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Optimizing Crop Nutrition

Editorial

Dear readers,

For many of us, recycling waste is now a common practice; we recycle bottles, newspapers, metals and much more. But can we reuse - or recycle - waste nutrients?

In short, the answer is yes. Recycling is possible at various stages of the crop/food cycle, starting when nutrients are absorbed into plants. Nutrients lost in the field cannot be reclaimed, however further along the food chain nutrients can be reused effectively - from human excretion and sludge, sugarcane mills, and food processing plants - through various industrial processes before they are released into the environment.

At the field level, nutrients are already recycled: for example, nutrients in crop residues, harvested and left on the field, are a good source of nutrients. At the discharge point, treated waste water contains useful nutrients that can be made available to plants through irrigation. Yet, considering the enormous amount of lost or wasted nutrients, are there additional ways to use them?

Can agricultural systems, the fertilizer industry and the whole food chain participate in the circular economy? The answer is 'Yes we can and we should'. Doing it right will generate benefits for all.

I wish you a good read.

Hillel Magen
Director

Photo cover page:
Soybean seeder in Luís Eduardo Magalhães in Western Bahia, Brazil. IPI has a long-term experiment in this region to test the effect of potassium chloride on soybean and maize, and the negative effect of its leaching in sandy soils. Photo by IPI.

Research Findings

Experiment site in Gia Lai province, 2014. Photo by Nguyen Duy Phuong.

Potassium Effects on the Productivity and Quality of Sugarcane in Vietnam

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Abstract

Sugarcane (*Saccharum* spp.) is an important industrial agricultural crop in Vietnam. Average sugarcane productivity in Vietnam is 64 Mg ha^{-1}, and the average commercial cane sugar (CCS) content is 10%, significantly lower than in leading sugarcane producing countries that achieve 75 Mg ha^{-1} and 14-15% CCS content. Under rain-fed conditions in Vietnam, low sugarcane performance may be the result of poor nutrition management. In farmers' practices (FP), nitrogen (N) is generously applied, while phosphorus (P) and potassium (K) are generally ignored. The objectives of this 3-year study were to examine and demonstrate the contribution of increased K application to sugarcane yield, quality, and economic benefit under commercial conditions. Field experiments took place from 2012 to 2015 in a parallel design in Gia Lai (Central Highlands) and in Khanh Hoa (Central Coast) provinces. Treatments included six K (KCl) rates (0, 200, 300,

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Photos 1. Sugarcane with a bowl of refined sugar (left) and cut sugarcane (right). *Source:* http://www.scienceimage.csiro.au/.

350, 400, 450 kg K_2O ha^{-1}) together with 250 kg N and 150 kg P_2O_5 ha^{-1}. A local FP was also included as a control. Potassium application significantly improved sugarcane yields by 18.5-31.5% in Khanh Hoa, and 9.2-26.8% in Gia Lai, compared to FP. CCS content increased from 8% at 0 kg K_2O ha^{-1} to 11-12% at 200 kg K_2O ha^{-1}, reaching about 12.5% at the highest doses. In spite of the impressive response to K, the K agronomic efficiency (KAE) was very low, at 67 and 40 kg of cane per kg K_2O, in Gia Lai and Khanh Hoa, respectively. The low KAE may be attributed to water deficit problems and rapid nutrient leaching from the root zone. Thus, although the apparent economic optimal K dose is 350-400 kg K_2O ha^{-1}, use of additional approaches – such as soil enrichment with organic matter, more frequent K applications, and irrigation - are expected to improve K uptake efficiency, further increase sugarcane yield and quality, and reduce the required annual K dose.

Introduction

Sugarcane is an important industrial crop in Vietnam's agriculture sector and has greatly contributed to the economic development of rural communities in midland and mountainous regions. Vietnam Sugarcane Association (VSA) estimated that total cane production area in 2014 was about 305,000 ha, distributed across different ecological zones (Fig. 1), with production of 19.8 million tonnes of sugar for domestic consumption and export (VSA, 2014).

The average sugarcane yield in 2014 reached 64.2 Mg ha^{-1}, with an average national commercial cane sugar (CCS) content of 10%. In spite of a significant improvement in sugarcane productivity from 50 Mg ha^{-1} in 2000 to 64 Mg ha^{-1} in 2012 (FAO, 2012), sugarcane production in Vietnam still faces many challenges such as climate change, large-scale droughts in midland and mountainous regions, outdated varieties, and slow adoption of new cultivation technologies. Thus, Vietnamese sugarcane productivity and economic efficiency is lower than in Thailand (74.2 Mg ha^{-1}), Brazil (74.3 Mg ha^{-1}), and the United States (75.4 Mg ha^{-1}). Moreover, Vietnamese CCS content remains low (10%), compared to Thailand and Indonesia (12-13%), and Australia and some regions of China (14-15%) (Trang, 2015). The relatively low sugarcane productivity and quality is currently considered to be the major disadvantage of the sector. Therefore, improving these parameters is a priority to ensure sustainable sugarcane production in Vietnam.

Potassium (K) is an essential nutrient in sugarcane production, with a number of roles being attributed to it within the plant (Anderson and Bowen, 1990). These roles include: translocation of sugar in plants; starch formation; chlorophyll development and the promotion of photosynthesis; prevention of premature cell

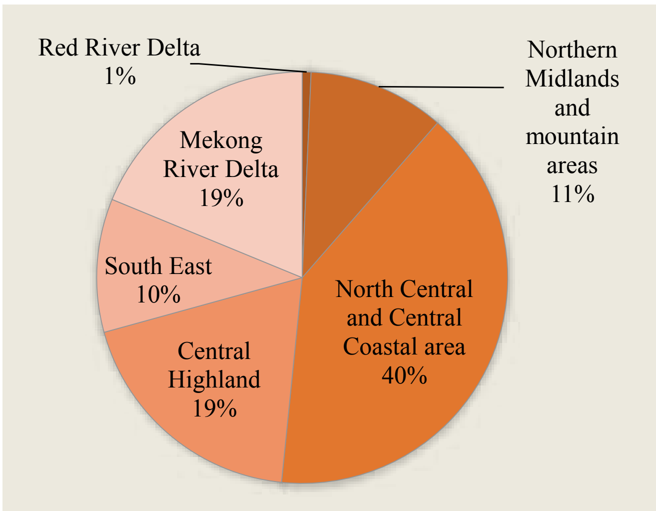


Fig. 1. Distribution of sugarcane area in Vietnam.

death; stomatal opening and closure; and uptake of water (and nutrients) by osmosis. However, the importance of these roles is not fully understood by growers when considering K application to their crops (Wood and Schroeder, 2004). Although K deficiency symptoms are apparent in sugarcane, sub-optimal concentrations do not generally give rise to a marked yield depression. This is probably the result of processes that occur in soils in replenishing the plant available K (exchangeable and soil solution K) from non-exchangeable K sources (Chapman, 1980). Nevertheless, rapid soil erosion processes, particularly typical to afforestation in humid tropical regions, significantly reduce the ability of soils to replenish nutrients (D'haeze *et al*., 2005; Tran Minh Tien *et al*., 2015).

A field survey on sugarcane fertilization, carried out in Khanh Hoa and Gia Lai provinces in 2012, indicated that farmers commonly applied inadequate quantities of fertilizers and suffered from an imbalanced ratio of nutrients. On average, fertilizer rates for N, P_2O_5, and K_2O in Gia Lai were 190, 110, and 90 kg ha^{-1} respectively, and 160, 120, and 120 kg ha^{-1} in Khanh Hoa. The recommended application rates are 120-350 kg ha^{-1} N, 50-170 kg ha^{-1} P_2O_5, 100-350 kg ha^{-1} K_2O, and 15-20 Mg ha^{-1} of farm yard manure (FYM), depending on the soil fertility of each agro-ecological zone (SFRI, 2005). These data reveal a significant deficit in fertilizer application of about 45-54% of N, 65-71% of P_2O_5, and 26-34% of K_2O. Moreover, the survey revealed that about 90% of farmers ignored the recommendation to apply FYM to sugarcane. Inadequate fertilization, especially of K, in the farmers' fields, appears to be the main reason for low productivity and poor quality.

The objectives of this study were to: i) reassess K fertilization efficiency on sugarcane yield and quality in Central Highlands and Central Coast provinces; ii) define an optimum K application rate for economic yield and quality; and, iii) broaden the research results to national scale for future sugarcane production.

Materials and methods

Experiment site: Field experiments were conducted in three consecutive years (2012-2015) at two sites. The first, Gia Lai province, which represents Central Highlands provinces, and the second, Khanh Hoa province, representing South-Central Coast provinces of Vietnam. These two regions contain 60% of Vietnam's total sugarcane area.

Soil properties in experiment sites

Soil samples from the two experimental sites were collected at a depth of 0-20 cm and their soil properties and soil fertiity status analyzed (Table 1). In both sites, analyzed data indicated that soil fertility was low in both total and available forms. The available K contents at both sites were especially poor, ranging from 7.73-8.20 mg 100 g^{-1} of soil. Soil texture was light (more than 80% loess and sand). Therefore the light texture and low soil fertility are the main constraints for sugarcane production in these regions.

Map 1. Experiment sites in Gia Lai and Khanh Hoa provinces.

Table 1. Soil characteristics in the experimental sites.

Soil properties	Khanh Hoa	Gia Lai
pH_{KCl}	4.7	4.6
Organic carbon (OC) (%)	0.92	0.85
N (%)	0.07	0.074
P_2O_5 (%)	0.029	0.051
K_2O (%)	0.33	0.12
P_2O_5 available (mg 100 g^{-1})	1.36	3.85
K_2O available (mg 100 g^{-1})	8.20	7.73
Cation exchange capacity (CEC) (meq 100 g^{-1})	4.13	5.42
Clay (%)	14	14.8
Limon (%)	12	16.6
Sand (%)	74	68.6

Climate

The climate of Vietnam's central regions is tropical. Average temperatures range from 26-32°C and annual precipitation varies from 1,200-2,400 mm, with distinct dry and wet seasons. In Gia Lai, the average annual rainfall is about 1,940 mm, 50% higher than in Khanh Hoa. Also, the wet season occurs from June to September in the Central Highlands (Gia Lai), providing about 67% of annual rainfall. In South Central Coast, the wet season is milder and more prolonged, taking place from May to November. The dry season in both regions occurs from December to March, providing less than 5% of annual rainfall (Fig. 2).

Field experiments

The sugarcane cultivar tested in the study was K88-92, a new variety from Thailand. Experiments in each site included seven treatments with three replications using a random complete block (RCB) design. The area of each plot was 200 m², with total area of 4,200 m². Seven different levels of K were examined (Table 2). Fertilizers were applied directly to the furrow and both field experiments were conducted under rainfed conditions.

Fertilizer application during the year was divided into three steps (Table 3): i) basal fertilization, applied at planting; ii) fertilization carried out 3 months after planting; and, iii) fertilization conducted 6 months after planting.

Harvest productivity: Sugarcane harvesting takes place between March and April in Khanh Hoa, and between December and January in Gia Lai. Total yield was determined for each plot. Sugarcane quality was determined through laboratory analysis that included °Bx, and % juice and CCS content.

Economic analysis: The economic efficiency of K fertilization in sugarcane was calculated as a cost and benefit analysis, based on yield, quality, and prices.

Results

Large differences in sugarcane productivity occurred between the two experimental sites. Average 3-year yields in Gia Lai were 15-40% higher than in Khanh Hoa. The farmers' practice control in Gia Lai obtained an average of 84 Mg ha^{-1}, 40% higher than the same treatment in Khanh Hoa. Furthermore, while the yields in Khanh Hoa fluctuated significantly year-to-year, yield levels in Gia Lai remained considerably stable during the 3-year experiment (Fig. 3). Potassium application gave rise to significant yield increases in both sites, however, the intensity and pattern of this response were remarkably different (Fig. 4). As a rule, wherever K was applied at doses equal to or higher than 200 kg K_2O ha^{-1}, yields were higher than those of the FP (Fig. 3). In Gia Lai, yield response to K application was quite linear and sharp, as expressed by the constant contribution margin of about 67 kg^{-1} K_2O, and produced 38% more yield at the highest K application dose. In Khanh Hoa, the average contribution margin was much smaller at about 40 kg^{-1} K_2O, remaining constant up to a K dose of 350 kg K_2O ha^{-1}, after which it diminished to a negligible level of about

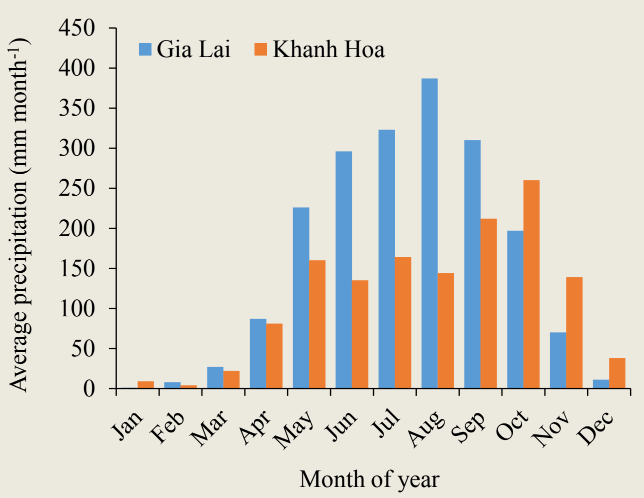


Fig. 2. Monthly distribution of average annual precipitation in Gia Kai and Khanh Hoa. *Sources:* http://mekongarcc.net/sites/default/files/province_profile-gia_lai_press.pdf; and http://en.climate-data.org/location/717532/.

Table 2. Treatments of K application dose (kg ha^{-1}) in Gai Lai and Khanh Hoa.

Treatment	N	P_2O_5	K_2O
T_1 Control(1)			
T_2	250	150	200
T_3	250	150	300
T_4	250	150	350
T_5	250	150	400
T_6	250	150	450
T_7(2)	250	150	0

(1)In FP Control (T_1) - rates of N, P_2O_5, and K_2O applied were 190, 110, and 90 kg ha^{-1} respectively at Gai Lai and 160, 120, and 120 kg ha^{-1} at Khanh Hoa.
(2)In Khanh Hoa, treatment T_7 was added only after the first cropping season.

Table 3. Proportion of fertilizers distributed to sugarcane during the year.

Fertilizer	Basal application, at planting	Second application, 3 months after planting	Third application, 6 months after planting
		%	
N	30	40	30
P	100	0	0
K	30	40	30

11 kg^{-1} K_2O. Thus, the highest yield was obtained at 350 kg K_2O ha^{-1}, only 17% higher than the 0 kg K_2O ha^{-1} treatment (Fig. 4). Noteworthy are the differences in the farmers' practices between the sites; while in Gia Lai FP yield matched the general response to K dose, it was significantly below the expected value in Khanh Hoa (Fig. 4).

Sugarcane quality is often determined by CCS content of the raw material. This parameter is used by manufacturers to define the raw material's price. In contrast to the clear differences in yield (Figs. 3 and 4), CCS content reached quite similar values in both sites (Fig. 5). Again, significant differences occurred between years at Khanh Hoa. CCS content response to K application dose became clear when 3-year averages were used. At 0 kg K_2O (T_7), CCS content was very low at about 8%. CCS increased to values above 11% in response to the lowest K dose, but the response weakened with the increasing K doses. A maximum CCS content of 12.8% was obtained at the highest K dose, 450 kg K_2O ha^{-1} (Fig. 5). Noteworthy, however, is that the response was significant only in 2013 in Gia Lai and in 2014 in Khanh Hoa, whereas it was almost absent in the two other years. Also interesting were the intermediate CCS content values of 9.5-10% obtained from FP (T_1) which obeyed the general response to K doses (Fig. 5).

Juice content of the raw material is another important sugarcane quality parameter. Excluding the first year, 2013, where juice contents were significantly higher in both sites (especially in Khanh Hoa, where it was >75%), this parameter was quite stable, ranging from 58-68% throughout the study (Fig. 6). Potassium doses had no significant effect on sugarcane juice content.

