect of polyhalite on orange crops in Brazil, an experiment was conducted in 2017-2018 in Mogi Guaçu, Sao Paulo state (Silva and Vale, 2021). The treatments included fertilizer blends to partially replace KCl with polyhalite to maintain a constant dose of 300 kg ha^{-1} of K_2O. The foliar concentrations of Ca, Mg, and S significantly increased with the increasing polyhalite dose (Fig. 13). The treatment with the greatest proportion of polyhalite in the fertilizer blend (68% polyhalite) produced an increase in total soluble solid yield of 42% compared to the KCl control. Overall, the research indicated the optimal polyhalite application rate was close to 400 kg ha^{-1} (Fig. 14). This partial replacement of KCl with polyhalite presented significant advantages for the commercial orange production under tropical conditions.

Vegetables are usually grown in soils with high fertility, excessively corrected and fertilized, thus a low response to the use of nutrients in fertilization is expected. These soils usually have a high amount of chloride and sodium, and the use of less saline sources, such as polyhalite, can be an alternative for greater yield, health, and product quality. In the region of Piedade, state of São Paulo, a study evaluating potassium fertilization for cabbages showed that the partial replacement of KCl by polyhalite increased the yield by up to 12.4%, and the proportions between 40 and 80% of polyhalite in blends with KCl were the most suitable, even in high fertility soils. Plants that received polyhalite were less susceptible to leaf spot caused by *Xanthomonas campestris* (Vale and Silva, 2017). Using the same methodology in an experiment with potato, Vale *et al.* (2019) concluded that there was a positive effect on tuber production with the partial replacement of 50 to 75% of KCl by polyhalite. They also observed a reduction in the number of stems attacked with the bacterium *Pectobacterium carotovorum*, which causes blackleg.

Sugarcane production in Brazil is largely carried out in areas with Oxisols and Dystrophic Ultisols, which are poor in nutrients. Despite the corrections made at planting, S deficiency in ratoons is common. Vale and Sério (2019) evaluated the use of polyhalite compared to phosphogypsum and ammonium sulfate in the management of ratoon sulfur fertilization in the Catanduva region, state of São Paulo. The supply of S through blends of polyhalite with KCl presented the best result in relation to the yield of stalks and sugar. In this way, polyhalite is a viable source of S for sugarcane ratoons, being able to replace agricultural phosphogypsum.

Final considerations

Polyhalite is a natural fertilizer containing four macronutrients: K, Ca, Mg, and S. Polyhalite has a low salinity, which allows it to be used in various types of management and with a wide range of crops in general. The prolonged availability of nutrients is a significant characteristic, making it an interesting source for adjusting the nutritional balance of crops.

Photo 9. Continuous mining machine used to extract the polyhalite mineral from 1,200 m below ground in the polyhalite mine at Boulby, Yorkshire, UK. Photo: ICL, UK.

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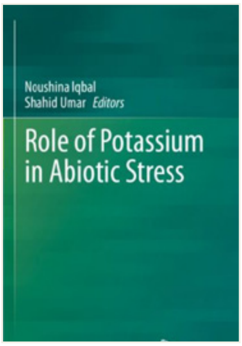
The paper "Fertilization Efficiency with Polyhalite Mineral: A Multi-Nutrient Fertilizer" also appears on the IPI website.

Publications

Role of Potassium in Abiotic Stress

Editors: Noushina Iqbal, Shahid Umar. 2022. 281p.



This publication from Springer Singapore is designed to fill the gap in literature with respect to role of potassium as a macro-nutrient in abiotic stress tolerance. The book deals with the ongoing trend in increasing abiotic stresses and interlinked issues of food security.

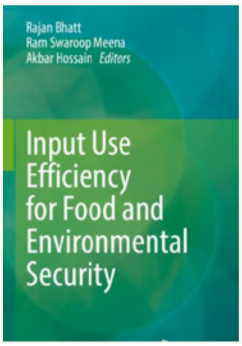
The International Potash Institute (IPI) authored one of the book's 13 chapters. Written by Adi Perelman (IPI Coordinator for India), Patricia Imas (IPI Scientific and Communications Coordinator), and S.K. Bansal (Potash Research Institute of India), the chapter **Potassium Role in Plants' Response to Abiotic Stresses** describes the role of potassium in plant's response to abiotic stress.

The publication is available at:
https://link.springer.com/book/10.1007/978-981-16-4461-0

The IPI chapter is available at:
https://link.springer.com/chapter/10.1007/978-981-16-4461-0_2

Input Use Efficiency for Food and Environmental Security

Editors: Rajan Bhatt, Ram Swaroop Meena, Akbar Hossain. 2021. 723p.



Input Use Efficiency for Food and Environmental Security is published by Springer Singapore. Through 19 individual chapters, the publication explores the role of input use efficiency in achieving the UN's sustainable global development priorities, including ending hunger, achieving food security and promoting sustainable development.

Within the publication, the chapter **Role of Potassium for Improving Nutrient Use Efficiency in Agriculture** (23 pages) was authored by The International Potash Institute (IPI). Written by Adi Perelman (IPI Coordinator for India), Patricia Imas (IPI Scientific and Communications Coordinator), and S.K. Bansal (Potash Research Institute of India), it describes how optimum potassium application improves the nutrient use efficiency of crops.

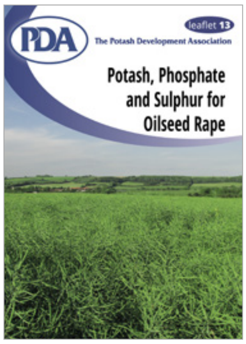
The publication is available at:
https://link.springer.com/book/10.1007/978-981-16-5199-1

The IPI chapter is available at:
https://link.springer.com/chapter/10.1007/978-981-16-5199-1_13

Publications by the PDA

Potash, Phosphate and Sulphur for Oilseed Rape

PDA Leaflet



Oilseed rape has faced a few challenges in the UK recently, rapidly falling out of favour on-farm due to difficulties with establishment following the loss of neonicotinoid seed treatments in 2014. This leaflet from the PDA explores the risks involved in growing the crop. The greatest risk period is the autumn around establishment. This is when the crop is most vulnerable. Improved establishment is key to the success of the crop, and the primary area of focus for this should be the soil. Soils should be well structured, at a neutral pH and soil indices should be at the target index of 2 for phosphate and 2- for potash. Read more on the PDA website.

Potash and Sugar Beet

POTASH News, March 2022

During the last four decades, yields of clean beet and sugar in the UK have been increasing linearly, at an average annual rate of 0.8 t/ha of clean beet. This article considers if the currently recommended potash application rates are adequate to support this. Read more on the PDA website.

Potash Development Association (PDA) is an independent organisation formed in 1984 to provide technical information and advice in the UK on soil fertility, plant nutrition and fertilizer use with particular emphasis on potash. See also www.pda.org.uk.

Scientific Abstracts in the Literature

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Foliar Spray of Amino Acids and Potassic Fertilizer Improves the Nutritional Quality of Rice

Mirtaleb, S.H., Y. Niknejad, and H.Fallah. 2021. Journal of Plant Nutrition 44(14):2029-2041. DOI: 10.1080/01904167.2021.1889588.

Abstract: The effect of amino acid (AA) fertilizers on the quality and nutritional value of rice have rarely been studied. A field trial to determine the effect of foliar application of amino acids (AA) and potassium (K) on mineral nutrients (Fe, Cu, Mn, Zn, Ca and Mg), the contents of protein, amylose and amino acids (non-essential and essential) of two rice varieties (Tarom mahali and Neda), comprising of four treatments (control, AA, K and AA+K) using randomized complete block design with three replications was conducted at the Rice Research Institute of Iran (Amol). The two years data during 2018 and 2019 showed that the foliar spray of AA and AA+K improved the concentrations of mineral nutrients, protein and amylose contents of brown and milled rice in both rice varieties compared to the control treatment. The foliar application of AA+K also significantly increased the contents of essential and non-essential amino acids of brown and milled rice in both rice varieties. In all similar treatments, the concentrations of element nutrients and the contents of protein, amylose, and amino acids of T. mahali variety were higher than Neda. Therefore, it can be concluded that the combined spray of AA and K can be a suitable practice for improving the quality of rice.

Response of Rice Yield and Quality to Nano-Fertilizers in Comparison with Conventional Fertilizers

Valojai, S.T.S., Y. Niknejad, H.F. Amoli, and D.B. Tari. 2021. Journal of Plant Nutrition 44(13):1971-1981. DOI: 10.1080/01904167.2021.1884701.

Abstract: Nano-fertilizers propose new techniques to be used for crop management. Present study investigated the influence of conventional and nano-fertilizers on grain yield and quality of two rice cultivars (Tarom and Shiroudi) in 2016 and 2017. The treatments included 10 nano and/or conventional fertilizers, i.e., control (without fertilizer), conventional nitrogen (N), phosphorus (P), potassium (K), and NPK and nano-N (nN), nano-P (nP), nano-K (nK), and nano-NPK (nNPK) and its combination (NPK+nNPK). Results showed that application of conventional and nano-fertilizers, particular in NPK, nNPK and its combination (NPK+nNPK) increased the grain yield (11.24–149.78% in Tarom and 16.86–95.85% in Shiroudi cultivars) and milled rice yield (25.33–157.35% in Tarom and 16.05–112.39% in Shiroudi cultivars). Fertilization treatments, especially N, nN, nNPK and NPK+nNPK, improved the grain quality by increasing milling quality (brown, milled and head rice rate), elongation ratio and gelatinization temperature and reduction of gel consistency and amylose content. Between fertilizer forms, application of nN and nNPK significantly increased the grain yield and milled rice yield as compared to their conventional forms (N and NPK). Moreover, quality (milling quality, elongation ratio, gel consistency and amylose content) of rice grains fertilized with nK was higher than that K. However, the highest grain quality was observed in N, nN, nNPK and NPK+nNPK fertilizer, while application of nNPK and NPK+nNPK were more effective on grain and milled rice production. According to the obtained results, application of nNPK can be an effective approach to obtain a balance between rice yield and quality, along with maintaining fertilizers efficiency.