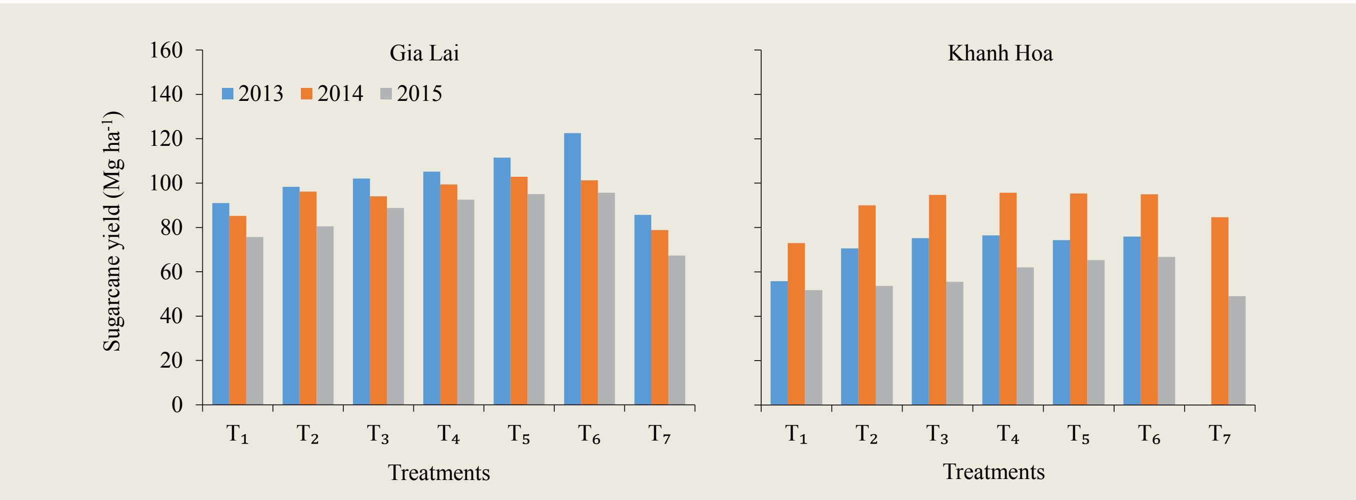


Fig. 3. Effect of annual K dose on sugarcane yield at Gia Lai and Khanh Hoa experiment sites.

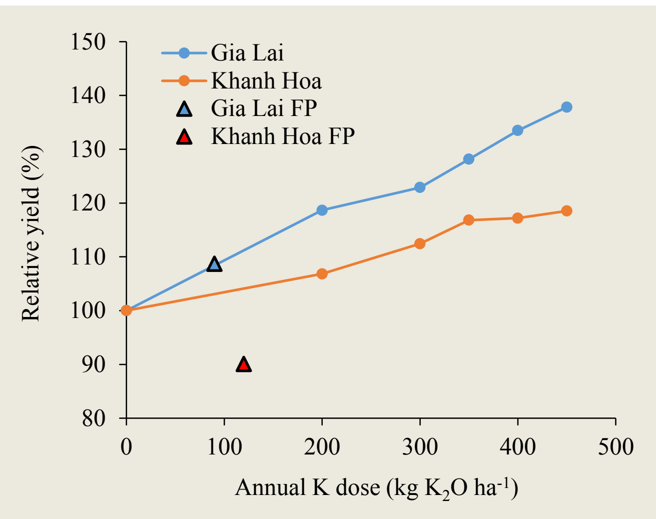
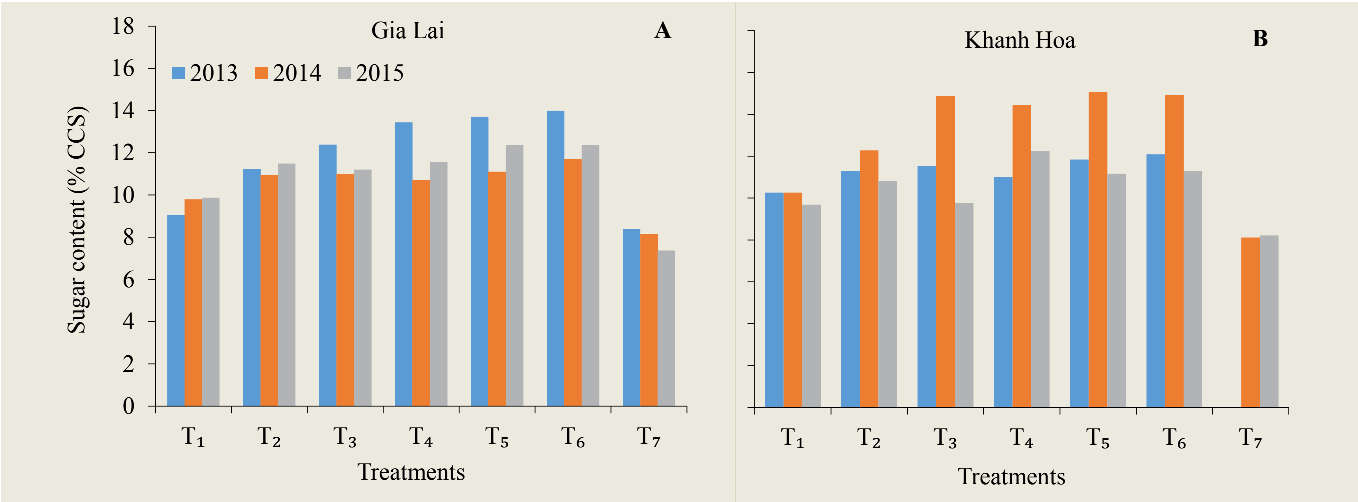


Fig. 4. Effect of increased annual K dose on the relative average sugarcane yield in Gia Lai and Khanh Hoa. Yield increments relate to the 0 kg K_2O control yield (T_7) as 100%. FP = farmers' practices.

Discussion

The substantial dissimilarity in sugarcane productivity between the Central Highlands (Gia Lai) and the South Central Coast experimental sites (Khanh Hoa), as well as the significant year-to-year variations in yields within each site, indicate that major factors, other than K availability, are involved. In spite of the humid tropic climate of Vietnam and the considerable annual precipitation, sugarcane crops often experience water stress that limit growth and productivity (Inman-Bamber and Smith, 2005; Zhao *et al.*, 2010; Cabral *et al.*, 2012; Zingaretti *et al.*, 2012; da Silva *et al.*, 2013). In central Vietnam, there are at least 5 months, from December to April, with less than 100 mm of rain per month (Fig. 2), which is below sugarcane water requirements. Therefore to improve sugarcane productivity in Vietnam, supplementing irrigation during the dry season must be considered alongside logistic and economic costs. Water shortages may also occur during the wet season, because water availability largely depends on soil water capacity and retention. Actually, in the humid tropics, water stress predominantly occurs in sugarcane due to



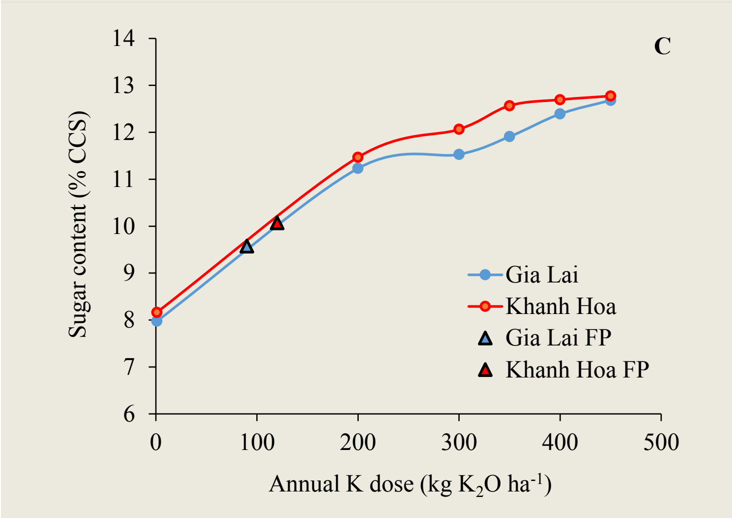


Fig. 5. Effect of annual K dose on CCS content in sugarcane raw material at Gia Lai and Khanh Hoa, 2013-2015. Fig. 5C: 3-year CCS content averages in response to elevated K doses. FP = farmers' practices.

inadequate soil water retention between consecutive rain events (Zhao *et al.*, 2010; Monteiro and Sentelhas, 2014). Light, sandy soils that typify the two experimental sites (Table 1) are characterized by low water retention and are therefore especially prone to frequent drought events. The considerably lower precipitation in the South Central Coast (Khanh Hoa) (Fig. 2), together with the larger sandy soil fraction (Table 1), may provide a sufficient explanation for the significantly lower productivity of this region.

On top of the current water availability problems, global climate change has already affected, and is predicted to further affect Vietnam (USAID, 2012; Nguyen *et al.*, 2014). A significant tendency of increasing annual precipitation has been identified in the central regions of Vietnam, however, rain quantities are anticipated to significantly increase during the wet season, and to decline

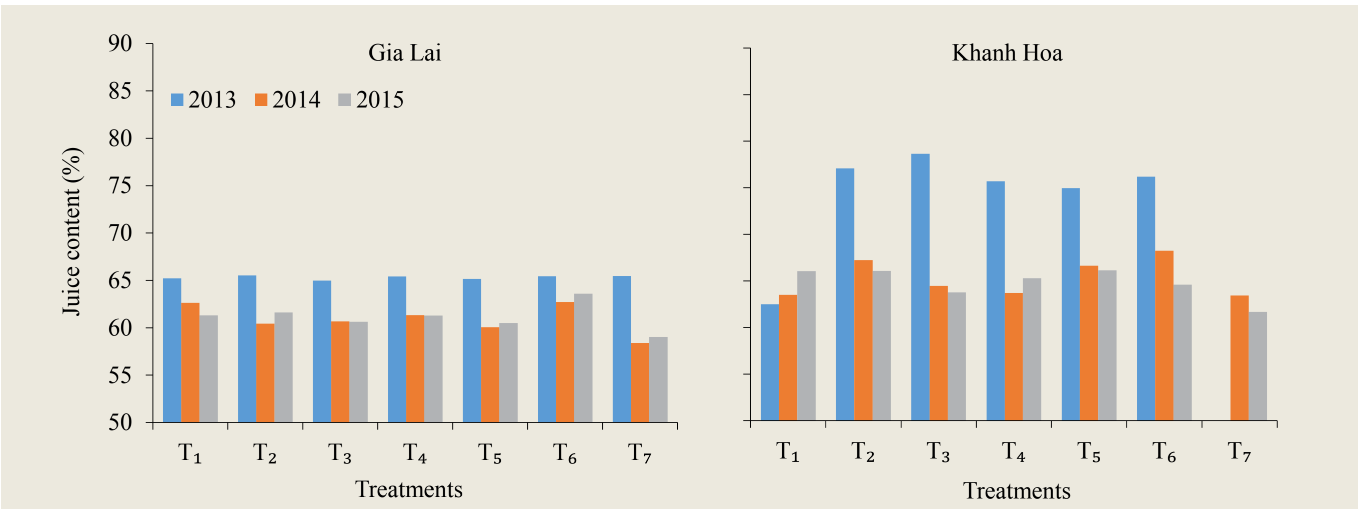


Fig. 6. Effect of annual K dose on sugarcane juice content (%) at Gia Lai and Khanh Hoa, 2013-2015.

Photos 2. Experiment sites in Gia Lai and Khanh Hoa provinces (2012-2015). Photos by Nguyen Duy Phuong.

during the dry season. In addition, year-to-year diversity and the number of extreme rain events are expected to grow (Nguyễn Thị Quỳnh Trang, 2014). As is already happening in other sugarcane growing countries that are facing climate change (de Carvalho *et al.*, 2015), the Vietnamese sugarcane industry may also face increasing water deficit problems that will require systematic as well as local solutions.

In agreement with many previous studies (Anderson and Bowen, 1990; Wood and Schroeder, 2004; Rice *et al.*, 2006; Singh *et al.*, 2008; Hunsigi, 2011; de Almeida *et al.*, 2015; de Oliveira *et al.*, 2016), K application resulted in unequivocal enhancements of sugarcane yields in both sites. The almost linear yield increase in Gia Lai (Fig. 4) suggests that K is the predominant limiting factor of sugarcane productivity in this region. However, the consistent increase, even at the highest K dose, may indicate a low K uptake efficiency. Singh *et al.* (2008) reported a K agronomic efficiency (KAE) ranging from 700-900 kg cane per kg K_2O; Hunsigi (2011) estimated that under rain-fed conditions, KAE would be about 270 kg kg^{-1}. In Gia Lai, KAE was lower by one order at only 67 kg kg^{-1} (Fig. 4), indicating a rapid depletion of available K in the root zone, curtailing the plants' opportunity for sufficient K uptake. This phenomenon is quite common in humid tropical regions, where loose soils are drained of nutrients by heavy rainfall events (Rhodes *et al.*, 2013; Rossato *et al.*, 2014; Tran *et al.*, 2015). Possible solutions may include soil enrichment with organic matter (de Almeida *et al.*, 2015), and much more frequent K broadcast (Wood and Schroeder, 2004).

The situation in the South Central Coast (Khanh Hoa) seems different. Here, water deficit is probably the major limiting factor to plant growth. Potassium uptake, when it occurs, cannot be fully manifested by the drought-affected plants. Thus, KAE is even lower at about 40 kg kg^{-1}, remaining constant up to K dose of 350 kg ha^{-1}, thereafter no further response could be observed (Fig. 4). It may well be, however, that in South Central Coast K is also being rapidly leached from the root zone by intensive rain events, as leaching and water deficit problems may take place simultaneously.

Potassium is required for sugar production, translocation, and storage (Marschner, 1995). In sugarcane, fulfilling K requirements would contribute significantly to quality traits, namely CCS content (Singh *et al.*, 2008; Hunsigi, 2011; de Oliveira *et al.*, 2016). In this study, CCS content responded dramatically, increasing from 8% to 11-12% as a result of the lowest dose, 200 kg K_2O ha^{-1} (Fig. 5). Yet, a further increase in K gave rise to a much weaker response. In light of the very low KAE mentioned above, it is questionable whether high CCS contents could have been obtained at a much lower K dose under normal K uptake rates. CCS content, however, was enhanced by K application which improved the economic value of sugarcane at both sites.

An economic analysis of sugarcane productivity as a function of K application doses (as expressed by the net return in million VND ha^{-1}) (Fig. 7), demonstrated linear relationships in both sites. It appears that CCS content enhancement, with its significant influence on the price of raw sugarcane, compensated for the irresponsive yields in Khanh Hoa. Still, the differences in yields between the two sites are strongly expressed by the economic performances. According to this analysis, K application would be beneficial even at a dosage higher than tested here. Nevertheless, 450 kg K_2O ha^{-1} is considered too high. In Florida, recommended K dose has been as high as 450 kg K_2O ha^{-1} for the first growth cycle (ratoon), but reduced to 270 kg K_2O ha^{-1} for the second and third ratoons (Rice *et al.*, 2006). Hunsigi (2011) suggested focusing on the responsive phase of sugarcane's K-optimum curve, applying up to 350 kg K_2O ha^{-1} and 117 kg K_2O ha^{-1} for the

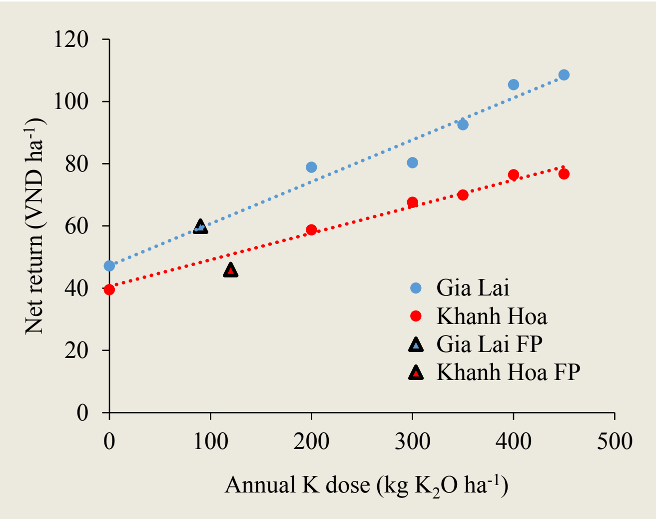


Fig. 7. Economic analysis: Net return (in Million Vietnamese Dollars, VND) of sugarcane production as a function of K application in Gia Lai and Khanh Hoa, Vietnam. FP = farmers' practices.

Photo 3. Harvesting sugarcane. Photo by Nguyen Duy Phuong.

first and second ratoons, respectively. Singh *et al.* (2008) settled on a standard dose of 150 kg K_2O ha^{-1} in their experimental studies in India, while de Oliveira *et al.* (2016) concluded that a dose of 98 kg K_2O ha^{-1} would be sufficient to obtain a stable sugarcane yield of 80 Mg ha^{-1}. The presence of such high K doses at the responsive phase also indicates a very low K uptake efficiency in the present study.

Apparently, the results shown here suggest that to improve sugarcane yield, quality and economic benefits, farmers should apply about 400 kg K_2O ha^{-1}, together with 250 kg N and 150 kg P_2O_5 ha^{-1}, in both regions. Potassium clearly plays a pivotal role in sugarcane production, however most K fertilizer, and probably N fertilizers, seem to be lost and wasted due to rapid draining and leaching processes. All facets relating to K in the soil-plant system need to be optimized to ensure efficient K supply, uptake and utilization by the crop (Wood and Schroeder, 2004). This will ensure that the crop is able to take up a more balanced suite of nutrients and can better withstand periodic drought conditions that occur in the sugarcane growing regions. Thus, enriching the soil with organic material would be a reasonable step toward improving soil CEC, and consequently increase K uptake rates. The fact that the farmers' practices tested here, which included considerable FYM application, resulted in the highest benefit to cost ratios of 8.5 (Gia Lai) and 6.7 (Khanh Hoa) compared to 7.8 (Gia Lai) and 5.9 (Khanh Hoa) in the chemically fertilized treatments, clearly supports this approach. Additionally, dividing the annual dose to frequent applications along the year, where practical, may significantly improve K uptake rates. Applying these two approaches may increase the agronomic efficiency of nutrients, which might even lead to reduced fertilizer doses and lessen the negative impacts on the environment.

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Research Findings

Potash campaigning in West Bengal. Photo by Potash for Life, India.

The 'Law of Optimum' and its Application for Realizing Targeted Yields in India - A Mini-Review

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Abstract

The 'Law of Optimum' is put forward as the unifying concept in plant nutrition for realizing 'targeted yield of crops' through soil test-based nutrient management. This concept has been calibrated using a novel factorial field experiment technique, designed and used under the All India Coordinated Soil Test Crop Response (STCR) project. This initiative was conducted in India on a range of soils and crops over four decades and was validated through hundreds of demonstration trials in farmers' fields.

Early results established that the relationship between wheat grain yield and the total nutrient uptake by the plant followed a linear relationship implying that, for obtaining a given yield, a definite quantity of nutrients must be absorbed by the plant. Based on crop nutrient uptake required to obtain a desired yield level (targeted yield), the 'Law of Optimum' calculates nitrogen

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(N), phosphorus (P), and potassium (K) application doses, taking into account nutrient contribution from three measurable sources: 1. soil fertility (available nutrients, based on chemical soil tests); 2. added fertilizers; and, 3. added organic manure. Over 2,000 demonstration trials in farmers' fields conducted so far have validated the concept, realizing the yield targets within a 10% deviation. Operationally, the 'Law of Optimum' harmonizes the much debated approaches of 'fertilizing the soil' versus 'fertilizing the crop', ensuring a real balance is achieved among available nutrients. The principles underlying the 'Law of Minimum', 'Law of Diminishing Returns' and the 'Law of the Maximum' governing plant nutrition are strongly embedded in the 'Law of Optimum'. Furthermore, this law also provides a basis for maintaining consistent soil fertility with high productivity and efficient nutrient management in 'Precision Farming', to achieve sustainable agriculture.

Introduction

Nutrient application in agricultural systems is expected to increase in the coming years to produce more food, feed, and fiber from the diminishing arable lands. Efficient application of nutrients is key to sustainability in agricultural systems. Efficient fertilization means optimizing crop yields, while minimizing nutrient losses to the environment, which is important economically and environmentally. Efficient nutrient application necessitates balanced fertilizer use and sound management decisions and practices.

Soil's nutrient supplying capacity, namely soil fertility, can be easily determined in laboratories. However, soil fertility assessment of specific locations at a countrywide scale requires systematic soil sampling, delivery, and feedback reporting. Crop responses to added nutrients can be tested in field experiments; nevertheless, results are site-specific and often not applicable to other locations with different soils or climate. Recognizing the lack of correlation between soil tests and crop responses to fertilizer in multi-location fertilizer-rate trials in the past, and the frequent need for site-specific refinements of fertilizer prescriptions, a novel and unique field experimentation methodology was designed for soil test crop response (STCR) correlation studies (Ramamoorthy, 1968). This novel approach has been developed to become a leading concept and a useful strategy to increase fertilizer use efficiency and boost food production in India. This paper highlights the 'Law of Optimum', articulated by Ramamoorthy and Velayutham (2011), and its application and validation over the past four decades.

Historical perspectives

Quantitative relationship studies on plant growth factors and their effect on plant growth and yields dates back to Sprengel (1832) and von Liebig (1843). The well-known Liebig's 'Law of Minimum' says that the yield achieved is in direct relation to the quantity of the limiting nutrient. This is the factor governing yield, which remains constant irresponsive to any increases in other nutrients. When this most limiting factor is corrected, yields are then regulated by the next limiting nutrient. In agricultural production, the soil nutrient status is adjusted with step-wise yield increases until there are no remaining growth limiting factors. Paris (1992) demonstrated the applicability of this law in two crop response experiments. Mitscherlich (1909), in his 'Law of Diminishing Returns' stated that crop yields are influenced by all limiting factors simultaneously and the influence of each such factor is proportional to the severity of its limitation. His equation provided a basis for optimizing fertilizer doses from fertilizer rate trials. Mitscherlich's concept and equation was challenged and modified by Balmukand (1928), Bray (1945), Willcox (1955), and Boyd (1956).

Based on his nutrient mobility concept, Bray (1945) modified Mitscherlich equation as follows:

$$\log (A-Y) = \log A - C1b - CX$$

Where:

A = maximum yield when all nutrients are present in adequate quantities;
Y = yield obtained with nutrient 'b' in soil, when it is less than adequate;
C1 = efficiency factor of the nutrient supplied by the soil;
X = quantity of fertilizer added; and,
C = efficiency factor for the method of applying fertilizer.

The exponential function of the 'Mitscherlich-Bray yield curve' is the curve that never reaches a maximum; regardless of the nutrient level present in the soil, the indicated yield never reaches 100%. The computational basis for calculating maximum yield, a vital parameter to the percent yield sufficiency concept, has thus been questioned. The exponential curve will never indicate yield depression from an excess or toxic nutrient level. This method also does not take into account nutrient interactions, their effect on yield and hence on the fertilizer requirement for 'balanced fertilization'.

Colwell (1978) proposed an orthogonal polynomial model for calculating fertilizer requirement from multi-location fertilizer rate trials. However, similar experiments and data generated under the STCR project failed to optimize fertilizer requirements due to underestimation of soil test values in the orthogonal polynomial model.

Wallace (1993) proposed the 'Law of the Maximum', having two major characteristics. First, the effect of a given input is progressively magnified as other limiting factors are corrected. The final result is greater than the sum of the effects of the individual inputs because of the way in which they interact; the interaction multiplies the effects of each. Second, yields can be highest or maximum only if there are no remaining limiting factors; the fewer limiting factors that remain, the higher the yield will be. How closely this can be approached and attained, of course, depends on relative economics. When dealing with Mitscherlich-type limiting factors, those most economical to use can be chosen first. Using examples of multi-nutrient rate trials, Wallace's model demonstrates the negative synergy of imperfection. While shortage of a single factor limits yield, for instance, to 90% of its agronomic potential, a similar limit by two factors is manifested by 81% of the potential yield. Five such limiting factors would yield 59%, and for ten, it would be 35%. A farmer may do everything to 90% of perfection and yet only achieve 35% of the maximum possible yield. This underlines the need for best management practices and precision nutrient management.

Soil test crop response (STCR) correlation studies

The usefulness of a soil testing service as a vital part of the expanding fertilizer use program was widely recognized and 24 soil testing laboratories were first established in 1955-56 with assistance from United States Agency for International Development (USAID). With the initial research work carried out at the Indian Agricultural Research Institute (IARI) with the then tall varieties of rice and wheat, the fertilizer doses arrived at for different crops on the basis of agronomic experiments in the US were taken as applicable to the 'medium' soil fertility status. Those doses were either reduced or increased by 30 to 50% empirically for soils tested as 'high' or 'low' respectively (Muhr *et al*., 1965). Ramamoorthy and Velayutham (1971) reported an average increase in yield of only 11% when the fertilizers were applied based on such recommendation without soil testing. With the introduction of high yielding varieties and hybrids of crops during the mid-1960's Green Revolution era, fertilizer input demands increased significantly. Fertilization became very costly and hence an urgent need for more precise fertilizer requirement calibration.

Recognizing the reported lack of correlation between soil test and crop response to fertilizer in multi-location agronomic trials in the past and the need for refinements in fertilizer prescriptions for varying soil test values for economic crop production, Ramamoorthy (1968) designed a novel field experimentation methodology for STCR correlation studies and initiated the All India Coordinated Research Project of the Indian Council of Agricultural Research (ICAR) in 1967-1968. In the 'inductive approach' of STCR field experimentation, the required variation in soil fertility level is obtained - not by selecting soils at different locations as in earlier agronomic trials - but by creating it in the same field in order to reduce heterogeneity in the soil (types and units) studied, adopted management practices, and climatic conditions. Ramamoorthy and Velayutham (1971; 1972) and Velayutham *et al.* (1985a) have elaborated this inductive approach, and the STCR field design has also been recognized and accepted abroad (Black, 1993).

A field design for creating simultaneous heterogeneity of soil fertility that combines chemical fertilization and organic manure has been developed. The manure variation (organic sources) is created by three parallel strips, each of which is applied with a different level of organic manure (OM_0, OM_1, and OM_2) using FYM (farm-yard manure), slurry, or compost about one month before sowing of the test crop. Four strips of selected nitrogen (N) fertiliser levels are set in a perpendicular direction to the OM set. Twelve combinations of phosphorus (P) and potassium (K) levels are selected according to a predetermined soil fertility status and scattered among the N levels. The full set of 24 fertilizer treatments are allotted in each of the three strips (Fig.1).

	OM_0	OM_1	OM_2
N_0	$P_0 K_1$	$P_2 K_2$	$P_1 K_2$
	$P_1 K_2$	$P_0 K_0$	$P_2 K_2$
	$P_0 K_0$	$P_0 K_1$	$P_0 K_0$
	$P_2 K_2$	$P_1 K_2$	$P_0 K_1$
N_1	$P_1 K_1$	$P_2 K_1$	$P_1 K_2$
	$P_2 K_1$	$P_2 K_2$	$P_2 K_2$
	$P_1 K_2$	$P_1 K_1$	$P_2 K_1$
	$P_2 K_2$	$P_1 K_2$	$P_1 K_1$
N_2	$P_1 K_1$	$P_1 K_2$	$P_2 K_1$
	$P_0 K_2$	$P_2 K_1$	$P_2 K_0$
	$P_1 K_2$	$P_1 K_1$	$P_2 K_3$
	$P_2 K_2$	$P_2 K_3$	$P_0 K_2$
	$P_2 K_1$	$P_3 K_2$	$P_3 K_3$
	$P_2 K_0$	$P_2 K_2$	$P_3 K_2$
	$P_2 K_3$	$P_3 K_3$	$P_1 K_1$
	$P_3 K_2$	$P_2 K_0$	$P_2 K_2$
	$P_3 K_3$	$P_0 K_2$	$P_1 K_2$
N_3	$P_1 K_1$	$P_2 K_2$	$P_2 K_1$
	$P_2 K_1$	$P_3 K_2$	$P_3 K_1$
	$P_2 K_2$	$P_1 K_1$	$P_2 K_3$
	$P_3 K_1$	$P_3 K_3$	$P_3 K_2$
	$P_3 K_2$	$P_2 K_3$	$P_3 K_3$
	$P_2 K_3$	$P_3 K_1$	$P_1 K_1$
	$P_3 K_3$	$P_2 K_1$	$P_2 K_2$

Fig. 1. An example of STCR experimental design. Three strips of different organic manure (OM) levels are set in a perpendicular direction to N fertilizer gradient of four levels. Twelve combinations of P and K levels are selected according to a predetermined soil fertility status and scattered among the N levels. Overall, 24 different N-P-K fertilizer combinations are simultaneously examined in each strip of OM level.

The ICAR supported All India Coordinated Research Project (AICRP) on STCR was initiated in 1967-68 with eight centers and has now increased to 17 centers at different agro-eco regions across the country. The STCR project has used the multiple regression approach to develop the relationship between crop yield and soil test estimates and fertilizer inputs.

Table 1 demonstrates the effect of balanced nutrition on the agricultural and economic efficiencies of fertilizer use on wheat. At a low rate of added N (50 kg N ha^{-1}), yield response was highest, 14.8 kg grains kg^{-1} added N, at the lowest P-K input (25 kg ha^{-1} of each P_2O_5 and K_2O). Elevating P-K rates at the same N level resulted in even lower grain yield.

When N dose was elevated to 90 kg ha^{-1}, yield response dropped, averaging at 10-12 kg kg^{-1}, under different P-K combinations. To return to the high response of 14.5 kg kg^{-1} at the new N level, a precise P-K combination of 75 and 50 kg ha^{-1}, respectively, was required. These results demonstrate the diminishing contribution of elevated N input, unless corrected with a new optimum P-K requirement.

Recent studies exploring the optimum nutrient balance which aimed to achieve maximum productivity or economic benefits (Boldea *et al.*, 2015) also demonstrated this principle and, furthermore, yields can be increased as long as the site-specific N-P-K optimum combination is met. Table 1 also shows that the response to absorbed N only varies within narrow limits compared to the response to added N. Thus, the varying yield response to applied fertilizers is primarily influenced by nutrient uptake restrictions but, once taken up, the efficiency of applied nutrients is nearly the same.

Table 1. Effect of balanced nutrition on efficiency and economy in fertilizer use at Delhi with wheat Sonora 64 (1965-1966). (Ramamoorthy *et al.*, 1967).

Nitrogen dose	Associated treatment	Yield	Yield response to added N	Yield response to absorbed N
kg ha^{-1}		------*kg ha^{-1}*------	--------------*kg grain kg^{-1} N*--------------	
90	P_{75} K_{50}	5,047	14.5	38.7
	P_{50} K_{50}	4,779	11.8	38.9
	P_{50} K_{25}	4,760	11.7	40.3
	P_{50} K_{75}	4,588	9.9	42.0
	P_{25} K_{50}	4,665	10.7	40.2
50	P_{25} K_{25}	4,330	14.8	43.1
	P_{50} K_{50}	4,302	14.2	43.5
Control	P_0 K_0	3,590	-	-

Targeted yield concept

Based on a large number of complex field experiments on diverse soils at STCR different centers of growing major crops, a technology for fertilizer recommendations based on soil tests for targeted yields of crops has evolved. Truog (1960) illustrated the possibility of a 'prescription method' of fertilizer use for obtaining high yields of maize using empirical values of nutrient availability from soil and fertilizer. It was generally believed that crop requirements for P and K follow the rate sufficiency concept of Mitscherlich-Baule (Baule, 1917) and of Mitscherlich and Bray (Bray, 1945). Nevertheless, Ramamoorthy *et al.* (1967) established the theoretical basis and field experimental proof and validation for the fact that Liebig's 'Law of Minimum' operates equally well for N, P, and K for the high yielding varieties of wheat, rice and pearl millet. They demonstrated the importance of P and K in determining crop response to N and the role of balanced nutrition in achieving efficient fertilizer use (Ramamoorthy *et al.*, 1967; Ramamoorthy and Pathak, 1969). Their work founded the 'targeted yield' concept for fertilizer recommendations.

The linear relationship between yield level and N-P-K uptake implied that, for obtaining a given yield, a definite quantity of nutrients (both from soil and fertilizers) must be taken up by the plant. Once this requirement is determined for a given yield, the quantity of fertilizer needed can be calculated, taking into account contribution rates from soil available nutrients and those from added fertilizers and organic manure.

The implementation of the targeted yield concept is described in the following examples. A soil test based calibration of wheat var. WH-157 on Sierozem soil at Hissar resulted in the following fertilizer adjustment equations, in their simplest form:

$$Nf = 4.96TY - 0.63Ns;$$
$$P_2O_5f = 3.83TY - 4.63Ps;$$
$$K_2Of = 2.66TY - 0.22Ks$$

Where:
Nf, P_2O_5f and K_2Of are fertilizer doses in kg ha^{-1} respectively; TY is the yield target in q ha^{-1} (100 kg); Ns, Ps, and Ks are soil test values for available N, P, and K in kg ha^{-1}, respectively.