Relationships Between N, P, and K in Corn Biomass for Assessing the Carryover Effects of Winter Pasture to Corn

Maccari, M., T.S. Assmann, A. Bernardon, A.B. Soares, A. Franzluebbers, M. de Bortolli, B.B. de Bortolli, C.L. Glienke. 2021. European Journal of Agronomy 129:126317. DOI: 10.1016/j.eja.2021.126317.

Abstract: Pasture fertilization may influence the subsequent corn crop in integrated crop-livestock systems, but few tools exist to assess the likelihood and magnitude of this carryover effect. Our goals were to determine whether a previous pasture with N fertilization could supply adequate N nutrition to a succeeding corn crop and affect its P and K nutrition using the concept of N dilution curve and relationships between N, P, and K in corn shoot biomass. The experiment consisted in a winter grazed pasture followed by a corn crop in summer. Treatments were N fertilization of a black oat (*Avena strigosa*) winter pasture (0 and 200 kg N ha^{-1}) as main plots and four sidedress N fertilization rates (0, 100, 200, and 300 kg N ha^{-1}) applied to corn as sub-plots in a randomized complete block design with split-plot restriction. The N nutrition index, that is, the ratio of observed shoot N concentrations to critical N concentration determined by a critical N dilution curve, adequately identified situations of deficient N nutrition in corn following a pasture with or without N fertilization. This carryover effect from a winter pasture should therefore be accounted for in N fertilizer recommendations for corn in tropical soils. Corn P nutrition, based on critical P concentrations derived as a function of N concentration, was nearly optimal when no N was applied to the pasture, but it was less than optimal when N was applied. Although no critical K curves have been published, our results confirm that the relationship between shoot K and N concentrations varies with the level of N nutrition as does the relationship between shoot P and N concentrations. Our results confirm that the concept of critical N and P concentrations serves as a useful reference to assess the status of N

and P nutrition during corn growth in tropical soils with the potential to improve nutrient management of corn following a pasture in an integrated crop-livestock system.

Determination of Soil Nutrients (NPK) using Optical Methods: a Mini Review

Potdar, R.P., M.M. Shirolkar, A.J. Verma, P.S. More, and A. Kulkarni. 2021. Journal of Plant Nutrition 44(12):1826-1839. DOI: 10.1080/01904167.2021.1884702.

Abstract: In the present situation, plants have to meet the food supply demand for a large and increasing population. In order to get high yield, it is essential for the plantations to be nourished with soil containing an appropriate amount of nutrients like Nitrogen (N), Phosphorus (P) and Potassium (K). Various methods such as, physical (optical) and chemical (electrochemistry) have been adopted to analyze the soil nutrients. This paper reviewed optical methods of soil nutrient detection suitable for building a portable sensor because it can sense nutrients in dry soil samples directly without the need for complicated sample pretreatments. We concentrate and elaborate on optical methods of experimentation. Starting from laboratory testing standards followed in India we move on to off the lab crude methods like soil testing kits and colorimetric approaches. Further, we review the effective and utilitarian spectroscopic approaches and also the technologically advanced and latest methods like imaging systems, microfluidic, and micro-electromechanical system (MEMs) based sensors. However, optical methods are affected by environmental factors that affect the accuracy of sensor results. This paper then discusses boons and curses of optical methods of soil nutrient sensing. It also explains briefly the working of each method and mentions the most recent advancements made in the given testing method. We hope that this paper can serve as a guide for the experimenters and give a direction for carrying out further work required in developing a portable and efficient soil NPK detection sensor.

Hop Dry Matter Yield and Cone Quality Responses to Amino Acid and Potassium-Rich Foliar Spray Applications

Afonso, S., M. Arrobas, J.S. Morais, and M.Â. Rodrigues. 2021. Journal of Plant Nutrition 44(14):2042-2056. DOI: 10.1080/01904167.2021.1889597.

Abstract: The use of amino acid and K-rich foliar sprays was evaluated in a commercial hop field in North-eastern Portugal. Four applications of an amino acid-rich foliar spray were performed in place of a second side dress N application of ~70 kg N ha^{-1}, which is usually applied by the farmer. The K-rich foliar spray was applied once at the cone developing stage as a supplement to the farmer's fertilization plan. The amino acid-enriched foliar spray maintained crop dry matter yield at the levels of the control treatment and increased cone alpha-acids concentration (41.8% in 2018 and 9.3% in 2019). Foliar K did not increase cone dry matter yield, cone size or bitter acid concentration. Tissue K concentration was not significantly affected by foliar treatments whereas the application of K seemed to increase N uptake, with leaves and stems being the predominant allocation tissues. Both foliar treatments increased leaf and stem Mg concentrations. The results seem to emphasize the importance of amino acids in the biosynthesis of bitter acids, while K and Zn seemed to play an important secondary role, maybe related to N metabolism and its reduction into amino acids. The concentrations of total phenols in cones and leaves were lower in the foliar treatments in comparison to the control, and the higher values registered in leaves. In this study, the use of amino acids as a foliar spray provided an interesting result, since they maintained cone dry matter yield and increased cone bitter acid concentration with reduced N use.

Potassium and Phosphorus Fertilizer Impacts on Alfalfa Taproot Carbon and Nitrogen Reserve Accumulation and use During Fall Acclimation and Initial Growth in Spring

Berg, W.K., S.M. Brouder, S.M. Cunningham, and J.J. Volenec. 2021. Frontiers in Plant Science 12:1698. DOI: 10.3389/fpls.2021.715936.

Abstract: Phosphorus (P) and potassium (K) impact alfalfa (*Medicago sativa* L.) performance, but how these nutrients alter taproot physiology during fall acclimation and subsequent growth in spring is unclear. Our objectives were to: (1) determine seasonal patterns for taproot P and K concentrations during fall acclimation and during initial shoot growth in spring; (2) determine how P and K nutrition impacts accumulation of taproot C and N reserves during fall and their subsequent use when shoot growth resumes in spring; and (3) assess how addition of P and K fertilizer impacts survival and shoot growth in spring. Two P (0 and 75 kg ha^{-1}) and two K (0 and 400 kg ha^{-1}) treatments were applied and taproots were sampled between September and December, and again from March to May over 2 years. Concentrations of taproot sugar, starch, buffer-soluble protein, amino-N, and RNA pools were determined. While P and K fertilizer application increased taproot P and K concentrations two- to three-fold, concentrations of P and K in taproots over time did not change markedly during cold acclimation in fall, however, taproot P declined in spring as plant growth resumed. Compared to the 0K-0P treatment, taproots of plants fertilized with 400K-75P had higher starch, protein, amino-N, and RNA, but reduced sugar concentrations in fall. Concentrations of all these pools, except starch, declined during the initial 2 weeks of sampling beginning in late March as shoot growth resumed in spring. Herbage yield in May was highest for the 400K-75P treatment and least for the 0K-0P treatment, differences that were associated with variation in mass shoot^{-1} and not shoots m^{-2}. High yield of the 400K-75P plants in May was consistently associated with greater concentrations and use of amino-N, soluble protein, and RNA pools in taproots, and not with accumulation and use of starch and sugar pools. Understanding factors leading to the accumulation

of taproot N reserves and RNA during cold acclimation in fall and their use during the initial growth in spring should enhance efforts to improve alfalfa growth and herbage yield in spring.

Corn Yield Response to Phosphorus and Potassium Fertilization in Arkansas

Drescher, G.L., N.A. Slaton, T.L. Roberts, and A.D. Smartt. 2021. Crop, Forage & Turfgrass Mgmt. 7:e20120. DOI: 10.1002/cft2.20120.

Abstract: Phosphorus and potassium are key nutrients for plant physiological processes and are required in large amounts for adequate corn (*Zea mays* L.) production. Corn is a major row crop, and up-to-date soil test-based fertilizer recommendations are required to enhance production and profitability. The results from 32 P and 42 K field trials evaluating irrigated corn response to fertilizer P and K rates were used to (i) correlate corn's relative yield response to Mehlich-3 soil test P and K, (ii) determine the frequency and magnitude of the yield response to fertilization, and (iii) calibrate fertilizer P and K rates to soil test P and K. The quadratic and linear models identified 36 parts per million (ppm) P (r^2 = .68, P < .0001) and 110 ppm K (r^2 = .36, P < .0001) as the Mehlich-3 soil test P and K values needed to produce 95% of maximum yield without fertilization. Additional research is needed on soils with P < 15 and > 35 ppm and K < 60 and > 120 ppm to enhance the scope of data in the analyses and improve our understanding of corn's response to P and K fertilization. The current thresholds defining soil test K levels perform well in interpreting soil K availability and corn's response to K fertilization. Mehlich-3 soil test P level definitions should be modified to improve the accuracy of soil test-based decisions for irrigated corn. The calibration results suggest the recommended P_2O_5 and K_2O rates are greater than needed to maximize yield.

Biofortification of Common Wheat Grains with Combined Ca, Mg, and K through Foliar Fertilisation. Agronomy

Cobalchin F., M. Volpato, A. Modena, L. Finotti, F. Manni, A. Panozzo, and T. Vamerali. 2021. Agronomy 11(9):1718. DOI: 10.3390/agronomy11091718.

Abstract: Common wheat grains are characterised by low concentrations of Ca, K, and Mg, which can be partially removed with the bran during milling processes. This preliminary study investigated the effects of foliar fertilisation at the earing stage with nitrates of Ca, Mg, and K contemporarily, together with a small amount of urea and protein hydrolysate as potential carriers, in two contrasting common wheat varieties, i.e., Solehio (medium proteins content) and Vivendo (high proteins content). Based on the preliminary grain-to-straw concentration ratio of these minerals, two biofortification targets were applied in order to increase their grain contents by +20% and +40%, in comparison with untreated controls. Here, we demonstrate that the highest fertilisation dose was effective in increasing grain K by 13% and Mg by 16% in Vivendo, and Ca by 7% in Solehio, with no boosting effects of the co-formulants urea and protein hydrolysate. In addition to some qualitative benefits due to nitrates supply, negligible phytotoxicity symptoms were observed, as revealed by the NDVI vegetational index dynamics. Although the biofortification target was not fully achieved, this study firstly reports the possibility to increase at the same time Mg and K, and to a lower extent Ca in wheat grains. It is concluded that efficient multiple biofortification should consider a variety-depend response, while further studies are necessary to investigate the effects of different fertilisation timings and doses for improving the poor mineral translocation to the grains.