These simplified linear equations demonstrate the relationships between expected levels of wheat grain yield and the N-P-K doses required in site-specific variation of soil fertility (Fig. 2). Evidently, fertilizer requirements vary according to soil N-P-K availability. Fertile soils would require considerably less fertilization than poor soils. Under rain-fed conditions, differences are more relevant at lower yield levels, where relatively small changes in fertilizer input can make significant differences, turning economic failure to success. The farmer, after being informed of the particular situation of his field, may choose expected yield

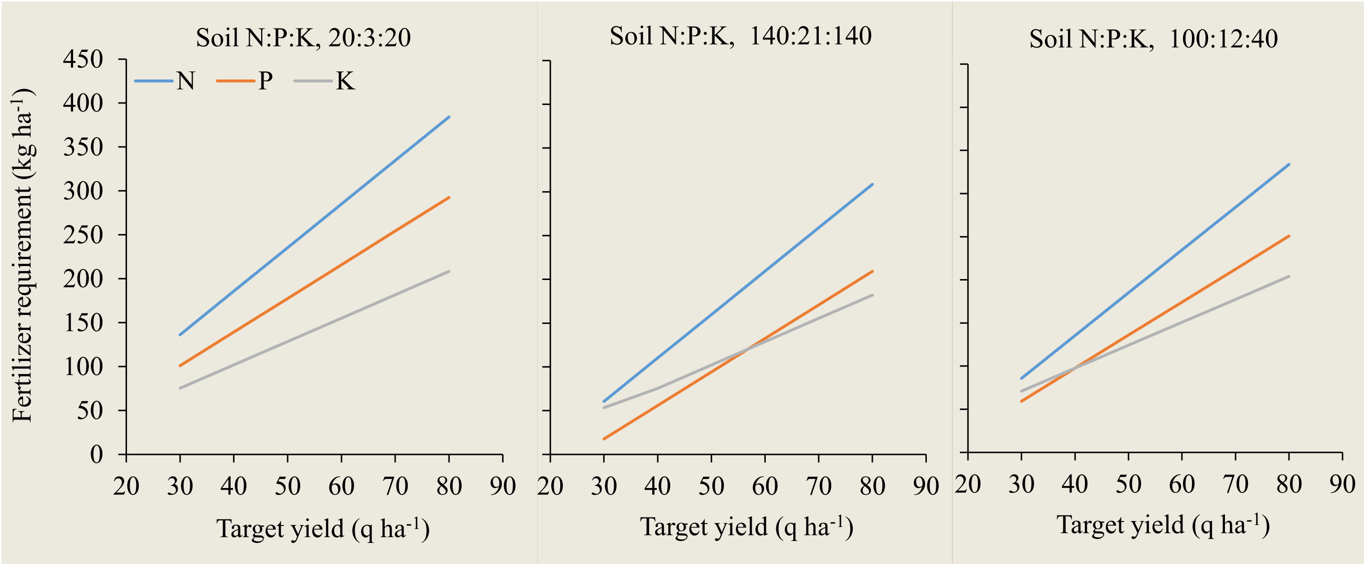

Fig. 2. Resolving fertilizer requirements as a function of the expected wheat grain yield and according to soil available N-P-K at three hypothetical situations of initial soil fertility, as determined through soil tests. Wheat cultivar: WH-157; soil type: Sierozem; location: Hissar, India.

according to fertilizer costs and available budget. According to Fig. 2, a farmer with an exhausted soil, who desires a high yield of 60 q ha^{-1} should invest in 285, 216, and 155 kg ha^{-1} of N, P_2O_5, and K_2O, respectively. However, if too costly, this farmer might be satisfied with 40 q ha^{-1}, reducing his fertilizer expenses by 35%. Obviously, fertilizer requirements decline with the increasing initial soil fertility. Obtaining the same 60 q grains ha^{-1} requires 209, 133, and 129 kg ha^{-1} of N, P_2O_5, and K_2O, and reducing the target yield to 40 q ha^{-1} would lessen fertilizer costs by 47, 58, and 41%, respectively (Fig. 2).

The utilization of organic manure adds a significant factor to the targeted yield equations. Santhi *et al.* (2013) documented a range of 53 soil-crop situations in Tamil Nadu, Southern India. One such example for rice grown on Noyyal soil series (typical Haplustalf) is given below, as a set of equations:

$$Nf = 4.39TY - 0.52Ns - 0.80No;$$
$$P_2O_5f = 2.22TY - 3.63Ps - 0.98Po;$$
$$K_2Of = 2.44TY - 0.39Ks - 0.72Ko$$

Where, Nf, P_2O_5f and K_2Of are fertilizer doses in kg ha^{-1} respectively; TY is the yield target in q ha^{-1} (100 kg); Ns, Ps, and Ks are soil test values for available N, P, and K in kg ha^{-1}, respectively, and No, Po, and Ko are the quantity of N, P, and K, respectively, in kg ha^{-1} supplied through FYM.

FYM use significantly reduces fertilizer requirements, but this effect is considerably greater in fertile soils (Fig. 3). Choosing relatively low targeted yield levels, farmers who use sufficient FYM may significantly reduce their expenses for chemical fertilizers. Nevertheless, the targeted yield concept also provides farmers with the opportunity to recognize possible economic benefits that might arise from rational, calculated increase of fertilizer use.

The fertilizer prescription equations have been rigorously tested and evaluated for their predictability through a series of field verification trials (follow up trials) in farmer's fields on similar soils. After evaluation in the follow-up trials, these equations are used to recommend fertilizer doses for all the major crops grown across Indian states.

The practical application of yield target for a fixed cost of fertilizer investment by the farmer or under resource (fertilizer/credit) constraints and for maintenance of soil fertility in crop rotation were documented by Velayutham (1979), Randhawa and Velayutham (1982), Velayutham *et al.* (1985b), Reddy *et al.* (1989) and Dey and Santhi (2014). STCR field experiments have been conducted at all the cooperating centers and fertilizer prescription equations were developed for various crops for advisory use, and have been documented (Anonymous, 1968-2013; Subba Rao and Srivastava, 2001; Muralidharudu *et al.*, 2012; Dey and Das, 2014). Founded on reliable field data flow (site-specific soil tests) and economically considered practice of chemical and organic fertilizers, the targeted yield concept can promote a gradual but consistent increase in crop productivity.

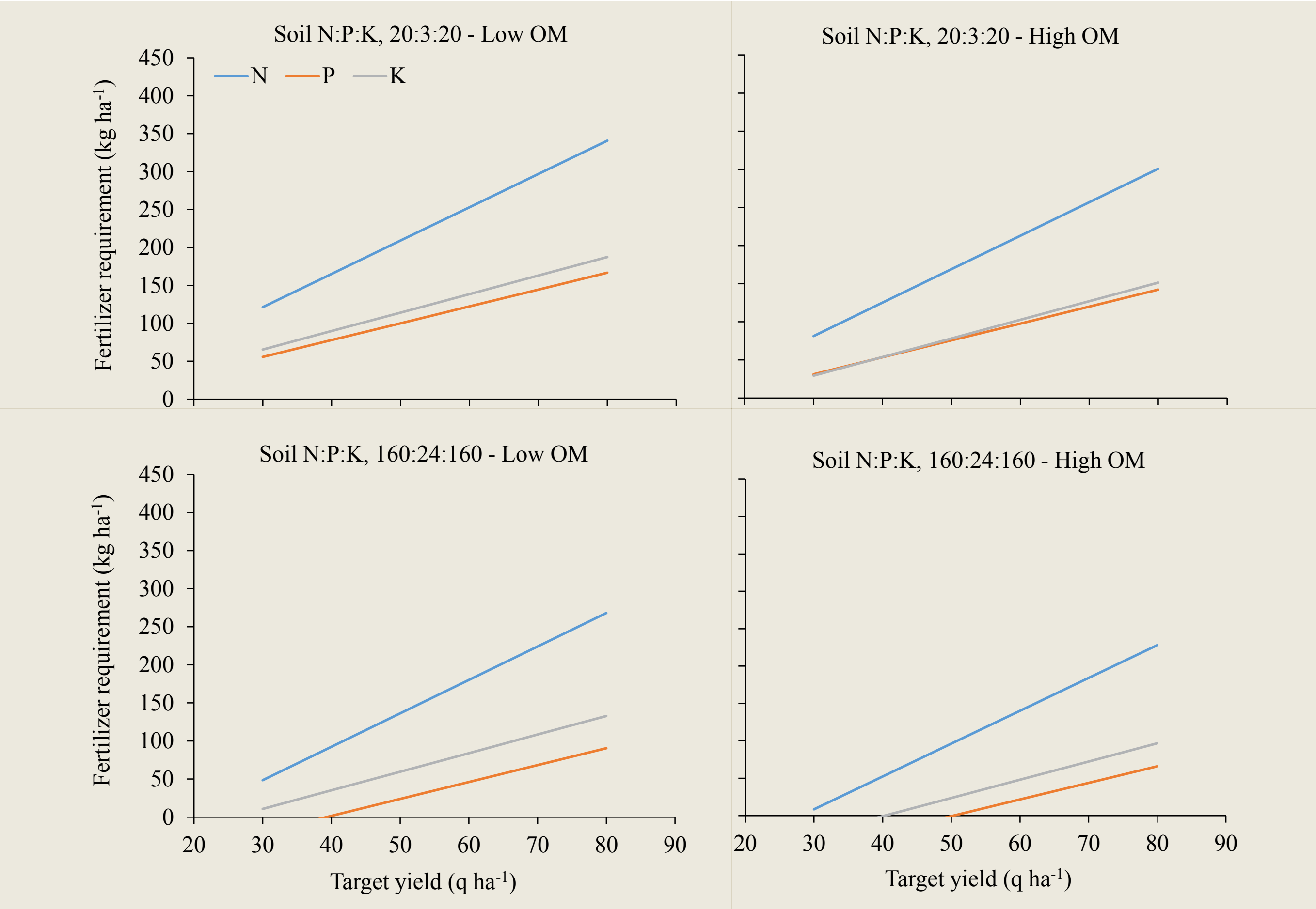

Fig. 3. Resolving fertilizers' requirements as a function of expected rice yield and according to soil + FYM available N-P-K. Soil type: Typic Haplustalfs; location: Tamil Nadu, India.

Yield targeting and maintenance of soil fertility

Among the various methods for formulating fertilizer recommendations, the one based on yield targeting is unique in the sense that, beyond a defined fertilizer dose for the desired yield level, it ensures considerable maintenance of soil fertility, taking into account nutrient removal by the crop for a given yield level (Velayutham, 1979; Velayutham and Tandon, 2014).

Using the fertilizer prescription equations for rice at a fixed field site since 1998 (Tamil Nadu Agricultural University, Coimbatore, Southern India), the yield targeting block demonstration has amply shown the value of soil test-based integrated plant nutrition system (IPNS) (Velayutham and Santhi, 2013) for obtaining high yields (6 to 7 tonnes ha^{-1} of paddy yield). These results from 15 years of continuous cropping (Maragatham *et al.*, 2015) were consistent with profitable fertilizer use and maintenance of long-term soil fertility (Tables 2 and 3). Velayutham (1979) illustrated that, by choosing appropriate yield targets of crops in rotation, soil fertility can be maintained and even upgraded.

Potassium and the 'Law of Optimum'

Among the essential plant nutrients, K assumes greater significance since it is required in relatively larger quantities by plants and, besides increasing yield, it improves the quality of crop produce, as well as improving N and P use efficiency (Rao *et al.*, 2014). Potassium has many roles in plant physiology: it activates enzymes involved in photosynthesis and in carbohydrate and protein metabolism; it assists in synthesis and translocation of carbohydrates, protein synthesis, membrane permeability, and stomatal regulation; it regulates water utilization; it improves N uptake and utilization; and, it enhances plants' tolerance to abiotic stresses and diseases (Mengel and Kirkby, 1987).

Efficiency of K soil uptake differs among crops and is influenced by many factors, such as crop type, crop growth stage, plant root density and distribution, soil type, soil moisture status, etc. Dynamic equilibrium among different pools of soil K also has a significant influence on crop uptake efficiency. Soil K status and its distribution among different pools is governed by its

Table 2. Yield targeting in rice and efficiency of fertilizer use (mean of 15 crops per season) on an Alfisol (Maragatham *et al.*, 2015). AE - agricultural efficiency; IPNS - integrated plant nutrition system.

Treatments	Kharif season (1998-2013)			Rabi season (1998-2013)		
	Target yield	Grain yield	AE	Target yield	Grain yield	AE
	--------*Mg ha⁻¹*--------		*kg kg⁻¹*	--------*Mg ha⁻¹*--------		*kg kg⁻¹*
General agronomic recommendation		5.37	12.0		4.95	11.4
STCR - NPK alone	6	5.72	13.7	5	5.10	15.2
STCR - NPK alone	7	6.52	14.4	6	5.90	15.7
STCR - IPNS	7	6.74	16.0	6	6.05	17.5
Absolute control		2.80	-		2.78	-

Table 3. Yield targeting and maintenance of soil fertility status after 30 crops of rice on an Alfisol (Maragatham *et al.*, 2015).

Treatments	Targeted yield	Soil organic carbon	Available nutrients		
			N	P	K
	Mg ha⁻¹	*g kg⁻¹*	-----------------*kg ha⁻¹*-----------------		
General agronomic recommendation		6.0	210	19.8	472
STCR-NPK alone	6	7.0	218	21.5	492
STCR- NPK alone	7	7.4	260	27.0	498
STCR - IPNS	7	8.6	268	28.5	550
Absolute control		5.2	165	15.1	412
Initial status (1998 Kharif)		4.6	280	20.2	670

mineralogy. There are three major soil K pools: exchangeable, non-exchangeable, and organic. The exchangeable pool contains the K^+ ions which adhere to the negatively charged surface layer of the finest soil particle fraction. This pool maintains a steady equilibrium with the soil water solution, is affected by soil pH, and interacts with other dissolved ions. The exchangeable K pool is considered the most available K resource in the soil. However, due to its high solubility, exchangeable K is extremely mobile in the soil, being strongly affected by the dynamics of water status and movement in the soil.

The non-exchangeable K pool is present within the soil particles, as an inherent element of their chemical composition. The size of this pool depends on the soil mineral composition. The availability of this K pool to the plant depends on the type and rate of soil weathering processes. While definitely not immediately available, this pool may contribute significant portions of K crop requirements (Rao *et al.*, 2014). Nevertheless, this availability is very difficult to estimate hence the non-exchangeable K pool is not taken into account in regular assessments of fertilizer requirements. In a similar way, the K availability incorporated in organic soil material is difficult to assess.

Soil available K status is therefore a consequence of contradictory flow rates; crop K uptake and K leaching both reduce soil K status, while soil weathering and mineralization of organic matter enrich the soil with K. Under intensive agriculture, soil available K might be rapidly exhausted due to over-exploitation by successive crops, and where soil weathering becomes soil erosion, as fine-textured soil particles are removed by water and wind. Consequently, soil K balance may be severely depleted, resulting in yield reduction, insufficient revenue for farmers, and reduced food security. Unfortunately, the present trend of fertilizer use in the majority of Indian states is not sufficient and is dominated by mainly NP fertilization; this has led to a negative K balance in most of the soils across India (Rao *et al.*, 2014).

Potassium fertilization is therefore a necessity. However, restoring soil's K balance means much more than a one-time replenishment of absent K. Soil's capacity to store K is limited, as it depends on the soil's cation exchange capacity (CEC). Similarly, crop K uptake rate is limited, depending on crop type, growth rate, and stage of plant development. Excess K application can be lost through leaching, particularly under prolonged or heavy rains (e.g. during monsoons). Therefore, a wise approach to K application should be adopted, accounting for the current crop requirements, weather conditions, and the present and future soil K status. Here, the 'Law of Optimum', and the approaches deriving from this law, provide an excellent strategy and practical means for soil fertility restoration and for the upkeep of sustainable, highly productive agricultural systems. Annual soil tests will determine the current soil K status, CEC, and potential K contribution by non-exchangeable K. Adding organic manure enriches the soil with slow-release nutrients, increases soil CEC and water retention, thus preserving future soil fertility. Crop type and targeted yield determine K requirements of the crop cycle. Then, using the 'Law of Optimum' equations, a fertilization prescription can be determined for the required nutrient dose. However, the distribution of K application during the cropping season should be carefully planned taking into consideration the limits of K uptake and soil capacity. A single basal application, although easiest for the farmer, is the least preferred option in most cases. The predetermined K dose should preferably be divided into several applications distributed throughout the cropping season, considering the current stage of crop development (and K requirements) and expected rainfall events. Where irrigation is employed, K should be applied with the irrigation water.

Concluding remarks

Although India's economy has experienced remarkable progress during recent decades, 70% of the population live in rural areas and are still agriculture-dependent. The ever-increasing demands for food, feed, and fibers with limited arable land necessitate preserving, managing, and enriching the natural resources, and furthermore, scaling up their use efficiency. Soil forms the basis for any crop production activity and is the most precious natural resource. Declining soil fertility is one of the important factors that directly affect crop productivity. Therefore, soil fertility management is crucial to ensure productivity and nutritional security, while maintaining soil health and sustainability. Fertilizers are one of the costly inputs in agriculture, yet their use is key to ensuring soil productivity. It has been proved, however, that imbalanced use of fertilizer not only causes deterioration in soil quality but also afflicts nutrient use efficiency. To achieve maximum benefit, enhanced nutrient use efficiency and reduced nutrient losses, fertilizers must be applied in the right quantity, from the right sources and in the right combination at the right time using the right methods (Dey, 2015; Singh, 2016).

Based on a large number of complex field experiments on diverse soils at different centers of STCR growing major crops, a technology for fertilizer recommendations based on soil tests for targeted yields of crops has evolved. During the last 15 years, the different AICRP centers on STCR developed prediction equations by using the targeted yield equation for different cropping systems. The predicted values can be utilized for recommending fertilizer doses for succeeding crops, thus lessening the need for recurrent expensive soil tests. Financial returns vary across soils, crops and locations. However, many demonstrations confirmed an increase in benefit/cost ratios through STCR technology over the control, or farmer's practices, or application of a general recommended dose (Majumdar *et al.*, 2014). Moreover, the targeted yield concept enables farmers to adjust their fertilizer inputs to anticipated yield levels, thus having better financial and economic control.

Thus, the 'Law of Optimum' enables farmers to optimize their farm management by providing a competent method to precisely fulfil site-specific crop nutrient requirements while preserving, and even ameliorating soil fertility. The expected resulting increases in farmers' income and in national agricultural productivity, while maintaining soil fertility, may altogether bring about more sustainable agriculture in India.

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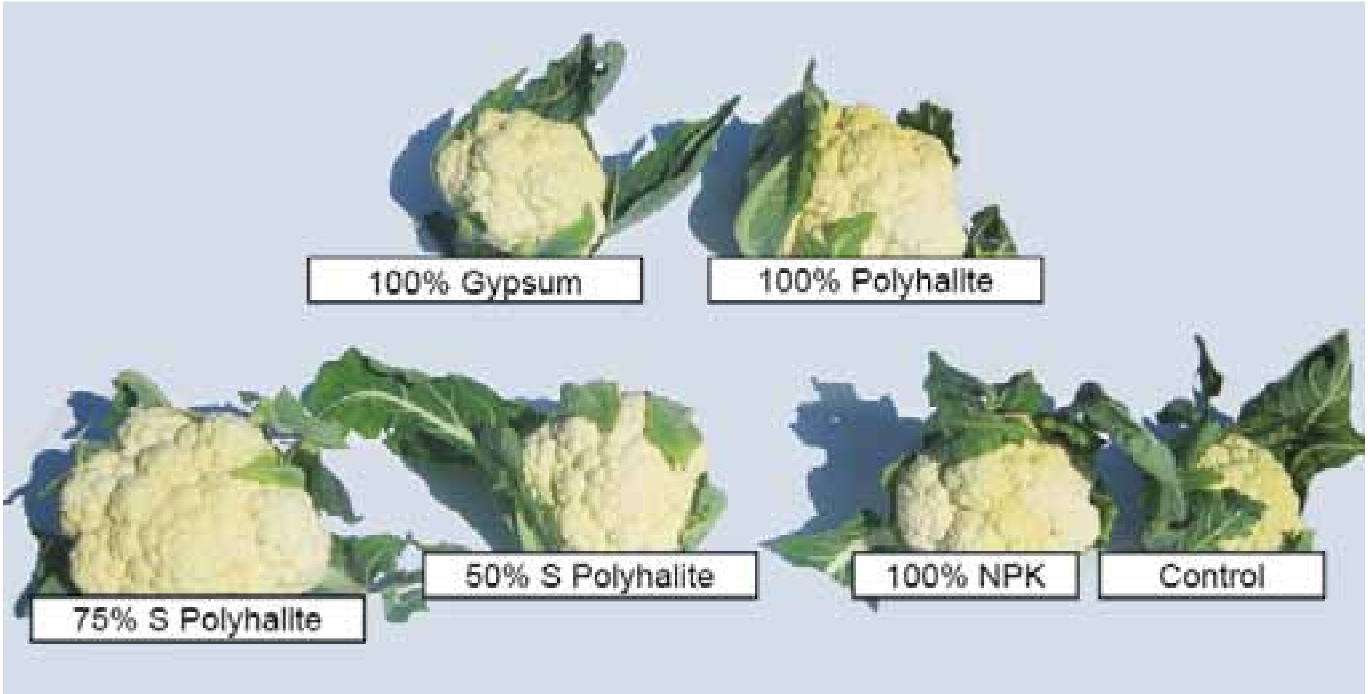
Research Findings



Bioefficacy of Polyhalite Application on Yield and Quality of Cabbage and Cauliflower

Satisha, G.C.[(1)*], and A.N. Ganeshamurthy[(1)]

Abstract

Sulfur (S) has been recognized as an important plant macronutrient, associated with high yield and quality, particularly in crops of the Brassica genera. Polyhalite is a natural mineral which occurs in sedimentary marine evaporates, consisting of a hydrated sulfate of potassium (K), calcium (Ca) and magnesium (Mg). The objective of this study was to test the bioefficacy of polyhalite on the performance of two major *Brassica oleracea* cole crops in India, cauliflower and cabbage. Sulfur application gave rise to significantly increased yield and quality of the two crops. Potassium enhanced S uptake, while in turn, S appeared to promote phosphorus (P) and Ca uptake. The highest yields of cabbage and cauliflower, 32.8 and 39.5% more than the control, respectively, were obtained with 100% and 75% of the recommended N-P-K and S doses, respectively, delivered through polyhalite. Possible reasons for the failure of a 100% S dose, either through polyhalite or gypsum, to further increase yield attributes are discussed. More research is required to adjust nitrogen (N) and K fertilization practices where S administration takes place.

Introduction

Sulfur (S) is recognized as the fourth major plant nutrient after nitrogen (N), phosphorus (P) and potassium (K) (Khan *et al.*, 2005), and has been associated with high production goals (Zhao *et al.*, 1999; Hawkesford, 2000; Saito, 2004; Jamal *et al.*, 2010; Kovar and Grant, 2011; Steinfurth *et al.*, 2012). A good response to S application has been reported with respect to crop yield related to the Brassica genera (McGrath and Zhao, 1996; Gironde

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et al., 2014; Tiwari *et al*., 2015), and particularly to cole crops (*Brassica oleracea*) (Susila and Locacsio, 2001).

Brassica oleracea is a major edible crop worldwide that includes several morphologically distinct subtaxa, such as acephala (kale/collards), alboglabra (oriental kale), botrytis (cauliflower), capitata (cabbage), gemmifera (Brussels sprout), gongylodes (kohlrabi), italica (broccoli/calabrese), sabauda (Savoy cabbage) and sabellica (borecole/curly kale), in which the entire shoot is generally harvested (Broadley *et al*., 2008). Over the last three decades, crops in the Brassicaceae have been the focus of intense research based on their human health benefits (Stoewsand, 1995; Björkman *et al*., 2011). Sulfur-containing secondary metabolites, such as glucosinolates and others, have been associated with some anti-cancer activities (Cartea and Velasco, 2008; Sarıkamış, 2009) and with a reduced risk for degenerative diseases, cardiovascular diseases and diabetes (Björkman *et al*., 2011, and references therein). Some S-containing compounds are desired as flavor components in cooked Brassica vegetable products (Schutte and Teranishi, 1974; Engel *et al*., 2002). Glucosinolates contents largely depend on S availability and significantly varies with S fertilization (Falk *et al*., 2007).

Nevertheless, crop responses to S application have been found to also vary widely due to differences in location, soil type, various S-containing compounds in the soil and consequent S availability, crop genotype, environmental conditions and crop management (Björkman *et al*., 2011). Cole crops have a significant S requirement and, where the availability of this mineral is limited, crop yield and quality often decline (McGrath *et al*., 1996; Haneklaus *et al*., 2008). Over the last 20 years, due to strict regulations against industrial S emissions, the yearly global S atmospheric deposition has significantly declined (Kovar and Grant, 2011). During the same time, demands for food production have increased with the growing human population. Subsequently, requirements for S fertilizers have risen dramatically to meet annual crop demands. Sulfur-deficient plants are typically small and spindly, characterized by interveinal chlorosis of young developing leaves that may become curved and brittle and eventually may fail to grow (Haneklaus *et al*., 2008). The chlorosis is very characteristic in that the veins stand out as a rather blurred, blue-green pattern against a pale green background. On the abaxial (lower) side of the leaf, these dark areas are purple, and this coloration may later spread to the whole leaf. Symptoms tend to develop slowly. In Brussels sprouts, characteristic symptoms include yellowing tops and restricted rooting. Sulfur deficiency is likely to occur in soils that have low levels of organic matter, light-textured sandy soils that have been leached by heavy rainfall or excessive irrigation, soils exhausted by intensive cropping, and soils derived from parent material that is inherently low in S (Jordan and Reisenauer, 1957).

Polysulphate (Cleveland Potash Ltd., UK) is the trade mark of the natural mineral ‘polyhalite’, which occurs in sedimentary marine evaporates, and consists of a hydrated sulfate of K, calcium (Ca) and magnesium (Mg) with the formula: $K_2Ca_2Mg(SO_4)_4{\cdot}2(H_2O)$. The deposits found in Yorkshire in the UK typically consist of 14% K_2O, 48% SO_3, 6% MgO, and 17% CaO. The S content of gypsum, a common S and Ca supplement alternative, is only 18.6%.

Map 1. Experimental site in India, Karantaka State, at Hessaraghatta, north-west of Bengaluru. *Source:* Google Maps.

The objective of this study was to test the bioefficacy of polyhalite on the performance of two major cole crops (cauliflower and cabbage) in India.

Materials and methods

Field experiments were conducted at the experimental research farm (Block 5) at the Indian Institute of Horticultural Research (IIHR), Hessaraghatta, Bengaluru, Karnataka between October 2013 and March 2014. Cabbage (cv. Tetries) and cauliflower (cv. Unathi) were sown in portrays with fermented coco peat as a rooting medium, and the seedlings were raised in a greenhouse.

The experimental fields were thoroughly ploughed and levelled. Farm yard manure (FYM) was applied at 25 Mg ha^{-1} in the last plough. The recommended dose of fertilizers (RDF) was 150 kg N, 100 kg P_2O_5 and 125 kg K_2O ha^{-1}, and 20 kg S ha^{-1} was also applied as per the treatments. Initial soil samples from the experimental fields were collected before application of FYM and basal doses of fertilizers (Table 1). Transplanting was carried out on 28 October 2013. Appropriate plant protection measures were taken for control of different pest and diseases throughout the cropping period.

The experiments, laid out in a randomized block design with three replicates, included six treatments:

- T_1: Control without S and K fertilization (100% NP only through Urea, DAP).
- T_2: 100% NPK (Urea, DAP, Muriate of Potash (MOP)).
- T_3: 100% NP + 50% S through polyhalite (balanced K through MOP to make 100% K).
- T_4: 100% NP + 75% S through polyhalite (balanced K through MOP to make 100% K).
- T_5: 100% NP + 100% S through polyhalite (balanced K through MOP to make 100% K).
- T_6: 100% NPK (Urea, DAP, MOP) + 100% S through gypsum.

Five plants from each plot were randomly selected periodically (30 and 60 days after transplanting (DAT) and towards harvest)

Table 1. Physico-chemical characteristics of the soil at the experimental site.

Particulars	Value
Particle size analysis (over dry basis)	
Sand (%)	69.6
Silt (%)	9.9
Clay (%)	20.5
Textural class	Sandy clay loam
Soil classification	Typic haplustepts
Chemical properties	
Soil reaction (1:2.5)	6.84
Electrical conductivity (dS m^{-1})	0.125
Organic carbon (g kg^{-1})	11.5
Available nutrients	
Nitrogen (kg ha^{-1})	268.7
Phosphorus (kg ha^{-1})	47.8
Potassium (kg ha^{-1})	298.8
Sulfur (ppm)	16
Exchangeable cations (cmol (p+) kg^{-1})	
Calcium	4.8
Magnesium	0.35
DTPA extractable micronutrients (mg kg^{-1})	
Iron	25
Manganese	9
Zinc	0.8
Copper	2

Photos 1. General view of cabbage (left) and cauliflower (right) experimental fields at Block 5 of IIHR farm. Photos by authors.

and used for growth/biometric observations, such as plant height and number of leaves per plant. Plant height was measured from the base of the plant to the base of the fully opened top leaf.

Crops were harvested after complete maturity, when heads/curds were firm and compact. Yield per plot was expressed in Mg ha^{-1}. Five randomly selected plants from each plot were used to determine shoot and head/curd fresh weight, and head/curd circumference. Crude protein (%), ascorbic acid (mg 100 g^{-1}), and total soluble content (TSS, ºBrix) were determined using a 100 g sample of each plant. Shoot and head/curd samples were weighed, and then dried at 70°C to a constant weight in a hot air oven, thus determining % dry weight and calculated dry matter production. The dried samples were ground and used to determine N, P, K, Ca, Mg, S, and zinc (Zn) contents in the shoot and head/curd samples.

Results

Lacking K and S fertilizers, control plants (T_1) grew and developed significantly slower than plants that received all other treatments (Fig. 1). Cabbage plants grew faster and taller in response to sufficient K application (T_2). Additional S application in the form of polyhalite, up to 75% of the recommended S dose, further enhanced plant growth and development (T_4). The application of the recommended S dose (20 kg ha^{-1}), either as polyhalite (T_5) or gypsum (T_6) brought about some reduction in plant development (Fig. 1). In cauliflower, towards harvest, only T_4 plants were significantly taller, but differences between treatments were more obvious regarding the number of leaves. While T_1 and T_4 possessed the lowest and highest numbers of leaves, respectively, T_2, T_3, and T_6 displayed a similar intermediate number of leaves. Noteworthy is the drop in the number of leaves in T_5 (Fig. 1).

A similar response pattern to K and S application rates and source was found regarding the plant's fresh and dry aboveground biomass, in both cabbage and cauliflower (despite the considerable differences in the absolute figures between the two cultivars). The smallest shoots and heads were produced by the control plants. Sufficient K application caused a significant increase in plant weight. Whereas the 75% S dose (T_4) provided the largest plants,

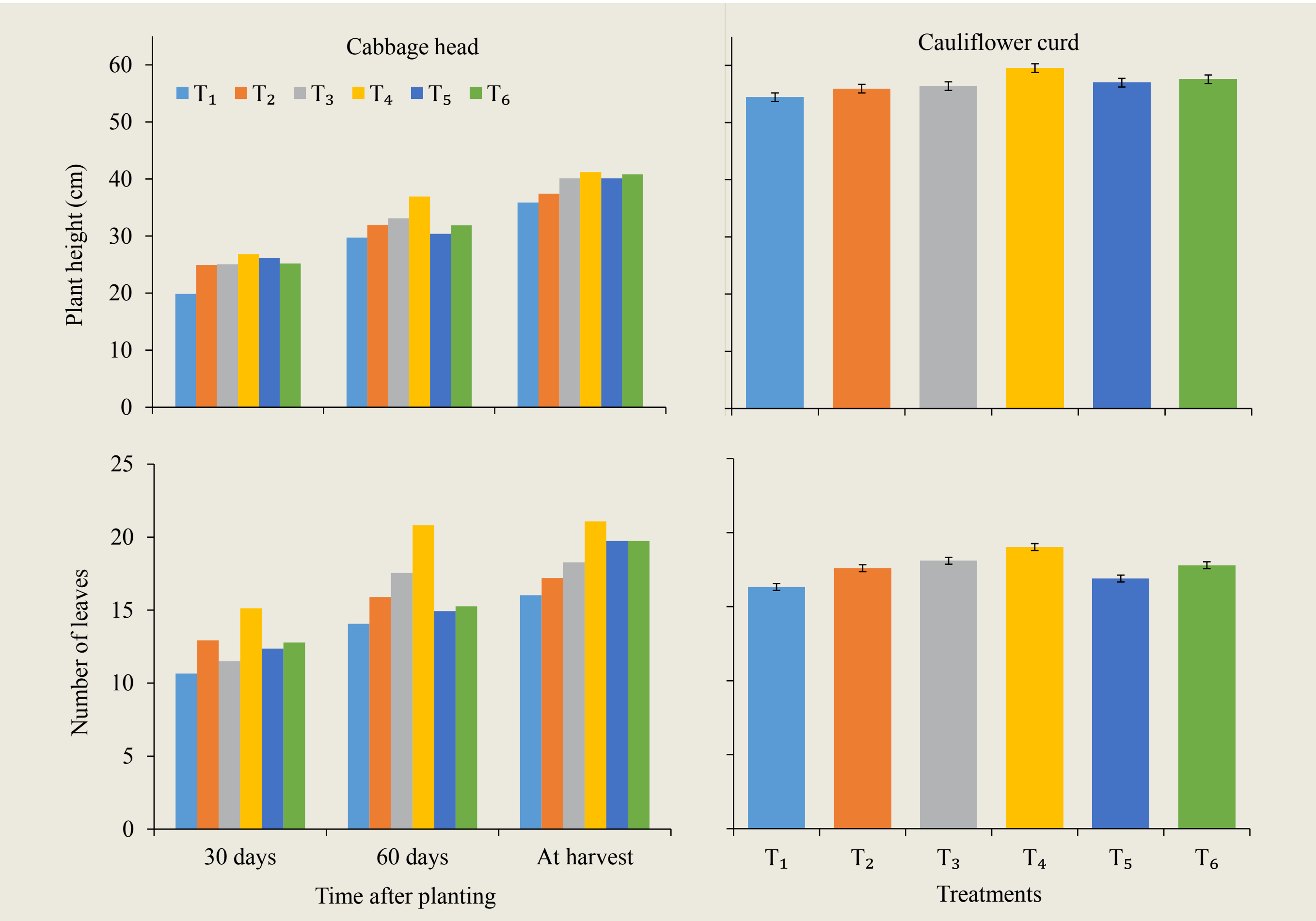

Fig. 1. Effects of K and S application on cabbage height and number of leaves 30 and 60 days after planting and toward harvest (left), and on cauliflower toward harvest (right).

the half S dose (T_3) was not responsive, and the full S doses (T_5, T_6) gave rise to plants that were significantly smaller than those of T_4 (Fig. 2).