Potassium Fertilization Improves Growth, Yield and Seed Quality of Sunflower (*Helianthus annuus* L.) under Drought Stress at Different Growth Stages

Dar, J.S., M.A. Cheema, M.I.A. Rehmani, S. Khuhro, S. Rajput, A.L. Virk, S. Hussain, M.A. Bashir, S.M. Alghanem, F.M. Al-Zuaibr, M.J. Ansari, K. Hessini. 2021. PLOS ONE, September 2021. DOI: 10.1371/journal.pone.0256075.

Abstract: Water scarcity is a major concern for sunflower production in the semi-arid and arid regions of the world. Potassium (K) application has been found effective to alleviate the influence of drought stress; however, the impact of drought stress on seed quality of sunflower has not been reported frequently. Therefore, a field experiment was performed to determine the optimum K requirement for mitigating the adverse effects of water stress and improving growth and seed quality of spring-planted sunflower. Sunflower plants were exposed to water stress at different growth stages, i.e., I_o = no stress (normal irrigation), I_1 = pre-anthesisi stress (irrigation skipped at pre-anthesis stage), I_2 = anthesis stress (irrigation skipped at anthesis stage) and I_3 = post-anthesis stress (irrigation skipped at post-anthesis stage). Potassium was applied at four different rates, i.e., K_o = 0, K_1 = 50, K_2 = 100 and K_3 = 150 kg ha^{-1}. The results revealed that water stress at pre- and post-anthesis stages significantly reduced plant height, head diameter, number of achenes, oleic acid contents, and phosphorus (P) uptake. However, pre-anthesis stress improved linoleic acid contents. Treatment I_oK_3 (stress-free with 150 kg ha^{-1} K) was optimum combination for 1000-achene weight, biological and achene yields, oil contents, protein contents, and N and P uptake. Results indicated that a higher amount of K and irrigation resulted in higher yield, whereas yield and yield components decreased with early-stage water stress. Nevertheless, potassium application lowered the impacts of waters stress compared to no application. Keeping in view these results, it is recommended that sunflower must be supplied 150 kg ha^{-1} K in arid and semi-arid regions to achieve higher yield and better seed quality.

Responses to Controlled Release Potassium Fertilisers in Agriculture Following Phosphate Mining

Ruthrof, K.X., E. Steel, R. Yates, P. Skinner, N. Ballard, L. De Prato, H. Calmy, S. Misra, J. McComb, G. O'Hara, G.E. St J. Hardy, and J. Howieson. 2021. Soil Research 59:727-736. DOI: 10.1071/SR20309.

Abstract: The transition from mining to agriculture is hampered by a range of abiotic challenges to crop growth, including nutritional issues and heavy metal stress. Building on our previous work showing that potassium (K) limits legume growth in post-phosphate mining substrates on tropical Christmas Island, Australia, we undertook two field trials. The first compared the efficacy of controlled release K fertilisers (CRFs: KCl 2-month release, K_2SO_4 3-month and K_2SO_4 9-month) with immediately available potassium sulfate (K_2SO_4) fertiliser, on the legume *Lablab purpureus*. The second trial tested responses of *L. purpureus* to different rates of K_2SO_4 9-month CRF, and a combination treatment (CRF and K_2SO_4). Both trials were undertaken to determine how CRFs compare with immediately available K_2SO_4 in terms of increasing biomass, reducing cadmium (Cd) concentrations, maximising plant K concentrations and maintaining K soil retention. The first trial revealed that K_2SO_4 3-month and 9-month CRFs were similar to the 160 kg/ha K_2SO_4 treatment in significantly increasing *L. purpureus* biomass. Plant Cd and other heavy metal concentrations were significantly lower as plant biomass increased with increasing K, including with CRFs. The second trial showed no difference between various rates of K_2SO_4 9-month CRF and immediately available 160 kg/ha K_2SO_4 to increase biomass, reduce Cd or increase K concentrations. We have shown that although post-phosphate mining substrates can limit legume growth, high biomass can be attained with some CRFs, or K_2SO_4 at 160 kg/ha. Optimising nutrient input in post-mining agriculture is critical for developing safe, sustainable crops.

Cotton Yield Response to Soil Applied Potassium across the U.S. Cotton Belt

Lewis, K, G. Morgan, W.H. Frame, D. Fromme, D.M. Dodds, K.L. Edmisten, B. Robertson, R. Boman, T. Cutts, D.P. Delaney, J.A. Burke, and R.L. Nichols. 2021. Agronomy Journal 113:3600-3614. DOI: 10.1002/agj2.20719.

Abstract: Across the U.S. Cotton Belt, potassium (K) deficiency symptoms in cotton (*Gossypium hirsutum* L.) have become more common over the past decade. In 2015–2017, an experiment was conducted in Alabama, Arkansas, Louisiana, Mississippi, North Carolina, Oklahoma, South Carolina, two regions in Texas, and Virginia for a total of 23 site-years. The objectives were (a) to quantify soil K levels at-depth in representative soils where cotton is commonly grown in major cotton production regions with observed K deficiencies; and (b) to evaluate the effects of application method and K rates on cotton lint yield, loan value, and return on fertilizer investment. Granular and liquid potassium chloride were broadcast or injected, respectively, 2–4 wk prior to planting at 0, 45, 90, 135, and 180 kg K_2O ha^{-1}. Locations other than Texas and Oklahoma generally had soil K levels <less than 150 mg kg^{-1}, the Mehlich III critical K level, and thus, a yield response to applied K fertilizer was expected. However, among the 23 site-years, a treatment effect was determined at 5 site-years. Two of those, Williamson County, Texas, and Virginia endured severe moisture stress and resulted in low yields (<526 kg lint ha^{-1}). A positive lint yield response to knife-injected 0–0–15 was determined in 2015 at the Lubbock County, Texas, location—a location with high yield (>1,653 kg lint ha^{-1}). Inconsistent yield responses among locations indicate that K dynamics in the soil–cotton plant system are not well understood and deserve continued investigation.

Biochar Compound Fertilisers Increase Plant Potassium Uptake 2 Years after Application without Additional Organic Fertiliser

Farrar, M.B., H.M. Wallace, , C.Y. Xu, S. Joseph, T.T.N. Nguyen, P.K. Dunn, and S.H. Bai. 2021. Environ Sci Pollut Res. DOI: 10.1007/s11356-021-16236-9.

Abstract: Biochar compound fertilisers (BCFs) are an emerging technology that combine biochar with nutrients, clays and minerals and can be formulated to address specific issues in soil-plant systems. However, knowledge of BCF performance over consecutive crops and without re-application is limited. This study aims to assess the residual effect of organic BCFs soil-plant nutrient cycling 2 years after application and without additional fertiliser inputs. We applied BCFs and biochar with organic fertiliser amendments and established a crop of ginger and a second crop of turmeric (*Curcuma longa*) without re-application or additional fertilisation. All treatment formulations included bamboo-biochar and organic fertiliser amendments; however, two novel BCFs were formulated to promote agronomic response in an intensive cropping system. We report here on the effect of treatments on soil and plant macronutrient and micronutrient cycling and turmeric growth, biomass and yield at harvest. Both BCFs (enriched (10 t ha^{-1}) and organo-mineral biochar (8.6 t ha^{-1}) increased foliar K (+155% and +120%) and decreased foliar Mg (−20% and −19%) concentration compared with all other treatments, suggesting antagonism between K and Mg. Plants were limited for K, P and B at harvest but not N, Ca or Mg. Foliar K was dependent on the biochar formulation rather than the rate of application. Biochar-clay aggregates increased K retention and cycling in the soil solution 2 years after application. Clay blended BCFs reduced K limitation in turmeric compared to biochar co-applied with organic amendments, suggesting these blends can be used to manage organic K nutrition. All formulations and rates of biochar increased leaf biomass and shoot-to-root ratio. Novel BCFs should be considered as an alternative to co-applying biochar with organic fertiliser amendments to decrease application rates and increase economic feasibility for farmers. Applying BCFs without

re-application or supplementary fertiliser did not provide sufficient K or P reserves in the second year for consecutive cropping. Therefore, supplementary fertilisation is recommended to avoid nutrient deficiency and reduced yield for consecutive organic rhizome crops.

Effects of Straw Returning and Potassium Fertilizer Application on Root Characteristics and Yield of Spring Maize in China, Inner Mongolia

Fan, Y., J. Gao, J. Sun, J. Liu, Z. Su, Z. Wang, X. Yu, and S. Hu. 2021. Agronomy Journal 113:4369-4385. DOI: 10.1002/agj2.20742.

Abstract: Exploring the effects of straw return (ST) and potassium fertilizer on soil structure, spring maize (*Zea mays* L.) root growth, K-absorption efficiency and yield is essential for devising optimized straw return and potassium fertilizer management practices to increase grain yield for food security. In this study, two straw return levels used were straw return, no straw return and two potassium application levels used were 6K (90 kg/ha potassium application), no potassium (0K). Analyzed the effects of the above four treatments on soil structure, spring maize root indicators, K-absorption efficiency and yield in three ecological regions in two years. The results showed that the effect of straw return on soil structure and root growth was better than that of applying potassium fertilizer. The effect of potassium fertilizer application on maize grain yield and K-absorption efficiency was better than that of straw return. The impact of the interaction was better than straw return or the application potassium fertilizer alone. Straw return improved the effects of potassium fertilizer on soil bulk density, soil porosity, spring maize root length, root surface area, root volume, maize grain K-absorption efficiency and yield by 3.99%–7.27%, 3.89%–7.40%, 1.35%–71.01%, 19.16%–42.45%, 10.49%–22.73%, 13.57%–19.67% and 4.43%–7.05%, respectively. Therefore, the interaction of straw return and potassium fertilizer was the best measure to maintain high and stable maize yield, increasing K-absorption efficiency and improving the nutrient resource management of straw and potassium fertilizer, which was appropriate for spring maize planting.