T_4 displayed the highest cabbage and cauliflower yields, of 45.7 and 26.1 Mg ha^{-1} respectively, which were significantly different from all other treatments (Fig. 3). The advantage of T_4 was also observed in quality attributes, such as head/curd diameter and compactness at harvest (Fig. 3). T_1 (control, 100% NP, no K and S application) displayed the lowest yields, of 34.4 and 18.7 Mg ha^{-1} for cabbage and cauliflower respectively, which was far below all other treatments. In cabbage, application of sufficient K (T_2) significantly improved yield, head diameter and head compactness, whereas adding 50% S RDF failed to bring about any change. Supplement of 100% S RDF (T_5, T_6) significantly increased yield and some quality attributes, but these remained below the performance of T_4 (Fig. 3). In cauliflower, curd diameter did not respond to the fertilization treatments, excluding T_4. Curd compactness increased significantly with K application but was not affected by further supply of S, excluding T_4 (Fig. 3).

Crude protein content in cabbage heads at harvest, which was significantly lower at T_1 (11.3%), rose to 12.4% in response to sufficient K application dose (T_2), but was not affected further by the addition of S, at any rate or source (Fig. 4). T_4 displayed the highest ascorbic acid (50.8 mg 100 g^{-1}) content at harvest, but it was not significantly different from the other treatments, excluding T_1, which had a far lower concentration of 46 mg 100 g^{-1}. TSS fluctuated considerably among treatments, nevertheless the highest rates were displayed by T_4 and T_6 (Fig. 4).

Although N and P were equally applied in all treatments, considerable differences occurred in their contents in cabbage and cauliflower shoots at harvest (Table 2). T_1 showed the lowest concentrations of these two elements. Nitrogen concentrations increased significantly in T_2, indicating K requirements for N

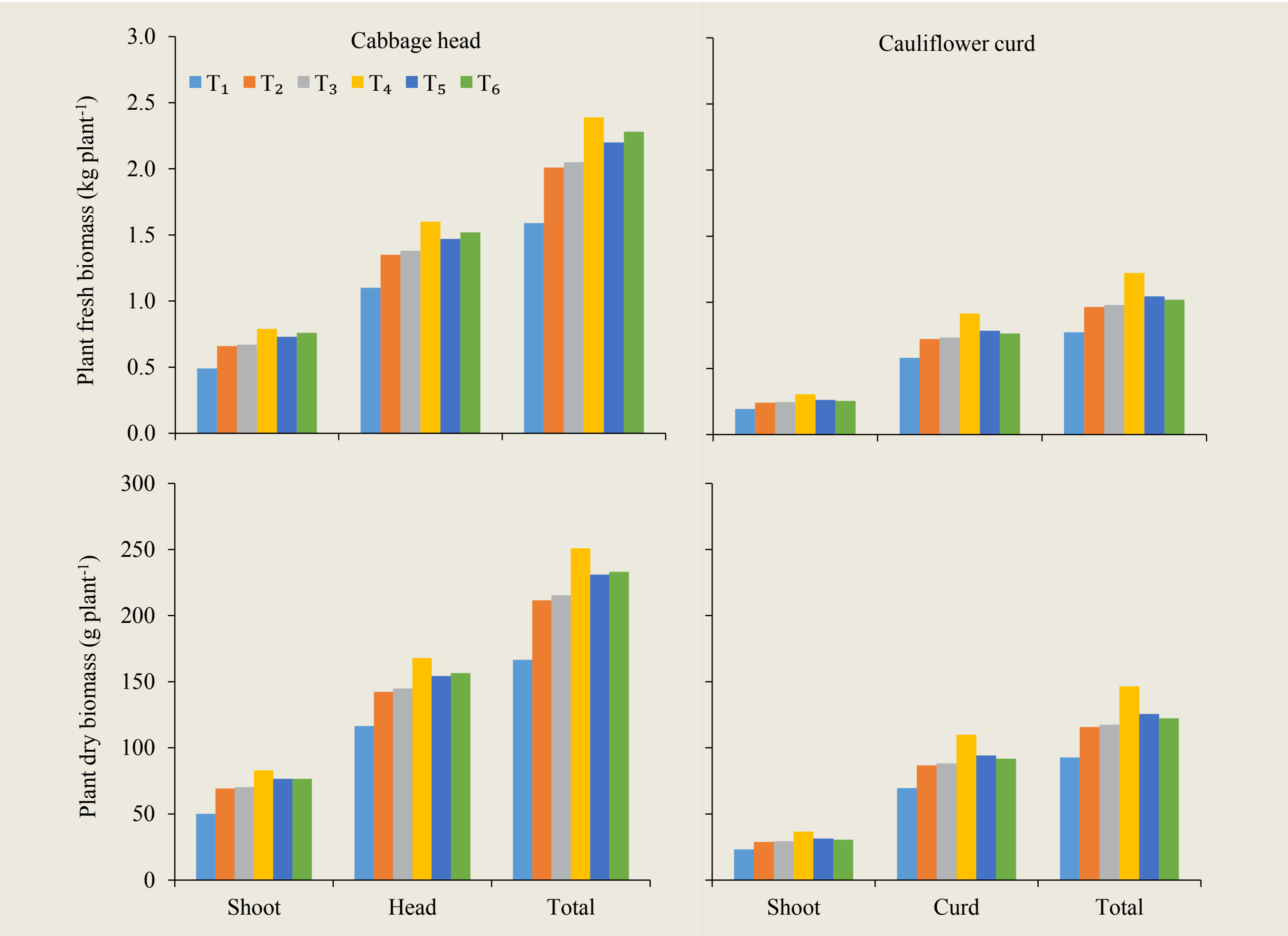

Fig. 2. Effects of K and S application on shoot and head/curd fresh and dry weight of cabbage and cauliflower at harvest.

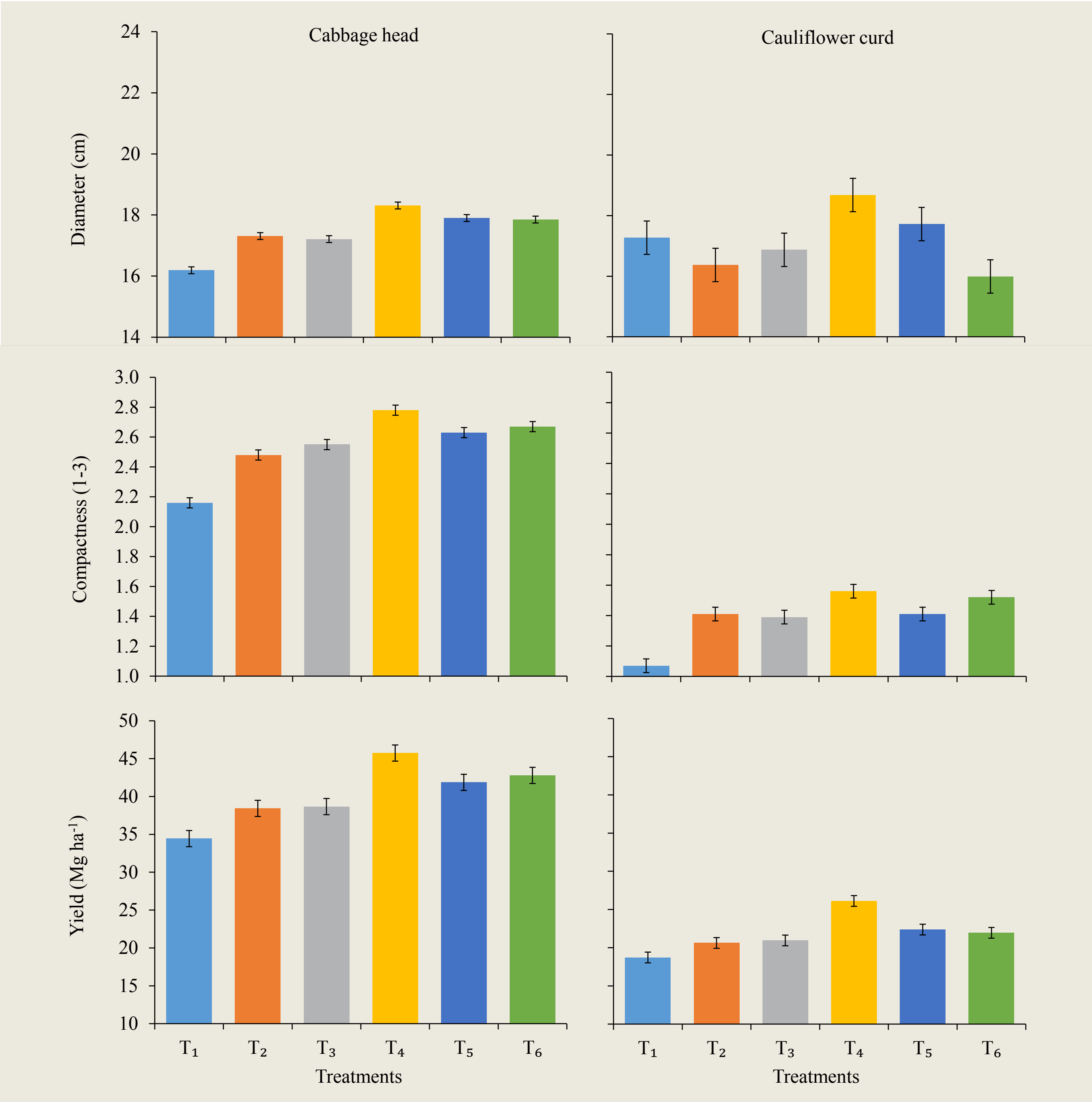

Fig. 3. Effects of K and S application and source on cabbage head (left) and cauliflower curd (right) diameter, compactness, and yield. Bars indicate LSD at P<0.05.

metabolism. No consistent influence of S dose was observed on N concentrations. Nevertheless, S application had some positive impact on P concentrations in the shoots of both crops (T_3-T_6). Nitrogen concentrations in the head or curd were generally lower than in the shoots. In cabbage, K application gave rise to moderate increases in N concentration, with no further effect of S application. In cauliflower, N concentration was somewhat higher in the curds of S-supplied plants.

While a significant increase in P occurred only in T_4 cabbage heads, the concentration of this element in cauliflower curds was significantly higher in all S-supplied plants, with T_4, again, obtaining

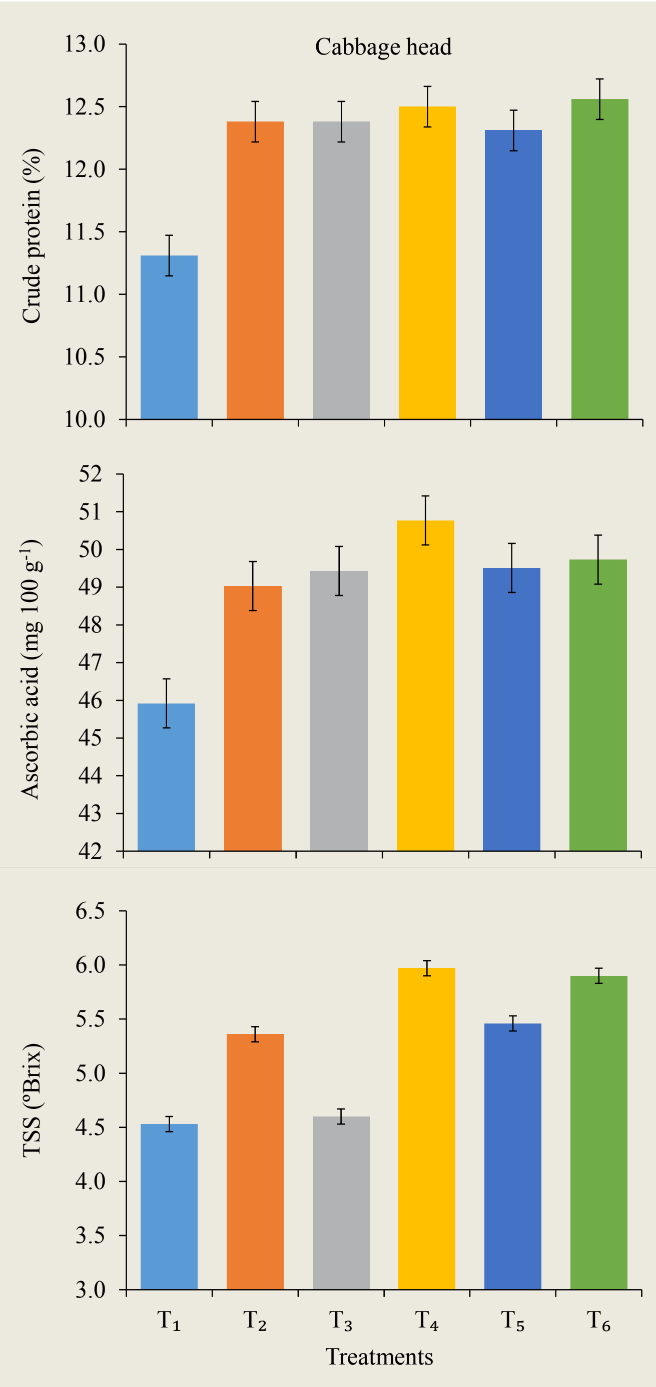

Fig. 4. Effects of K and S application and source on internal quality attributes of cabbage. Bars indicate LSD at P<0.05.

the highest results (Table 2). As expected, T_1 displayed the lowest K concentration, which was slightly increased by supplemented K in treatments T_2-T_6 (Table 2). In the shoots, S application seemed to contribute to further increases in K concentration in both crops. As indicated by treatments T_3-T_6, the rising S dose dramatically increased K concentrations in cabbage heads, whereas this effect was absent in cauliflower curds.

Calcium accumulation in the shoot was considerably influenced by S application dose, particularly in cabbage, where Ca concentrations increased from 2.51 to 4.12%, in T_2 and T_6, respectively (Table 2). This phenomenon was similar but to a lesser extent in cauliflower shoots. In spite of the drastically smaller Ca concentrations in cabbage heads, the enhancing impact of S application remained obvious. In cauliflower curds, which possessed Ca concentrations similar to those of shoots, S effect on Ca accumulation was observed up to 75% S dose (T_4), but declined with further elevations of S. Magnesium concentrations were less affected by the fertilization treatments (Table 2).

Surprisingly, an adequate K dose was enough to increase S concentration in cabbage shoots from 0.75% (T_1) to 1-1.1%; a level that was not further changed by S applied in the form of polyhalite. Gypsum application of 100% S RDF (T_6) did increase S concentration in the shoot (Table 2). On the contrary, S concentration in the cabbage head did respond to elevated S applications up to 75% S RDF (T_4) but slightly decreased with further increase of S. Sulfur concentrations in cauliflower shoots and curds also increased in response to K application in the absence of S supply, but continued to rise with increasing S supplement up to 75% of the S RDF. Further increase in S application dose did not have an impact (Table 2). Zinc concentrations in plants organs fluctuated from 12-23 ppm with no consistent response to fertilizer application.

As a function of the plant's final biomass and nutrient concentration in the plant at harvest, the cumulative nutrient uptake provides an integrative idea of fertilization effects at each treatment (Fig. 5). T_4, which was applied with 100% NPK but only 75% S RDF, obtained the maximum uptake of all measured nutrients. In cabbage, T_4 was followed by T_6 regarding N, K, Ca, and S uptake, whereas the picture in cauliflower was more complex (Fig. 5). In both crops, N uptake benefited significantly from K application, while the response to S was restrained. Phosphorus uptake increased as a result of K application, and continued to rise with S application in cabbage as well as in cauliflower up to 75% S RDF. Potassium uptake was highly responsive to S application in cabbage, but failed to respond in cauliflower, excluding T_4. Calcium uptake, which increased in response to K application in both crops, continued to rise in cabbage with increasing S doses but remained quite constant in cauliflower (again, excluding T_4). A similar Mg uptake profile was shared by the two crops: a significant rise in response to K application and a very modest response to S fertilizers. Sulfur uptake was predominantly affected by K availability, but it also increased due to S supplements (Fig. 5).

Table 2. Effects of K and S application dose and source on nutrient contents (in dry matter) in the shoot and head of cabbage and cauliflower at harvest.

Nutrient	Cabbage						Cauliflower					
	Treatment											
	T_1	T_2	T_3	T_4	T_5	T_6	T_1	T_2	T_3	T_4	T_5	T_6
	Shoot						Shoot					
	% DM											
N	2.75	3.15	3.32	3.16	2.94	3.22	2.14	2.85	2.8	2.98	2.84	2.93
P	0.48	0.48	**0.56**	0.52	0.52	0.52	0.32	0.4	0.42	0.42	0.44	**0.48**
K	3.56	3.68	3.67	**3.92**	3.85	**3.93**	2.33	3.17	2.61	3.04	**3.32**	**3.30**
Ca	1.75	2.51	3.39	**3.92**	3.75	**4.12**	1.04	1.04	1.11	**1.34**	1.18	1.08
Mg	0.20	0.24	0.27	0.28	0.28	**0.30**	0.19	0.23	0.27	0.29	**0.32**	0.24
S	0.75	1.10	1.00	1.10	1.00	**1.47**	0.30	0.48	0.66	**0.86**	0.75	0.71
	ppm											
Zn	12	16	**18**	**18**	**18**	14	16	16	16	**23**	12	13
	Head						Curd					
	% DM											
N	1.77	2.00	2.04	2.00	1.97	**2.16**	0.85	0.93	0.85	0.95	0.98	0.95
P	0.36	0.40	0.44	**0.52**	0.40	0.44	0.32	0.34	0.44	**0.58**	0.50	0.45
K	2.47	2.85	3.38	**3.67**	3.38	3.36	2.93	**3.97**	**3.92**	**3.98**	3.25	3.08
Ca	0.16	0.19	0.20	0.36	0.36	**0.41**	0.90	1.11	1.17	**1.31**	0.96	1.16
Mg	0.21	0.23	0.23	0.23	0.25	0.23	0.23	0.27	0.25	0.25	0.25	0.23
S	0.54	0.66	0.70	**0.90**	0.82	0.83	0.26	0.36	0.46	0.47	0.46	0.51
	ppm											
Zn	17	18	16	17	17	12	14	13	18	12	13	14

Note: Bold numbers represent particularly higher values, while gray represent the lower ones.

Examining the impact of S doses on cabbage and cauliflower, a predominant and consistent effect was obtained from the application of 75% S RDF through polyhalite (with 100% RDF of N and K) administered in T_4, which gave rise to 32.8% and 39.5% increases in the yields of cabbage and cauliflower, respectively, compared to the non-fertilized control (T_1). Generally, no further increase was recorded when the full S RDF was applied, through polyhalite or gypsum; yields even declined (Fig. 3). This result may indicate the existence of one or more factors limiting plant response to additional available S resources.

Discussion

Practically and irrespective of doses, S application improved growth parameters, yield attributes and quality of cabbage and cauliflower. The important role of S fertilization in Brassica crops has been broadly addressed in previous studies (McGrath and Zhao, 1996; Khan *et al.*, 2005; Tiwari *et al.*, 2015), but particular evidence in cole crops, as demonstrated here, is quite rare (Susila and Locascio, 2001).

Nitrogen is known to positively interact with S; in many plant species, elevated availability of S promotes N uptake, and vice versa (McGrath and Zhao, 1996; Abdallah *et al.*, 2010; Jamal *et al.*, 2010). In this study, N was provided as a fixed recommended dose, which might reveal an underestimation of plant requirements when S availability is improved. Nevertheless, the impact of K seems even more interesting; S uptake sharply increased in response to K application, even in the absence of any additional S, but was much less pronounced in response to S application (Fig. 5). This indicates a strong dependency of S uptake and metabolism on K availability. Potassium is the most abundant inorganic cation in plants, comprising up to 10% of a plant's dry weight (Watanabe *et al.*, 2007), and K concentration in the

Photos 2. A T_4 plot (100% NP, 75% S through polyhalite) towards harvest. Photos by authors.

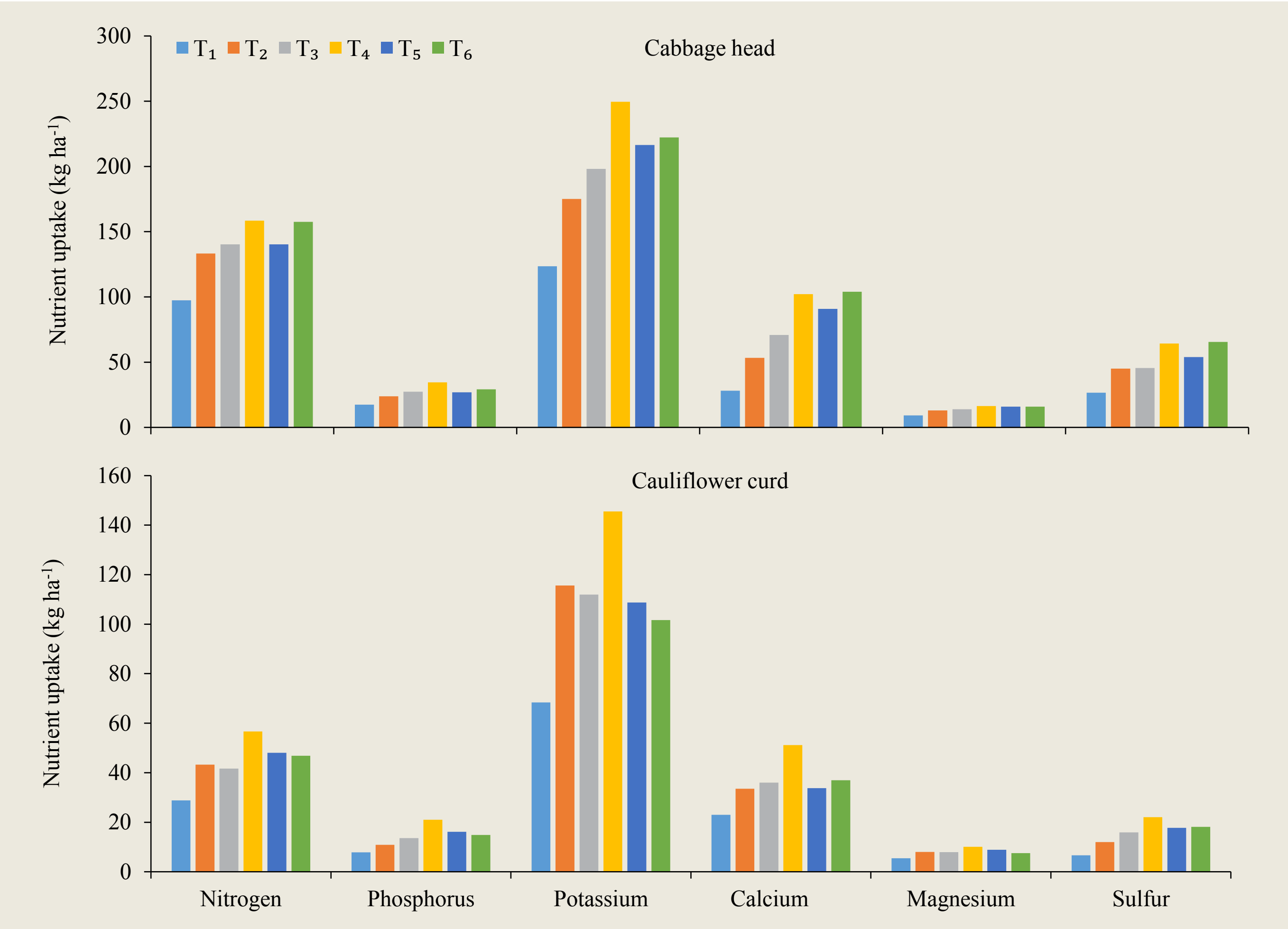

Fig. 5. Cumulative nutrient uptake by cabbage and cauliflower crops, as affected by K and S application dose and source.

shoot is often higher in plants from the Brassicaceae than in those from many other angiosperm families, when grown under comparable conditions (Broadley *et al.*, 2004). While involved in many physiological processes, K impact on plant-water relations, photosynthesis, assimilate transport and enzyme activation can have direct consequences on crop productivity (Marschner, 1995; Pettigrew, 2008; Hochmuth and Hanlon, 2010). Nevertheless, direct relationships or interactions between K and S uptake by plants have not yet been shown elsewhere (White *et al.*, 2010). The results of this study suggest that in cabbage and cauliflower, the recommended K dose was unable to support the exploitation of available S above a certain limit, and instead restricted further growth and development. Alternatively, considerable portions of N and K basal broadcast might have leached away from the rhizosphere, lacking at later stages of plant development. Another possibility is that the recommended S dose (20 kg ha^{-1}) is beyond the peak of the S optimum curve for cole crops. N-P-K fertilization practices, therefore, may require some adjustments when it comes to the practical application of S.

Interestingly, S application significantly promoted the uptake of P and Ca. Phosphorus is essential for plant growth and development. It is a major DNA/RNA keystone and is involved in all energy exchange processes and countless regulatory pathways (Marschner, 1995). The divalent cation Ca^{2+} has structural roles in plant cell walls and membranes, is a counter cation for inorganic and organic anions in the vacuole, and is an intracellular messenger in the cytosol. Calcium uptake is mediated by both symplastic and apoplastic fluxes in the root, while entry and exit of Ca to the symplast is exquisitely controlled by plasma membrane-localized Ca^{2+}-permeable ion channels and Ca^{2+}-ATPases, respectively (Broadley *et al.*, 2008). Evidence, however, of any direct interactions between S and P or Ca uptake is scarce, and therefore requires further investigation.

A comprehensive analysis of polyhalite performance as an S donor, including a full-scale dose comparison with alternative fertilizers, was beyond the scope of the present study. Here, using the full recommended S dose, no significant differences were found between gypsum and polyhalite. However, all yield and quality attributes were inferior to the 75% S dose, delivered through polyhalite. Optimum nutrient availability throughout the growing season is crucial, as their uptake rates are often slower than leaching processes, while plant requirements tend to increase (Hawkesford, 2000; Susila and Locascio, 2001; Abdallah *et al.*, 2010; Hochmuth and Hanlon, 2010; Steinfurth *et al.*, 2012; Girondé *et al.*, 2014). A considerable advantage of polyhalite may therefore be a slow-release pattern of nutrient delivery, including K, which is very mobile in well-watered soils.

In conclusion, S application significantly contributed to increased yield and quality of cabbage and cauliflower. Potassium enhanced S uptake, while in turn, S appeared to promote P and Ca uptake. The highest yields were obtained with a full dose N-P-K and 75% S dose delivered through polyhalite, which ascertained its legitimacy as an S-K-Ca-Mg fertilizer with some slow-release properties. Further research is required to adjust N and K fertilization practices when S is also administered.

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The paper "Bioefficacy of Polyhalite Application on Yield and Quality of Cabbage and Cauliflower" also appears on the IPI website at:

Regional activities/India

Events

International Symposia and Conferences

August 2016

5th Sustainable Phosphorus Summit (SPS 2016), 16-20 August 2016, Kunming, Yunnan, China.

SPS 2016 is the fifth in a successful series of Sustainable Phosphorus Summits that was launched in Linköping (Sweden) in 2010, and then went to Tempe (USA) in 2011, Sydney (Australia) in 2012 and Montpellier (France) in 2014, related to the Global Phosphorus Research Initiative. It is a global multidisciplinary event to discuss phosphorus production and utilization, management and sustainability. The conference will be hosted by China Agricultural University and Yuntianhua Group. See First Circular on the IPI website/Events and the announcement on the Phosphorus Futures website.

The 2nd International Conference on Agriculture and Sustainability (ICAS 2016) 24-26 August 2016, Xi'an, China.

This Conference will cover issues on Agriculture and Sustainability. It is dedicated to creating a stage for exchanging the latest research results and sharing the advanced research methods. For more information go to the conference website.

October 2016

CropWorld Global, 24-25 October 2016, Amsterdam RAI, Netherlands.

CropWorld Global is Europe's leading event dedicated to the latest developments & innovations on crop production, protection and agricultural technology. The event's new format connects a Congress and Expo. Leading global suppliers, buyers, scientists, regulators and key policy makers from the agriculture and crop industry will benefit from two days of first-rate networking and exposure to new business opportunities. See more details on the congress website.

December 2016

7th International Nitrogen Conference (INI 2016) "Solutions to Improve Nitrogen Use Efficiency for the World", 4-8 December 2016, Melbourne Cricket Ground, Victoria, Australia.

More information on this triennial event, which is supported by both IPNI and IFA, is available online on the conference website.

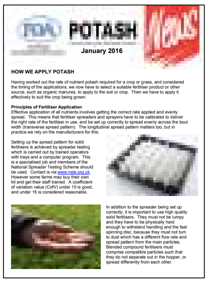
January 2017

Frontiers of Potassium - an International Conference, 25-27 January 2017, Rome, Italy.

The understanding of potassium behavior in soil and its vital role in plant health has been expanding rapidly. This conference will allow global experts to gather and discuss the frontiers of potassium science. IPNI will organize the conference to facilitate discussion of key technical questions and develop a pathway for additional potassium research and for improved nutrient management. See First Conference Announcement on the conference website.

Publications

Publication by the PDA



How We Apply Potash

POTASH News, January 2016.

Having worked out the rate of nutrient potash required for a crop or grass, and considered the timing of the applications, we now have to select a suitable fertiliser product or other source, such as organic manures, to apply to the soil or crop. Then we have to apply it effectively to suit the crop being grown. 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

K in the Literature

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Arabidopsis NRT1.5 Mediates the Suppression of Nitrate Starvation-Induced Leaf Senescence by Modulating Foliar Potassium Level

Shuan Meng, Jia-Shi Peng, Ya-Ni He, Guo-Bin Zhang, Hong-Ying Yi, and Yan-Lei Fu. 2016. Molecular Plant 9(3):461-470. DOI 10.1016/j.molp.2015.12.015.

Abstract: Nitrogen starvation induces leaf senescence. However, whether or how nitrate might affect this process remains to be investigated. Here, we reported an interesting finding that nitrate- instead of nitrogen-starvation induced early leaf senescence in *nrt1.5* mutant, and presented genetic and physiological data demonstrating that nitrate starvation-induced leaf senescence is suppressed by NRT1.5. NRT1.5 suppresses the senescence process

dependent on its function from roots, but not the nitrate transport function. Further analyses using *nrt1.5* single and *nia1 nia2 nrt1.5-4* triple mutant showed a negative correlation between nitrate concentration and senescence rate in leaves. Moreover, when exposed to nitrate starvation, foliar potassium level decreased in *nrt1.5*., but adding potassium could essentially restore the early leaf senescence phenotype of *nrt1.5* plants. Nitrate starvation also downregulated the expression of *HAK5, RAP2.11* and *ANN1* in *nrt1.5* roots, and appeared to alter potassium level in xylem sap from *nrt1.5*. These data suggest that NRT1.5 likely perceives nitrate starvation-derived signals to prevent leaf senescence by facilitating foliar potassium accumulation.

Efficiency of Celeriac Fertilization with Phosphorus and Potassium Under Conditions of Integrated Plant Production

Niemiec, M., M. Cupial, and A. Szelag-Sikora. 2015. Agriculture and Agricultural Science Procedia 7:184-191. DOI 10.1016/j.aaspro.2015.12.015.

Abstract: The goal of this work was to assess the efficiency of celeriac fertilization with phosphorus and potassium under conditions of integrated plant production. The goal was realized by performing a strict experiment. Celeriac (Diamant cultivar) was the test plant. A controlled-release fertilizer, with NPK content of 18%, 5% and 11%, was used for fertilization. Moreover, the following conventional fertilizers were used: ammonium nitrate, granular triple superphosphate, and potassium salt. The efficiency of the fertilization was evaluated by calculating the following indices: agronomic effectiveness, productivity coefficient and removal efficiency. The most favourable productivity coefficient and agronomic effectiveness were reached when 300 and 400 kg of the slow-acting fertilizer was used along with additional fertilization with ammonium nitrate, and this variant of fertilization under conditions of conducting the experiment would be optimal. In the conventionally fertilized treatments, values of these parameters were several times lower. That is why measures that improve the efficiency of production may bring positive results. Results of the conducted research indicate that optimization of fertilization under conditions of intensive production may significantly increase the efficiency of production.

Potassium Fertilization Increases Water-Use Efficiency for Stem Biomass Production without Affecting Intrinsic Water-Use Efficiency in *Eucalyptus grandis* Plantations

Patricia Battie-Laclau, Juan Sinforiano Delgado-Rojas, Mathias Christina, Yann Nouvellon, Jean-Pierre Bouillet, Marisa de Cassia Piccolo, Marcelo Zacharias Moreira, José Leonardo de Moraes Gonçalves, Olivier Roupsard, Jean-Paul Laclau. 2016. Forest Ecology and Management 364:77-89. DOI 10.1016/j.foreco.2016.01.004.