Screening of the Optimal Potassium Fertilization Rate for Maximizing Bulb Yield and Potassium Nutrient Evaluation in *Fritillaria thunbergii* Miq

Wang, L., J. Sun, G. Kai, and N. Sui. 2021. Clinical Complementary Medicine and Pharmacology 1(1):100003. DOI: 10.1016/j.ccmp.2021.100003.

Background: The dry bulb of *Fritillaria thunbergii* Miq. is a traditional Chinese medicine, and is the leading product of the geo-authentic crude drugs ‘Zhebawei’ in Zhejiang Province. *Fritillaria thunbergii* requires more potassium (K) than nitrogen and phosphorus, while the response of *F. thunbergii* to K has rarely been studied.

Objective and Methods: To evaluate the K nutritional status of *F. thunbergii*, a 2-year field experiment was conducted under six K application rates (0, 40, 80, 120, 160, and 200 kg K_2O ha^{-1}) with two *F. thunbergii* cultivars (ZB1, narrow-leaf; ZB2, broad-leaf).

Results: The bulbus Fritillariae Thunbergii (BFT) yield increased to a plateau with more than ~120 kg K_2O ha^{-1}. The BFT quality met the standard of Pharmacopoeia of P. R. China with more than 40.0 kg K_2O ha^{-1}. Leaf K concentration was significantly correlated with BFT yield, and was more sensitive to K application rate as compared to those of stems and flowers. Potassium application extended the duration of rapid leaf-biomass accumulation and increased the accumulation rate. Two cultivars had similar response patterns to K application, but ZB2 had higher K partial productivity, leaf-biomass, and leaf K concentration than ZB1.

Conclusion: 108.4–128.0 kg K_2O ha^{-1} was the optimal K application range for BFT yield. The potassium nutrition index (KNI) model established based on leaf K concentration has biological significance and can be used for dynamic diagnosis of K nutritional status of *F. thunbergii* with both accuracy and simplicity.

Potassium Alleviates Post-anthesis Photosynthetic Reductions in Winter Wheat Caused by Waterlogging at the Stem Elongation Stage

Gao, J., Y. Su, M. Yu, Y. Huang, F. Wang, and A. Shen. 2021. Front. Plant Sci. 11:607475. DOI: 10.3389/fpls.2020.607475.

Abstract: Waterlogging occurs frequently at the stem elongation stage of wheat in southern China, decreasing post-anthesis photosynthetic rates and constraining grain filling. This phenomenon, and the mitigating effect of nutrient application, should be investigated as it could lead to improved agronomic guidelines. We exposed pot-cultured wheat plants at the stem elongation stage to waterlogging treatment in combination with two rates of potassium (K) application. Waterlogging treatment resulted in grain yield losses, which we attributed to a reduction in the 1,000-grain weight caused by an early decline in the net photosynthetic rate (Pn) post-anthesis. These decreases were offset by increasing K application. Stomatal conductance (G_s) and the intercellular CO_2 concentration (C_i) decreased in the period 7–21 days after anthesis (DAA), and these reductions were exacerbated by waterlogging. However, in the period 21–28 DAA, G_s and C_i increased, while Pn decreased continuously, suggesting that non-stomatal factors constrained photosynthesis. On DAA 21, Pn was reduced by waterlogging, but photochemical efficiency (Φ_{PSII}) remained unchanged, indicating a reduction in the dissipation of energy captured by photosystem II (PSII) through the CO_2 assimilation pathway. This reduction in energy dissipation increased the risk of photodamage, as shown by early reductions in Φ_{PSII} in waterlogged plants on DAA 28. However, increased K application promoted root growth and nutrient status under waterlogging, thereby improving photosynthesis post-anthesis. In conclusion, the decrease in Pn caused by waterlogging

was attributable to stomatal closure during early senescence; during later senescence, a reduction in CO_2 assimilation accounted for the reduced Pn and elevated the risk of photodamage. However, K application mitigated waterlogging-accelerated photosynthetic reductions and reduced yield losses.

Potassium Balance under Soybean–Wheat Cropping System in a 44 Year Old Long Term Fertilizer Experiment on a Vertisol

Priyanka Pathariya, B.S Dwivedi, A.K. Dwivedi, R.K. Thakur, M. Singh, and S. Sarvade. 2021. Communications in Soil Science and Plant Analysis 53(2):214-226. DOI: 10.1080/00103624.2021.1984516.

Abstract: Applications of fertilizers alone and in combination with organic manure significantly increased the organic carbon, available nitrogen, phosphorous, potassium, and K fractions, i.e., water soluble-K, exchangeable-K, non-exchangeable-K, lattice-K, and total-K in both surface and subsurface soils and without K input (100% NP & 100% N). Among the various K fractions, lattice K was the dominant K fraction. The highest values of these fractions were found in 100% NPK + 5 t FYM ha^{-1}. The relative contents of these fractions were in order, lattice-K > non-exchangeable K > exchangeable K > water soluble K, and these were higher in surface than the subsurface soils. Correlation studies revealed significant positive relationship of organic carbon and available N, P, and K with different K fractions in surface and subsurface soils. Furthermore, the minimum depletion of the K rate was recorded in 100% NPK + FYM (−2.25 kg ha^{-1} yr^{-1}) to that of other treatments, while control showed a maximum K depletion rate (−3.86 kg ha^{-1} yr^{-1}). Apparent K balance in soil was the lowest, −61 kg ha^{-1} yr^{-1}, in control plot followed by −165 kg ha^{-1} yr^{-1} in the treatment of 100% NPK + FYM. Hence, much attention is required for potassium fertilizers to maintain the K status of soil and to prevent K mining.

Co-Application of Charcoal and Wood Ash to Improve Potassium Availability in Tropical Mineral Acid Soils

Paramisparam, P., O.H. Ahmed, L. Omar, H.Y. Ch'ng, P.D. Johan, and N.H. Hamidi. 2021. Agronomy 11(10):2081. DOI: 10.3390/agronomy11102081.

Abstract: Potassium (K) is a macronutrient required by plants for energy production, enzyme activation, formation of cell wall, production of protein, and photosynthesis. However, K in the soil solution is leached from the rhizosphere before it interacts with soil colloids because of the abundance of kaolinite clay minerals in mineral acid soils such as Ultisols and Oxisols. These soils are highly weathered, low in organic matter, low in pH, but high aluminium (Al), and iron (Fe) ions. As a result, K becomes unavailable for plants, and this affects crop production and farmers' profitability. This problem has steered the attention to the application of amendments to minimise K loss. Animal manures, plant residues, and composts applications are some of the corrective measures taken to improve the K availability in tropical acid soils. However, there is dearth of information on co-application of charcoal and wood ash as soil amendments to improve the K availability and the changes they cause to the dynamic equilibrium of K in mineral acid soils. Hence, this review discusses the dynamics, availability of K, and proposed mechanisms involved when charcoal and wood ash are used to amend tropical acid soils. The optimisation and understanding of the role of charcoal and wood ash co-application as soil amendments have potential benefits to improve the K availability and physicochemical properties of mineral acid soils.

Sodium Influx and Potassium Efflux Currents in Sunflower Root Cells Under High Salinity

Hryvusevich, P., I. Navaselsky, Y. Talkachova, D. Straltsova, M. Keisham, A. Viatoshkin, V. Samokhina, I. Smolich, A. Sokolik, X. Huang, M. Yu, S.C. Bhatla, and V. Demidchik. 2021. Front. Plant Sci. 11:613936. DOI: 10.3389/fpls.2020.613936.

Abstract: *Helianthus annuus* L. is an important oilseed crop, which exhibits moderate salt tolerance and can be cultivated in areas affected by salinity. Using patch-clamp electrophysiology, we have characterized Na^+ influx and K^+ efflux conductances in protoplasts of salt-tolerant *H. annuus* L. hybrid KBSH-53 under high salinity. This work demonstrates that the plasma membrane of sunflower root cells has a classic set of ionic conductances dominated by K^+ outwardly rectifying channels (KORs) and non-selective cation channels (NSCCs). KORs in sunflower show extreme Na^+ sensitivity at high extracellular $[Ca^{2+}]$ that can potentially have a positive adaptive effect under salt stress (decreasing K^+ loss). Na^+ influx currents in sunflower roots demonstrate voltage-independent activation, lack time-dependent component, and are sensitive to Gd^{3+}. Sunflower Na^+-permeable NSCCs mediate a much weaker Na^+ influx currents on the background of physiological levels of Ca^{2+} as compared to other species. This suggests that sunflower NSCCs have greater Ca^{2+} sensitivity. The responses of Na^+ influx to Ca^{2+} correlates well with protection of sunflower growth by external Ca^{2+} in seedlings treated with NaCl. It can be, thus, hypothesized that NaCl tolerance in sunflower seedling roots is programmed at the ion channel level via their sensitivity to Ca^{2+} and Na^+.

Root K Affinity Drivers and Photosynthetic Characteristics in Response to Low Potassium Stress in K High-Efficiency Vegetable Soybean

Liu, C., X. Wang, B. Tu, Y. Li, H. Chen, Q. Zhang, and X. Liu. 2021. Front. Plant Sci. 12:732164. DOI: 10.3389/fpls.2021.732164.

Abstract: Significant variations of potassium absorption and utilization exist in vegetable soybean. Pot and hydroponic experiments were carried out to examine the characteristics of

root potassium (K) affinity-associated drivers and photosynthesis in vegetable soybean (edamame) [*Glycine max* (L.) Merr.] with different K efficiency. Two K high-efficiency vegetable soybean genotypes (Line 19 and Line 20) and two K low-efficiency genotypes (Line 7 and Line 36) were investigated in low K and normal K conditions. The root of K high-efficiency genotypes had a higher K^+ affinity associated with a higher maximum K^+ uptake rate (*I*max), but lower Michaelis constant for K^+ absorption (*K*m) and lower compensation concentration for K^+ uptake (*C*min). Seedlings of K high-efficiency genotypes also had higher root vigor [triphenyl tetrazolium chloride (TTC) reduction method] and greater absorbing activity (methylene blue method), especially in the low K condition. Furthermore, the root bleeding-sap rate of K high-efficiency genotypes in low K stress was 9.9–24.3% greater than that of normal K conditions, which was accompanied by a relatively higher K concentration of root bleeding-sap in contributing to K^+ upward flux. The root of K high-efficiency vegetable soybean genotypes exhibited K^+ high-affinity and driving advantages. Photosynthetic parameters of K high-efficiency vegetable soybean genotypes were less affected by low K stress. Low K stress decreased the net photosynthetic rate of K high-efficiency genotypes by 6.1–6.9%, while that of K low-efficiency genotypes decreased by 10.9–15.7%. The higher chlorophyll (Chl) a/b ratio with enhanced relative content of Chl a in response to low K stress might be an adapted mechanism for K high-efficiency genotypes to maintain photosynthetic capacity. Stronger root K affinity drivers associated with photosynthetic adaptability to low K stress are the key factors in determining the K high-efficiency of vegetable soybeans.

The Landscape of Alternative Splicing Regulating Potassium Use Efficiency in *Nicotiana tabacum*

He, B., L. Meng, L. Tang, W. Qi, F. Hu, Y. Lv, and W. Song. 2021. Front. Plant Sci. 12:774829. DOI: 10.3389/fpls.2021.774829.

Abstract: Alternative splicing (AS) occurs extensively in eukaryotes as an essential mechanism for regulating transcriptome complexity and diversity, but the AS landscape regulating potassium (K) use efficiency in plants is unclear. In this study, we performed high-throughput transcriptome sequencing of roots and shoots from allopolyploid *Nicotiana tabacum* under K^+ deficiency. Preliminary physiological analysis showed that root system architecture was dramatically changed due to potassium deficiency and that IAA content was significantly reduced in root and shoot. AS analysis showed that a total of 28,179 genes exhibited 54,457 AS events, and 1,510 and 1,732 differentially alternatively spliced (DAS) events were identified in shoots and roots under low K^+ stress. Nevertheless, only 120 DAS events occurred in both shoots and roots, implying that most DAS events were tissue-specific. Both in shoot and the root, the proportion of DAS genes in differentially expressed (DE) genes equaled that in non-DE genes, which indicated that AS might play a unique regulatory role in response to low potassium. Gene ontology analysis further indicated that transcription regulation and AS modulation worked independently in response to low K^+ stress in tobacco, as their target biological processes were different. Totally 45 DAS transcription factors (TFs) were found, which were involved in 18 TF families. Five Auxin response factor (ARF) TFs were significantly DAS in root, suggesting that response to auxin was probably subject to AS regulation in the tobacco root. Our study shows that AS variation occurs extensively and has a particular regulatory mechanism under K^+ deficiency in tobacco. The study also links changes in root system architecture with the changes in AS of ARF TFs, which implied the functional significance of these AS events for root growth and architecture.

Effect of Different Foliar Potassium Fertilization Forms on Vegetative Growth, Yield, and Fruit Quality of Kaki Trees Grown in Sandy Soil

Lo'ay, A.A., S.F.A. EL-Ezz, and A.A. Awadeen. 2021. Scientia Horticulturae 288:110420. DOI: 10.1016/j.scienta.2021.110420.

Abstract: Kaki cultivar 'Costata' suffers from potassium (K) deficiency especially it is growing in sandy soil, which results in decreased production. In the current study, we estimated the different foliar potassium fertilization forms (KCl, K_2SO_4, and potassium nanoparticles: K-NPs). K forms were applied on four fruit developmental stages (Flowering, Fruit set, version, at harvest stages). The treatment of K-NPs enhanced chlorophyll content and carotene pigments. Malondialdehyde content (MDA), and ions leakage (IL) were reduced comparison with the untreated control trees and other potassium form treatments. Furthermore, significantly increased K^+ and percent than other treatment forward with an increase in chlorophyll content, leaf area, and shoot carbohydrates at K-NPs form treatment. The overall results revealed that K-NPs application can induce K^+ uptake, modulate Na^+ levels and decrease cell wall damage in the treated plants comparing to the untreated control trees. Our results recommend that the application of K-NPs can assist support tree integrity in the kaki cultivar Costata' under the sandy soil.

Silencing of *GhKEA4* and *GhKEA12* Revealed Their Potential Functions Under Salt and Potassium Stresses in Upland Cotton

Li Y., Z. Feng, H. Wei, S. Cheng, P. Hao, S. Yu, and H. Wang. 2021. Front. Plant Sci. 12:789775. DOI: 10.3389/fpls.2021.789775.

Abstract: The K^+ efflux antiporter (KEA) mediates intracellular K^+ and H^+ homeostasis to improve salt tolerance in plants. However, the knowledge of KEA gene family in cotton is largely absent. In the present study, 8, 8, 15, and 16 putative KEA genes were identified in *Gossypium arboreum*, *G. raimondii*, *G. hirsutum*, and *G. barbadense*, respectively. These KEA genes were classified into three subfamilies, and members from the same subfamilies showed similar motif compositions and gene structure characteristics. Some hormone

response elements and stress response elements were identified in the upstream 2000 bp sequence of *GhKEAs*. Transcriptome data showed that most of the *GhKEAs* were highly expressed in roots and stems. The quantificational real-time polymerase chain reaction (qRT-PCR) results showed that most of the *GhKEAs* responded to low potassium, salt and drought stresses. Virus-induced gene silencing (VIGS) experiments demonstrated that under salt stress, after silencing genes *GhKEA4* and *GhKEA12*, the chlorophyll content, proline content, soluble sugar content, peroxidase (POD) activity and catalase (CAT) activity were significantly decreased, and the Na^+/K^+ ratio was extremely significantly increased in leaves, leading to greater salt sensitivity. Under high potassium stress, cotton plants silenced for the *GhKEA4* could still maintain a more stable Na^+ and K^+ balance, and the activity of transporting potassium ions from roots into leaves was reduced silenced for *GhKEA12*. Under low potassium stress, silencing the *GhKEA4* increased the activity of transporting potassium ions to shoots, and silencing the *GhKEA12* increased the ability of absorbing potassium ions, but accumulated more Na^+ in leaves. These results provided a basis for further studies on the biological roles of KEA genes in cotton development and adaptation to stress conditions.

NaCl Enhance the Growth of Swiss Chard (*Beta vulgaris* L.) Leaves Under Potassium-Deficient Conditions

Liu, L., D.V.M. Assaha, M.S. Islam, M.M. Hassan, A. EL Sabagh, and H. Saneoka. 2021. J Soil Sci Plant Nutr 21:1949-1956. DOI: 10.1007/s42729-021-00492-2.

Abstract: Potassium (K^+) deficiency significantly reduces crop yield and nutritional quality in many arable lands worldwide. As a non-essential element in plants, Na^+ is effective in alleviating the toxic effects of salinity under low K^+ concentrations. The objective of this study was to evaluate the role of NaCl in modifying the response of Swiss chard (*Beta vulgaris* L.) to K^+ deficiency at high concentrations and the effects of K^+ deficiency on shoot growth, mineral assimilation, lipid peroxidation, and antioxidant enzyme activities in the presence of gradually increasing NaCl concentrations. Forty-seven-day-old Swiss chard seedlings were treated by individual K^+-deficient conditions and combined conditions of K^+ deficiency and salinity for 9 days. The results showed that both the shoot fresh and dry weights of the Swiss chard seedlings were markedly reduced when grown in the solely K^+-deficient conditions, but the addition of NaCl significantly ameliorated the K^+ deficiency–induced reductions in the shoot growth. NaCl also significantly enhanced the total phosphorus and PO_4^{3-} concentrations in the leaves. Moreover, NaCl addition to the K^+-deficient plants protected the cell membrane integrity instead of damaging the cell membranes. NaCl addition to Swiss chard seedlings grown in K^+-deficient conditions has the potential to minimize K^+ deficiency–induced damage and maintain the growth of the plants to levels comparable with control conditions.

Variation in the Ionome of Tropical 'Metal Crops' in Response to Soil Potassium Availability

Nkrumah, P.N., G. Echevarria, P.D. Erskine, R.L. Chaney, S. Sumail, and A. van der Ent. 2021. Plant Soil 465:185-195. DOI: 10.1007/s11104-021-04995-w.

Background and Aims: In tropical ultramafic soils, potassium (K) is typically the most growth limiting nutrient. However, tropical nickel (Ni) hyperaccumulator plants, including *Phyllanthus rufuschaneyi* and *Rinorea* cf. *bengalensis* (which are 'metal crops' used in agromining) from Malaysia, have unusually high K shoot accumulation compared to other species, despite naturally growing on severely K-impoverished ultramafic soils. This study aimed to establish the response to soil K availability in relation to uptake of K and other elements in the roots and shoots of *P. rufuschaneyi* and *R.* cf. *bengalensis*.

Methodology: We undertook an experiment in which soluble K was dosed to ultramafic soil in pots with *P. rufuschaneyi* and *R.* cf. *bengalensis* in Sabah (Malaysia).

Results: The results show that root K concentrations increased markedly as the soil K availability increased by 35-fold, whilst the corresponding effect on K accumulation in the shoots of *P. rufuschaneyi* and *R.* cf. *bengalensis* was not significantly different in relation to soil K dosing. Observed divergent responses between root and shoot K accumulation in these species suggests a separate genetic control of K uptake and xylem loading in *P. rufuschaneyi* and *R.* cf. *bengalensis*.

Conclusion: The tight control of root-to-shoot K translocation and constrained K accumulation in shoots under a soil K gradient is likely an adaptive mechanism to the evolution of these species to grow in highly nutrient-impoverished ultramafic soils. This study provides information that will be useful for better nutrient management of tropical Ni metal farms that use K-efficient Ni 'metal crops'.

Morphophysiological and Phytochemical Changes of *Mentha piperita* using Calcium, Potassium, Iron and Manganese Nano-Fertilizers

Bagheri, H., A. Ladan Moghadam, E. Danaee, and V. Abdossi. 2021. Eur. J. Hortic. Sci. 86(4):419-430. DOI: 10.17660/eJHS.2021/86.4.10.

Abstract: This study was conducted to investigate the effects of foliar application of iron, potassium, calcium and manganese nano-chelates on morphological, physiological and biochemical traits of *Mentha piperita* (Peppermint) in a completely randomized design with two experiments. In the first experiment, foliar application of plants was performed with three levels of iron, potassium, calcium and manganese nano-chelates (2, 4 and 6 mg L^{-1}). In the second experiment, foliar application of plants was performed with the best level of each treatment of the first experiment (6 mg L^{-1} in most traits

for the applied elements). The second experiment also consisted of 12 treatments, with 3 replicates. Foliar application was performed three times during a week and after two weeks of sampling, and the traits, including fresh and dry weight of the aerial parts, total leaf chlorophyll content, protein content, peroxidase activity, total phenol content, iron, potassium, calcium and manganese content values and essential oil percentage, were evaluated. The results showed that in the first experiment, the effect of treatment on leaf protein, phenol and iron content was significant at 5% and on other traits at 1%. In the second experiment, the effect of treatment on leaf protein, iron and calcium content was significant at 5% and on the other traits was significant at 1%. According to the results of both experiments, the effect of treatments on leaf protein and iron content values at different treatment concentrations was significant at 5% level. Among all applied concentrations Nano Ch Fe_6 showed the highest content in leaf fresh/dry weight, chlorophyll, peroxidase activity in the first experiment; Leaf fresh/dry weight, total leaf chlorophyll, leaf protein, peroxidase activity, phenol content, leaf iron, potassium, calcium, manganese content and essential oil percentage Nano Ch (Fe_6+ K_6+ Ca_6+ Mn_6) had the highest amount in the second experiment.

Does the Short-Term Fluctuation of Mineral Element Concentrations in the Closed Hydroponic Experimental Facilities affect the Mineral Concentrations in Cucumber Plants Exposed to Elevated CO_2?

Li, X., J. Dong, N. Gruda, W. Chu, and Z. Duan. 2021. Plant Soil 465:125-141. DOI: 10.1007/s11104-021-04993-y.

Aims: Studies dealing with plants' mineral nutrient status under elevated atmospheric CO_2 concentration (eCO_2) are usually conducted in closed hydroponic systems, in which nutrient solutions are entirely renewed every several days. Here, we investigated the contribution of the fluctuation of concentrations of N ([N]), P ([P]), and K ([K]) in nutrient solutions in this short period on their concentrations in cucumber plants exposed to different [CO_2] and N levels.

Methods: Cucumber (*Cucumis sativus* L.) plants were hydroponically grown under two [CO_2] and three N levels. [N], [P], and [K] in nutrient solutions and cucumber plants were analyzed.

Results: The transpiration rate (Tr) was significantly inhibited by eCO_2, whereas Tr per plant was increased due to the larger leaf area. Elevated [CO_2] significantly decreased [N] in low N nutrient solutions, which imposed an additional decrease in [N] in plants. [P] in nutrient solutions fluctuated slightly, so the change of [P] in plants might be attributed to the dilution effect and the demand change under eCO_2. [K] in moderate and high N nutrient solutions were significantly decreased, which exacerbated the [K] decrease in plants under eCO_2.

Conclusions: The short-term fluctuation of [N] and [K] in nutrient solutions is caused by the asynchronous uptakes of N, K, and water under eCO_2, which has an appreciable influence on [N] and [K] in plants besides the dilution effect. This defect of the closed hydroponic system may let us exaggerate the negative impact of eCO_2 itself on [N] and [K] in plants.

Potassium, an Important Element to Improve Water use Efficiency and Growth Parameters in Quinoa (*Chenopodium quinoa*) under Saline Conditions

Turcios, A.E., J. Papenbrock, and M. Tränkner. 2021. J Agro Crop Sci. 207:618- 630. DOI: 10.1111/jac.12477.

Abstract: Due to changes in the ecosystem and misuse of resources, salinity also increases. Approximately 20% of all irrigated land is affected by salinity and this will increase over time. Therefore, it is necessary to develop more environmentally friendly agricultural techniques but also to exploit potential crops with high nutritional value and tolerance to salinity like quinoa (*Chenopodium quinoa* Willd.). In this context, potassium is an essential macronutrient for plant growth and development. Furthermore, one of the strategies of some salt-tolerant plants is to increase the uptake of potassium under saline conditions such that the K^+/Na^+ ratio is maintained for a proper osmotic regulation in cells. Therefore, a study was conducted to investigate the effect of different concentrations of potassium (0.5, 2 and 6 mM K) on quinoa under different salinities (0, 100 and 200 mM NaCl). According to the results, an adequate supply of potassium under moderate salinity conditions benefited the plant growth, with a higher potassium uptake in the presence of salt. Under saline conditions, plant transpiration decreased significantly with a high correlation with stomatal density and a greater water use efficiency. Therefore, under saline conditions, adequate doses of potassium are highly recommended in quinoa cultivation.

Can Nutrient-Utilization Efficiency be Improved by Reduced Fertilizer Supply to Maize Plants Treated with the Plant Growth Regulator Paclobutrazol?

Hütsch, B.W., and S. Schubert. 2021. Journal of Agronomy and Crop Science 207:884-900. DOI: 10.1111/jac.12521.

Abstract: In previous investigations of several maize cultivars, an improvement of the harvest index was obtained by paclobutrazol (PAC) application combined with an increase in water-use efficiency. However, so far nutrient-utilization efficiencies could not be enhanced when control and PAC-treated maize plants received the same amount of fertilizers. With adjusted fertilizer supply according to the lower requirement of the smaller, PAC-treated plants, an improvement of nutrient-utilization efficiencies may be expected. Thus, in the present study, PAC was applied at growth stage V5 to two maize cultivars (*Zea mays* L. cvs. Galactus and Fabregas) grown in a container experiment. Shortly after PAC application, differential NPK fertilization was introduced in order to obtain a nutrient supply according to the requirement of control plants (100% NPK), the requirement of PAC-treated plants (85% NPK) and a

further slight decrease (78% NPK). Plant height and transpiration rates were significantly reduced due to PAC treatment with stronger effects on Galactus than on Fabregas. Pollen shed, silking and the anthesis-silking interval (ASI) were unaffected by PAC application and fertilizer supply. Senescence of PAC-treated plants was delayed, whereas it was accelerated with reduced fertilizer supply. The grain yield of cultivar Galactus was significantly decreased due to PAC application by 13% to 20%, and this effect was strengthened due to reduction in NPK supply. These grain yield reductions were solely caused by decreases in kernel number, which were closely linked to reductions in cob length. On the contrary, PAC treatment did not affect grain yield of Fabregas and reductions due to less NPK supply were small. Harvest index and water-use efficiency were enhanced by PAC treatment. Plant nutrient contents were similar for control and PAC-treated plants, but strongly related to fertilizer supply with significant decreases due to reductions in NPK application. The N-, P- and K-utilization efficiencies of both cultivars were either decreased or unaffected by PAC treatments. The key constraint for improvements of nutrient-utilization efficiencies is grain yield reduction due to PAC. This problem should be addressed in further studies with avoidance of grain yield decreases by delayed application time combined with fine-tuning of cultivar-specific PAC application rates.

Combined Effects of Cations in Fertilizer Solution on Antioxidant Content in Red Lettuce (*Lactuca sativa* L.)

Sawatdee, S., C. Prommuak, T. Jarunglumlert, P. Pavasant, and A.E. Flood. 2021. J. Sci. Food Agric. 101:4632-4642. DOI: 10.1002/jsfa.11106.

Background: Red lettuce is consumed worldwide because it is a great source of natural antioxidants. To design a fertilizer formula to boost its nutritional value, this research simultaneously studied the effects of significant cations among the macronutrients for plant growth (K, Mg and Ca) and the effects of the electrical conductivity (EC) of the nutrient solution on phenolic compound production and mass productivity of hydroponically grown red lettuce.

Results: Red lettuce grown under the control treatment provided the highest mass productivity (under low-stress conditions). The highest antioxidant content, measured as milligrams of phenolic compounds per gram dry weight (at a high-stress condition) via both Folin–Ciocalteu and HPLC analyses, was observed in growth media containing 100 ppmK: 20 ppm Mg: 70 ppm Ca (with EC equal to 1241 $\mu S\,cm^{-1}$). It was found that EC within the range of this examination had no significant effect on the mass productivity or on phenolic compound productivity. The phenolic compound productivity, defined as the amount of phenolic compounds produced per unit of planting area per unit of time, was optimized with the optimum formula for maximum phenolic compound productivity of 90 ppm K: 29 ppm Mg: 77 ppm Ca, or a corresponding EC of 1307 $\mu S\,cm^{-1}$.

Conclusions: The study demonstrates that health-promoting nutrient production in red lettuce could be stimulated in a practical manner by adjusting the cation concentrations in fertilizer solution.

Influence of Phosphorus Sources on the Partial Replacement of Potassium by Sodium in the Fertilization of Mombasa Grass

Guarnieri, A., R. da Costa Leite, G. do Carmo Alexandrino, L.U. Rodrigues, G.A. de Freitas, R.R. da Silva, and A.C. dos Santos. 2021. Journal of Plant Nutrition, 44:15, 2274-2284. DOI: 10.1080/01904167.2021.1889592.

Abstract: Supplementation of Na in reduced amounts can eliminate K deficiency through the partial substitution K^+ by Na^+, reducing pasture fertilization costs. This replacement requires adjustments considering the crop, since high levels of exposure to Na correlate negatively with the absorption and transport of phosphorus to the leaves by the plants. Therefore, this study aimed to evaluate the effects of phosphate sources associated with the partial replacement of K^+ by Na^+ in Mombasa grass (*Megathyrsus maximus*). The experiment was carried out under greenhouse conditions using a completely randomized experimental design with three replications. A total of twelve treatments were obtained in a 3 × 4 factorial scheme, represented by three sources of phosphorus: simple superphosphate, natural phosphate and UFT-fertil organic compound and for four doses of Na^+ (NaCl) in order to replace the recommended dose of K^+ (80 mg dm^{-3}): 0 + 80, 20 + 60, 40 + 40 and 60 + 20 mg dm^{-3} of $Na^+ + K^+$, respectively. Overall, superphosphate showed the lowest values for sodium adsorption ratio, percentage of exchangeable Na^+ and its contents in the soil. There was no reduction in the productivity of Mombasa grass due to the partial replacement of K^+ by Na^+ when using superphosphate.

Impact of Source and Method of Potassium Application on Dry Matter Accumulation and Partitioning of Potassium in Rice (*Oryza sativa* L.)

Kundu, A., P. Raha, and A.N. Dubey. 2021. J. Soil Sci. Plant Nutr. 21:2252-2263. DOI: 10.1007/s42729-021-00518-9.

Abstract: The experiment was carried out to assess dry matter accumulation and potassium partitioning in submerged rice upon application of three organic potassium salts, viz., potassium citrate (KC), potassium gluconate (KG), and potassium humate (KH), and inorganic salt, potassium sulfate (KS). Treatments included recommended dose of potassium (RDF-K, 60 kg ha^{-1}) via foliar or soil application of KS, alone or in combination with foliar application of three organic potassium salts (KC, KG, and KH), in three split doses at three rice phenological stages, viz., tillering, panicle initiation, and early flowering. Solely foliar application of organic K salts resulted in 76% K uptake in rice straw compared with 13% K uptake in grain, which diminished internal use efficiency (IUE) and partial factor productivity (PFP) of K. Conjoint application of KS (half of RDF-K as soil application) and KH (half of RDF-K as foliar

spraying) obtained highest grain K accumulation and significantly enhanced IUE and PFP of K. KH performed best among the different K salts used and significantly enhanced root dry matter which resulted in significantly highest grain N and P uptake. This study confirmed that organic salts of K altered dry matter and K partitioning, and soil application of KS (half of RDF-K) in combination with foliar application of KH (half of RDF-K) at three growth stages elevated K utilization efficiency of submerged rice.

Barley (*Hordeum vulgare* L.) Physiology Including Nutrient Uptake Affected by Plant Growth Regulators Under Field Drought Conditions

Askarnejad, M.R., A. Soleymani, and H.R. Javanmard. 2021. Journal of Plant Nutrition 44(15):2201-2217. DOI: 10.1080/01904167.2021.1889593.

Abstract: Finding a method, which may increase barley (*Hordeum vulgare* L.) growth and nutrient uptake under drought stress, is of significance. The objective of the research (conducted as a split plot with three replicates in two different research fields in 2018–2019) was to investigate the effects of different plant growth regulators (PGR) on the physiology including nutrient uptake of barley under field drought stress. The drought levels including 80 mm (control), 100 (mild) and 120 mm (high) evaporation from the pan class A were devoted to the main plots, and different PGR including spraying with water (control, T1), (2) gibberellic acid (GA_3 at 110 mg/l, T2), (3) salicylic acid (SA at 1.5 mM, T3), (4) benzyl adenine (BA_6 at 60 mg/l, T4), (5) GA_3 + SA (T5), and (6) superoxide dismutase (SOD at 5 mg/l, T6) were used as subplots. Different plant physiological properties including grain protein, chlorophyll a and b, leaf relative water content (at pollination and physiological maturity), wet and dry gluten, soluble and insoluble sugar, and grain nitrogen (N), phosphorous (P), and potassium (K) uptake were determined. Analyses of variance indicated the significant effects of the experimental treatments on the measured parameters. Although barley physiology including nutrient uptake were significantly decreased by drought stress, the use of PGR significantly improved such parameters under the stress, and T5 (GA_3 + SA) followed by T6 (super oxide dismutase) were the most effective ones. It is possible to enhance barley physiology including nutrient uptake, under drought stress, using the tested PGR.

Novel Water-Soluble Polymer Coatings Control NPK Release Rate, Improve Soil Quality and Maize Productivity

Akhter, M., G.A. Shah, M.B.K. Niazi, S. Mir, Z. Jahan, and M.I. Rashid. 2021. J. Appl. Polym. Sci. 138(42):e51239. DOI: 10.1002/app.51239.

Abstract: We investigated different combinations of polymers (5% each) (i) starch, gelatin (polymer coating; PC-1), (ii) polyvinyl alcohol (PVA), gum Arabica (PC-2), (iii) PVA, gelatin (PC-3), (iv) starch, gum Arabica (PC-4), (v) gelatin, gum Arabica (PC-5), (vi) starch, PVA (PC-6), for coating NPK (17, 17:17) in a fluidized bed granulator. Morphological characterization indicated a uniform coating of all formulations on NPK granules. A slow release of N (PC-3), P (PC-6), and K (PC-3) was observed in water. In soil, high mineral N (63%), plant-available P (72%), and K (24%) were observed in PC-3, PC-5, and PC-6, respectively than uncoated fertilizer. Microbial biomass NPK was also higher in these treatment. This resulted in higher maize yield (66%), N (114%), P (164%), and K (137%) uptakes and apparent N (267%), P (196%), and K (358%) recoveries from applied fertilizer in these treatments. Among these, PC-3 resulted in an increase of 115% shoot N, 169% P and 138% K uptakes and 268% apparent N, 206% P and 361% K recoveries than uncoated fertilizer. Hence, coating of NPK with this biodegradable polymer combination controlled N, P, and K release and synchronized these nutrients availabilities with maize nutrients demand therefore resulted in higher maize crop yield and nutrient utilization efficiencies.

Variation in Soil-test-based Phosphorus and Potassium Rate Recommendations across the Southern USA

Zhang, H., J. Antonangelo, J. Grove, D. Osmond, N.A. Slaton, S. Alford, R. Florence, G. Huluka, D.H. Hardy, J. Lessl, R. Maguire, R. Mylavarapu, J.L. Oldham, E.M. Pena-Yewtukhiw, T. Provin, L. Sonon, D. Sotomayor, and J. Wang. 2021. Soil Sci. Soc. Am. J. 85:975-988. DOI: 10.1002/saj2.20280.

Abstract: Thirteen states associated with the Southern Extension and Research Activities Information Exchange Group-6 (SERA-IEG-6) agreed to share their soil test based P and K rate recommendations for nine major crops. The objectives were to compare fertilizer P and K rate recommendations, to look for opportunities to rationalize similar recommendations across state lines, and to examine challenges to the development of a cooperative regional approach to P and K recommendations. Mehlich-3 (eight states), Mehlich-1 (five states), or Lancaster (one state) extractions were the basis of plant available soil P (STP) and K (STK) assessment. Fertilizer recommendation philosophies (sufficiency, build and maintain, and/or hybrid) variation among the states might be the main reason behind such discrepancies. Although a few similarities in P and K rate recommendations were found, the different philosophies, numerical presentations, and extraction procedures drove important recommendation differences. Widespread adoption of the Mehlich-3 extraction procedure has not reduced variation in fertilizer P and K rate recommendations among the states. Instead, for states using Mehlich 3, soil test critical concentrations ranged from 30 to 75 mg P kg^{-1} and 60 to 175 mg K kg^{-1} for corn (*Zea mays* L.) grain and warm-season grass hay production. The adoption of uniform soil testing terminology, sample collection guidelines, extraction methods, and interpretations across common physiographic regions, soils, and state lines remains a challenge. Differences arise because of the different soil orders and

properties, climate conditions, and resulting crop responses to added P and K fertilizers. Such differences in soil-test-based fertilizer P and K recommendations are state specific and highlight needs to examine the soil testing and recommendation process, make soil test results end-user friendly, and, when appropriate, standardize fundamental information used in the soil testing guidelines.

Evaluation of Soil Potassium-Holding Capacity based on Waterlogging-Simulation Experiments

Zhao, X., S. Gao, D. Lu, X. Chen, H. Wang, and J. Zhou. 2021. Agronomy Journal 113:2863-2874. DOI: 10.1002/agj2.20697.

Abstract: Evaluating the capacity and loss risk of soil nutrients is helpful to make fertilization strategies. Herein, the term of soil potassium (K)-holding capacity (SKHC) was put forward to assess the capacity and loss risk of plant-available K of specific soils. In this study, SKHC was evaluated via soil waterlogging-simulation experiments using 14 different soils. The K concentrations in surface water were measured, and a critical K concentration was selected to indicate high soil K loss. Results showed that the surface water K concentration (K_{sw}) was significantly affected by waterlogging time, temperature, and soil thickness. The average K_{sw} of 5-cm soil columns waterlogged for 24 h for the 14 soils was 5 mg L^{-1} (1.57–8.57 mg L^{-1}); this was subsequently used as the critical K concentration. By repeating the waterlogging simulation experiment with soils treated with different rates of K fertilizer, a quadratic relationship between the K rate and K_{sw} was found and used to determine the K rate required making the K_{sw} reach the critical K concentration. For the 14 soils, SKHC ranged from 133 to 2,054 mg kg^{-1} and can be classified into four levels: low, <500 mg kg^{-1}; moderate, 500–1,000 mg kg^{-1}; high, 1,000–1,500 mg kg^{-1}; and extremely high, >1,500 mg kg^{-1}. These results allowed the preliminary establishment of an SKHC evaluation method and grading system. Future studies should verify the SKHC under field conditions and optimize the assessment method proposed in this study.

Response of some Characteristics of Selected Beneficial Soil Microorganisms under Different Potassium Fertilizer Applications

Paul, C.S., S. Monidipta, J. Száková, S.N. Chandra, and P. Tlustoš. 2021. Int. Agrophys 35(3):289-299. DOI: 10.31545/intagr/143426.

Abstract: Among the three important nutrients of (NPK) for plants, potassium plays a vital role in increasing disease resistance capacity and also in the activation of over 80 different enzymes responsible for plant metabolism. This article presents changes in the population of some soil beneficial microorganisms responsible for the nutrient cycling process in the soil and in their respiration activity as related to the application of different potassium (K) fertilizers (KCl and K_2SO_4) at different doses in a model incubation experiment. The application of KCl and K_2SO_4 fertilizers increases soil acidity at higher doses. The parameters describing the soil microbial community, i.e. microbial respiration and colony forming unit counts of free living N_2-fixing bacteria, *Rhizobium* sp., *Pseudomonas* sp., potassium-solubilizing bacteria, and phosphate-solubilizing bacteria increased with the application of fertilizers at lower doses, but a minor decrease was observed for higher doses of fertilizers. The level of microbial activity showed a positive correlation with the application of different amounts of fertilizer but no effect was observed due to the use of different fertilizer types, thereby indicating that a substantial improvement in soil biological activities can be achieved regardless of the K fertilizer type at optimized doses.

Integrated Analysis of miRNAs Associated with Sugarcane Responses to Low-Potassium Stress

Zhang N., X. Feng, Q. Zeng, H. Lin, Z. Wu, X. Gao, Y. Huang, J. Wu, and Y. Qi. 2022. Frontiers in Plant Science 12:750805. DOI: 10.3389/fpls.2021.750805.

Abstract: Sugarcane is among the most important global crops and a key bioenergy source. Sugarcane production is restricted by limited levels of available soil potassium (K^+). The ability of plants to respond to stressors can be regulated by a range of microRNAs (miRNAs). However, there have been few studies regarding the roles of miRNAs in the regulation of sugarcane responses to K^+-deficiency. To understand how these non-coding RNAs may influence sugarcane responses to low-K^+ stress, we conducted expression profiling of miRNAs in sugarcane roots under low-K^+ conditions via high-throughput sequencing. This approach led to the identification of 324 and 42 known and novel miRNAs, respectively, of which 36 were found to be differentially expressed miRNAs (DEMs) under low-K^+ conditions. These results also suggested that miR156-x/z and miR171-x are involved in these responses as potential regulators of lateral root formation and the ethylene signaling pathway, respectively. A total of 705 putative targets of these DEMs were further identified through bioinformatics predictions and degradome analyses, and GO and KEGG enrichment analyses revealed these target mRNAs to be enriched for catalytic activity, binding functions, metabolic processes, plant hormone signal transduction, and mitogen-activated protein kinase (MAPK) signaling. In summary, these data provide an overview of the roles of miRNAs in the regulation of sugarcane response to low-K^+ conditions.

Recovery of Silicon and Potassium from Rice Straw through Thermal Conversion and Residue Leaching

Yang, Z., X. Li, X. He, and Y. Liu. 2021. J. Environ. Chem. Eng. 9(2):105057. DOI: 10.1016/j.jece.2021.105057.

Abstract: Retaining more soluble silicon (Si) and potassium (K) in the residue after the thermal conversion of straw and returning the

residue to farmland as fertilizer can promote the sustainable supply of Si and K in farmland and alleviate the disposal pressure of the residue. In this study, rice straw was thermally converted at 350–850°C under N_2/air/CO_2 atmospheres and the residues were leached for seven days to recover Si and K. Factors influencing recovery were analyzed with characterization data and recovery indicators. The results show that phytoliths dissolution affected the co-release of Si and K from residues produced below 650°C or at 750°C under CO_2 atmosphere. The Brunner−Emmet−Teller specific surface area of residues had logarithmic positive correlations with Si recovery rate above 750°C and K recovery rate in oxidizing environments. The total amount and content of soluble K in the residue had linear positive correlations with Si recovery rate. Residues with composite silicates or potassium carbonate tended to have lower Si recovery rates. The total K in rice straw was mainly lost by converted from soluble K to kinetically-insoluble K (≥14.5%) and oxidized-gasified K (≥19.8%), compared with thermodynamically-insoluble KAlSi3O8 (≤ 9.4%) and inert-gasified KCl (≤ 12.7%), respectively. The current straw thermal conversion technology can be improved concerning the above influencing factors to generate residues with more soluble Si and K, and to achieve both energy utilization of straw and resource utilization of residues.

Effects of Reduced Nitrogen Application Rate on Drip-Irrigated Cotton Dry Matter Accumulation and Yield Under Different Phosphorus and Potassium Managements

Liu, Y., M. Wen, M. Li, W. Zhao, P. Li, J. Cui, and F. Ma. 2021. Agronomy Journal 113:2524-2533. DOI: 10.1002/agj2.20625.

Abstract: To elucidate effects of reduced N application rate on dry matter accumulation and yield of drip-irrigated cotton (*Gossypium hirsutum* L.) under different phosphorus and potassium managements (PK-Ms), field studies with four reduced N application rates and four PK-Ms were conducted in 2018 and 2019. Results show that after early peak boll-forming (PB) stage, the leaf area (LA) in N3PK-M3 was the highest among all treatments. The net assimilation rate (NAR), crop growth rate (CGR), boll dry weight (BDW), and boll growth rate (BGR) were highest in N2, followed by N3 with insignificant differences, and those parameters in PK-M3 were the highest. The reproductive/vegetative biomass ratio (RVR) for N3PK-M3 was the highest. The CGR, BDW, BGR, and NAR for N3PK-M3 were insignificantly lower than those for N2PK-M3, which increased yield in N2PK-M3 and N3PK-M3 treatments. Correlation analysis showed that BGR was positively related with CGR and NAR from peak flowering (PF) stage to boll opening (BO) stage, and CGR was significantly correlated with NAR and LA from PF to BO stage, and BO stage, respectively. Moreover, the yield was positively correlated with boll weight (BW) and boll number (BN), and BGR was significantly correlated with BN and BW from peak squaring stage to late PB stage. Therefore, high yield in N3PK-M3 due to higher value in LA after boll-forming stage, with higher NAR, CGR, RVR, and BGR, suggesting that early boll formation and successive partitioning of dry matter in boll growth were important factors for yield formation.

Plant Growth and Water Economy of *Solanum tuberosum* in Response to Doubled CO_2: Interaction Between Potassium and Phosphorus

Yi, Y., and K. Yano. 2021. J. Agro. Crop Sci. 207:901-912. DOI: 10.1111/jac.12507.

Abstract: Potassium (K) and phosphorus (P) are essential macronutrients for potato (*Solanum tuberosum* L.); they play crucial roles in photoassimilate production that can also be affected by elevated atmospheric CO_2 concentration (e[CO_2]). However, the interactive effects of K and P nutrition under e[CO_2] in potato have not been investigated. A pot experiment was carried out on potato plants in 1-L pots with five K supply rates at two P supply rates in controlled-environment chambers with ambient CO_2 concentrations (a[CO_2]) and an e[CO_2] level of double a[CO_2]. There was a significant interaction between K supply and P supply, but not between CO_2 and K supply on total plant biomass, water use as well as water-use efficiency (WUE). K supply could remarkably enhance the accumulation of plant biomass under e[CO_2] by promoting tuber formation. The maximum total plant biomass increased by approximately 1.3-fold under e[CO_2] in this study, while the effect of CO_2 was dependent on both P and K supply. Additionally, WUE was increased by e[CO_2] and P and K supply. Both CO_2 enrichment and K supply increased WUE by stimulating biomass accumulation and reducing water consumption. We concluded that the CO_2-fertilization effect and WUE were dependent on both P and K supply. Less biomass accumulation in response to K supply in plants with P deficiency indicates that a balanced nutrient status is crucial for crop production under e[CO_2].

Silicon Alleviates Salt Stress-Induced Potassium Deficiency by Promoting Potassium Uptake and Translocation in Rice (*Oryza sativa* L.)

Yan, G., X. Fan, W. Zheng, Z. Gao, C. Yin, T. Li, and Y. Liang. 2021. Journal of Plant Physiology 258-259:153379. DOI: 10.1016/j.jplph.2021.153379.

Abstract: Under salt stress, plants suffer from potassium (K) deficiency caused by excess salts in growth substrate. Silicon (Si) can promote K status in many plant species under salt stress, however, the underlying mechanisms remain unclear. In this study, we assessed the effects of Si on K homeostasis in rice under salt stress and investigated the mechanisms behind using two low-Si rice mutants (*lsi1* and *lsi2*) and their wild types (WTs). After five days' treatment with Si, plant growth was improved and salt stress-induced K deficiency was alleviated in WTs but not in mutants.

Simultaneously, Si significantly enhanced K accumulation content, K uptake index and shoot K distribution rate in WTs but not in mutants. Besides, Si enhanced K concentration in xylem sap in WTs but not in mutants. Scanning ion-selected electrode technique (SIET) analysis showed net K influx rate was raised by Si addition under salt stress in WTs but not in mutants. Moreover, Si up-regulated the expression of genes responsible for K uptake (*OsAKT1* and *OsHAK1*) and xylem loading (*OsSKOR*) in WTs but not in mutants. Overall, our results strongly indicate that Si can improve K uptake and translocation by up-regulating the expression of relevant genes, thereby promoting K status and alleviating salt stress in rice.

Detection of Root Physiological Parameters and Potassium and Calcium Currents in the Rhizoplane of the Apple Rootstock Superior Line 12-2 With Improved Apple Replant Disease Resistance

Mao Y., Y. Yin, X. Cui, H. Wang, X. Su, X. Qin, Y. Liu, Y. Hu, and X. Shen. 2021. Front. Plant Sci. 12:734430. DOI: 10.3389/fpls.2021.734430.

Abstract: The cultivation of resistant rootstocks is one of the more effective ways to mitigate apple replant disease (ARD). We performed an ion current test, a pot experiment, and a pathogen infection test on the apple rootstocks 12-2 (self-named), T337, and M26. The ion current test showed that exposure to ARD soil extract for 30 min had a significant effect on K^+ ion currents at the meristem, elongation, and mature zones of the M26 rhizoplane and on Ca^{2+} currents in the meristem and elongation zones. ARD also had a significant effect on Ca^{2+} currents in the meristem, elongation, and mature zones of the T337 rhizoplane. Exposure to ARD soil extract for 5 min had a significant effect on K^+ currents in the meristem, elongation, and mature zones of 12-2 and on the Ca^{2+} currents in the elongation and mature zones. Compared to a 5-min exposure, a 30-min exposure to ARD extract had a less pronounced effect on K^+ and Ca^{2+} currents in the 12-2 rhizoplane. The pot experiment showed that ARD soil had no significant effect on any root architectural or physiological parameters of 12-2. By contrast, ARD soil significantly reduced some root growth indices and the dry and fresh weights of T337 and M26 compared with controls on sterilized soil. ARD also had a significant effect on root metabolic activity, root antioxidant enzyme activity (except superoxide dismutase for T337), and malondialdehyde content of T337 and M26. Pathogen infection tests showed that *Fusarium proliferatum* MR5 significantly affected the root structure and reduced the root metabolic activity of T337 and M26. It also reduced their root antioxidant enzyme activities (except catalase for T337) and significantly increased the root malondialdehyde content, reactive oxygen levels, and proline and soluble sugar contents. By contrast, MR5 had no such effects on 12-2. Based on these results, 12-2 has the potential to serve as an important ARD-resistant rootstock.

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