Abstract: Adaptive strategies to improve tree water-use efficiency (WUE) are required to meet the global demand for wood in a future drier climate. A large-scale throughfall exclusion experiment was set up in Brazil to study the interaction between water status and potassium (K) or sodium (Na) availability on the ecophysiology of Eucalyptus grandis trees. This experiment focused primarily on the changes in aboveground net primary production, stand water use, phloem sap and leaf $\delta^{13}C$, net CO_2 assimilation and stomatal conductance. The correlations between these response variables were determined to gain insight into the factors controlling water-use efficiency in tropical eucalypt plantations. The intrinsic WUE in individual leaves (the ratio of net CO_2 assimilation to stomatal conductance) was estimated at a very short time scale from the leaf gas exchange. Sap flow measurements were carried out to assess the WUE for stemwood production (the ratio of wood biomass increment to stand water use). Averaged over the two water supply regimes, the stemwood biomass 3 years after planting was 173% higher in trees fertilized with K and 79% higher in trees fertilized with Na than in trees with no K and Na addition. Excluding 37% of the throughfall reduced stemwood production only for trees fertilized with K. Total canopy transpiration between 1 and 3 years after planting increased from about 750 to 1300 mm y^{-1} in response to K fertilization with a low influence of the water supply regime. K fertilization increased WUE for stemwood production by approx. 60% with or without throughfall exclusion. There was a strong positive correlation between phloem sap $\delta^{13}C$ and short-term leaf-level intrinsic WUE. Whatever the water and nutrient supply regime, the gas exchange WUE estimates were not correlated with WUE for stemwood production. Phloem sap $\delta^{13}C$ and leaf $\delta^{13}C$ were therefore not valuable proxies of WUE for stemwood production. The allocation pattern in response to nutrient and water supply appeared to be a major driver of WUE for stemwood production. In areas with very deep tropical soils and annual rainfall <1500 mm, our results suggest that breeding programs selecting the eucalypt clones with the highest growth rates tend to select the genotypes with the highest water-use efficiency for wood production.

Foliar Application of Microbial and Plant based Biostimulants Increases Growth and Potassium Uptake in Almond (*Prunus dulcis* [Mill.] D. A. Webb)

Olivos-Del Rio, A., S. Castro, and P.H. Brown. 2015. Front. Plant Sci. DOI 10.3389/fpls.2015.00087.

Abstract: The use of biostimulants has become a common practice in agriculture. However, there is little peer-reviewed research on this topic. In this study we tested, under controlled and replicated conditions, the effect of one biostimulant derived from seaweed extraction (Bio-1) and another biostimulant derived from microbial fermentation (Bio-2). This experiment

utilized 2-years-old almond plants over two growing seasons in a randomized complete design with a full 2 × 4 factorial structure with two soil potassium treatments (125 µg g^{-1} of K vs. 5 µg g^{-1}) and four foliar treatments (No spray, Foliar-K, Bio-1, Bio-2). Rubidium was utilized as a surrogate for short-term potassium uptake and plant growth, nutrient concentration, and final plant biomass were evaluated. There was a substantial positive effect of both biostimulant treatments on total shoot leaf area, and significant increases in shoot length and biomass under adequate soil potassium supply with a positive effect of Bio-1 only under low K supply. Rubidium uptake was increased by Bio-1 application an effect that was greater under the low soil K treatment. Though significant beneficial effects of the biostimulants used on plant growth were observed, it is not possible to determine the mode of action of these materials. The results presented here illustrate the promise and complexity of research involving biostimulants.

The Role of Ethylene in Plant Responses to K^+ Deficiency

Schachtman, D.P. 2015. Front. Plant Sci. DOI http://dx.doi.org/10.3389/fpls.2015.01153

Abstract: Potassium is an essential macronutrient that is involved in regulating turgor, in driving plant growth, and in modulating enzyme activation. The changes in root morphology, root function, as well as cellular and molecular responses to low potassium conditions have been studied in the model plant Arabidopsis and in other plant species. In Arabidopsis ethylene plays a key role in roots in the transduction of the low potassium signal, which results in altered root function and growth. The first clues regarding the role of ethylene were detected through transcriptional profiling experiments showing changes in the expression of genes related to ethylene biosynthesis. Later it was shown that ethylene plays a foundational early role in the many responses observed in Arabidopsis. One of the most striking findings is the link between ethylene and reactive oxygen species (ROS) production, which is part of the signal transduction pathway in K+ deprived plants. This mini-review will summarize what is known about the role ethylene plays in response to low potassium in Arabidopsis and other plant species.

Relationship Between Potassium Fertilization and Nitrogen Metabolism in the Leaf Subtending the Cotton (*Gossypium hirsutum* L.) Boll During the Boll Development Stage

Hu, W., W. Zhao, J. Yang, D.M. Oosterhuis, D.A. Loka, and Z. Zhou. 2016. Plant Physiology and Biochemistry 101:113-123. DOI 10.1016/j.plaphy.2016.01.019.

Abstract: The nitrogen (N) metabolism of the leaf subtending the cotton boll (LSCB) was studied with two cotton (*Gossypium hirsutum* L.) cultivars (Simian 3, low-K tolerant; Siza 3, low-K sensitive) under three levels of potassium (K) fertilization (K0: 0 g K_2O $plant^{-1}$, K1: 4.5 K_2O $plant^{-1}$ and K2: 9.0 g K_2O $plant^{-1}$). The results showed that total dry matter increased by 13.1–27.4% and 11.2–18.5% under K supply for Simian 3 and Siza 3. Boll biomass and boll weight also increased significantly in K1 and K2 treatments. Leaf K content, leaf N content and nitrate (NO_3^-) content increased with increasing K rates, and leaf N content or NO_3^- content had a significant positive correlation with leaf K content. Free amino acid content increased in the K0 treatment for both cultivars, due to increased protein degradation caused by higher protease and peptidase activities, resulting in lower protein content in the K0 treatment. The critical leaf K content for free amino acid and soluble protein content were 14 mg g^{-1} and 15 mg g^{-1} in Simian 3, and 17 mg g^{-1} and 18 mg g^{-1} in Siza 3, respectively. Nitrate reductase (NR), glutamic-oxaloace transaminase (GOT) and glutamic-pyruvic transaminase (GPT) activities increased in the K1 and K2 treatments for both cultivars, while glutamine synthetase (GS) and glutamate synthase (GOGAT) activities increased under K supply treatments only for Siza 3, and were not affected in Simian 3, indicating that this was the primary difference in nitrogen-metabolizing enzymes activities for the two cultivars with different sensitivity to low-K.

The Influence of Nitrogen and Potassium Fertilisation on the Content of Polyphenolic Compounds and Antioxidant Capacity of Coloured Potato

Michalska, A., A. Wojdylo, and B. Bogucka. 2016. J. Food Composition and Analysis 47:69-75. DOI 10.1016/j.jfca.2016.01.004.

Abstract: The effect of fertilisation rates of nitrogen: 0 (control treatment - no soil fertilisation), 40, 80 and 120 kg/ha and potassium: 0 (control treatment), 120, 150 and 180 kg/ha on the content of anthocyanins, phenolic acids and antioxidant capacity in purple–blue potato cv. 'Blue Congo' was examined. Anthocyanins and phenolic acids were identified and quantified by LC–MS and UPLC–PDA. Nitrogen was more effective in increasing the anthocyanin content - their quantity in tubers after nitrogen application was twice as much as that found after potassium application. Among phenolic acids, the dominant one was chlorogenic acid, the content of which significantly increased after nitrogen fertilisation at 120 kg/ha, in line with the increase in total concentration of phenolic acids and antioxidant capacity. The adjustment of nitrogen and potassium fertilisation levels during the growth of purple–blue potatoes seems to be an effective way to increase the expression of polyphenolic compounds in these cultivars. Therefore, fertilisation with N at 120 kg/ha and K at 120 and 150 kg/ha is recommended as a way to improve the content of biologically active compounds and antioxidant properties, and consequently, to enhance the nutritional value and the functionality of purple-blue potatoes.

Function of Sodium and Potassium in Growth of Sodium-Loving Amaranthaceae Species

Yamada, M., C. Kuroda, and H. Fujiyama. 2016. Soil Sci. Plant Nutr. 62(1):20-26. DOI 10.1080/00380768.2015.1075365.

Abstract: We observed that the growth of three Amaranthaceae species was promoted by sodium (Na), in the order dwarf glasswort (*Salicornia bigelovii* Torr.) >> Swiss chard (*Beta Burgaris* L. spp. *cicla* cv. Seiyou Shirokuki) > table beet (*Beta vulgaris* L. spp. *vulgaris* cv. Detroit Dark Red). In the present study, these Na-loving plants were grown in solutions containing 4 mol m^{-3} nitrate nitrogen (NO_3-N) and 100 mol m^{-3} sodium chloride (NaCl) and potassium chloride (KCl) under six Na to potassium (K) ratios, 0:100, 20:80, 40:60, 60:40, 80:20 and 100:0, to elucidate the function of Na and K on specific characteristics of Na-loving plants. The growth of dwarf glasswort increased with increasing Na concentration of the shoot, and the shoot dry weight of plants grown in 100:0 Na:K was 214% that of plants grown at 0:100. In Swiss chard and table beet, growth was unchanged by the external ratio of Na to K. The water content was not changed in Swiss chard or table beet by the external Na to K ratio. These observations indicate that both Na and K have a function in osmotic regulation. However, dwarf glasswort could not maintain succulence at 0:100; therefore, Na has a specific function in dwarf glasswort for osmotic regulation to maintain a favorable water status, and the contribution of K to osmotic regulation is low. NO_3-N uptake was promoted by Na uptake in dwarf glasswort and Swiss chard. NO_3-N uptake and transport to shoots was optimal at 100:0 in dwarf glasswort and at 80:20 in Swiss chard. These functions are very important for the Na-loving mechanism, and the contribution of K was lower in dwarf glasswort than in Swiss chard.

Positional Difference in Potassium Concentration as Diagnostic Index Relating to Plant K Status and Yield Level in Rice (*Oryza sativa* L.)

Xinxin Xue, Jianwei Lu, Tao Ren, Lantao Li, Muhammad Yousaf, Rihuan Cong, and Xiaokun Li. 2016. Soil Sci. Plant Nutr. 62(1):31-38. DOI 10.1080/00380768.2015.1121115.

Abstract: Plant tissue testing is used as a guide for rice (*Oryza sativa* L.) fertilization and has been extensively used in the diagnosis of potassium (K) deficiency. However, little attention has been paid to the variation in the diagnostic index of K status in different parts of the rice plant. Here, we assessed the feasibility by testing K concentrations of whole plants, leaf blades and leaf sheaths to develop a suitable diagnostic index of plant K status and yield level in rice under different K application rates. The results showed that this research could satisfy the requirements of K status diagnosis, based on the quadratic-plus-plateau relationship between K application rates and grain yield. The K concentrations of the leaf blades and leaf sheaths on the main stem showed differences based on position. Leaf blade K concentrations significantly decreased from the top of the plant to the bottom in the effective tillering and jointing stages. Conversely, K concentrations in the lower leaf blades exceeded those in the upper leaf blades in the booting and full heading stages. K concentrations in the leaf sheath were significantly reduced with declining leaf position except during the jointing stage under high K treatments. Leaf sheath/leaf blade K concentration ratios increased significantly more in lower tissues than in upper plant tissues. Correlation analysis showed that the K concentrations of all sampled plant tissues were positively correlated to plant K uptake and grain yield. However, K concentrations of the whole plant were more useful as a diagnostic index at the effective tillering stage than at other growth stages. Leaf sheaths in lower positions were preferable to upper leaf sheaths and all leaf blades for evaluating plant K status, although their K concentrations were greatly influenced by plant growth stage. Furthermore, this study demonstrated that the ratio between the K concentrations of the first and fourth leaf blades ($LBKR_{1/4}$) was grouped into significantly exponential curves ($P < 0.01$) to describe the relationship between plant K uptake and relative grain yield. Thus, $LBKR_{1/4}$ could be an ideal indicator of rice plant K status and yield level, as it eliminated the effects of plant growth stage.

Potassium Transporter *KUP7* is Involved in K^+ Acquisition and Translocation in *Arabidopsis* Root under K^+-Limited Conditions

Min Han, Wei Wu, Wei-Hua Wu, and Yi Wang. 2016. Molecular Plant 9(3):437-446. DOI 10.1016/j.molp.2016.01.012.

Abstract: Potassium (K^+) is one of the essential macronutrients for plant growth and development. K^+ uptake from environment and K^+ translocation in plants are conducted by K^+ channels and transporters. In this study, we demonstrated that KT/HAK/KUP transporter *KUP7* plays crucial roles in K^+ uptake and translocation in *Arabidopsis* root. The *kup7* mutant exhibited a sensitive phenotype on low-K^+ medium, whose leaves showed chlorosis symptoms compared with wild-type plants. Loss of function of *KUP7* led to a reduction of K^+ uptake rate and K^+ content in xylem sap under K^+-deficient conditions. Thus, the K^+ content in *kup7* shoot was significantly reduced under low-K^+ conditions. Localization analysis revealed that *KUP7* was predominantly targeted to the plasma membrane. The complementation assay in yeast suggested that *KUP7* could mediate K^+ transport. In addition, phosphorylation on S80, S719, and S721 was important for *KUP7* activity. *KUP7* was ubiquitously expressed in many organs/tissues, and showed a higher expression level in *Arabidopsis* root. Together, our data demonstrated that *KUP7* is crucial for K^+ uptake in *Arabidopsis* root and might be also involved in K^+ transport into xylem sap, affecting K^+ translocation from root toward shoot, especially under K^+-limited conditions.

Can Nonexchangeable Potassium be Differentiated from Structural Potassium in Soils?

Wang, H., W. Cheng, T. Li, J. Zhou, and X. Chen. 2016. Pedosphere 26(2):206-215. DOI 10.1016/S1002-0160(15)60035-2.

Abstract: Nonexchangeable K (NEK) is the major portion of the reserve of available K in soil and a primary factor in determining soil K fertility. The questions of how much NEK is in soils and how to quantify total NEK in soils are so far still unclear due to the complicated effects of various minerals on K fixation. In this study, the NEK in 9 soils was extracted with sodium tetraphenylboron ($NaBPh_4$) for various time periods longer than 1 d. The results showed that the NEK extracted by $NaBPh_4$ gradually increased with time, but showed no more increase after the duration of extraction exceeded 10-20 d. As the temperature increased from 25 to 45 °C, the duration to obtain the maximum extraction of NEK was reduced from 20 to 10 d, and the maximum values of NEK released at both temperatures was almost the same for each soil. The maximum NEK (MNEK) of the 9 soils extracted by $NaBPh_4$ varied from 3 074 to 10 081 mg kg^{-1}, accounting for 21%-56% of the total soil K. There was no significant correlation between MNEK released by $NaBPh_4$ and other forms of K, such as NH_4OAc-extracted K, HNO_3-extracted K and total K in soils, which indicates that NEK is a special form of K that has no inevitable relationship to the other forms of K in soils. The MNEK extraction by $NaBPh_4$ in this study indicated that the total NEK in the soils could be differentiated from soil structural K and quantified with the modified $NaBPh_4$ method. The high MNEK in soils made NEK much more important in the role of the plant-available K pool. How to fractionate NEK into different fractions and establish the methods to quantify each NEK fraction according to their bioavailability is of great importance for future research.

Effect of Elevated CO_2 on the Growth and Macronutrient (N, P and K) Uptake of Annual Wormwood (*Artemisia annua* L.)

Zhu, C., Q. Zeng, H. Yu, S. Liu, G. Dong, and J. Zhu. 2016. Pedosphere 26(2):235-242. DOI 10.1016/S1002-0160(15)60038-8.

Abstract: Annual wormwood (*Artemisia annua* L.) is the only viable source of artemisinin, an antimalarial drug. There is a pressing need to optimize production per cultivated area of this important medicinal plant; however, the effect of increasing atmospheric carbon dioxide (CO_2) concentration on its growth is still unclear. Therefore, a pot experiment was conducted in a free-air CO_2 enrichment (FACE) facility in Yangzhou City, China. Two *A. annua* varieties, one wild and one cultivated, were grown under ambient (374 µmol mol^{-1}) and elevated (577 µmol mol^{-1}) CO_2 levels to determine the dry matter accumulation and macronutrient uptake of aerial parts. The results showed that stem and leaf yields of both *A. annua* varieties increased significantly under elevated CO_2 due to the enhanced photosynthesis rate. Although nitrogen (N), phosphorus (P), and potassium (K) concentrations in leaves and stems of both varieties decreased under elevated CO_2, total shoot N, P, and K uptake of the two varieties were enhanced and the ratios among the concentrations of these nutrients (N:P, N:K, and P:K) were not affected by elevated CO_2. Overall, our results provided the evidence that elevated CO_2 increased biomass and shoot macronutrient uptake of two *A. annua* varieties.

Cotton Yield and Potassium Use Efficiency as Affected by Potassium Fertilizer Management with Stalks Returned to Field

Fuqiang Yang, Mingwei Du, Xiaoli Tian, A. Egrinya Eneji, and Zhaohu Li. 2016. Crop Sci. 56(2):740-746. DOI 10.2135/cropsci2015.03.0136.

Abstract: Widespread potassium (K) deficiencies in cotton (*Gossypium hirsutum* L.) have been documented throughout cotton producing countries. Potassium fertilizer is needed for high production of cotton yield. This study was conducted to determine whether K fertilizer management can improve efficiency of K nutrition in cotton. The effects of K source, rate, and application timing on yield and K use efficiency of cotton were investigated under conditions of cotton-stalk recycling to the field in the North China Plain (NCP). The results showed that there was no significant difference in yield between K sources of K_2SO_4 and KCl. However, we found that the low rate produced a 2 to 4% higher K agronomic efficiency (AEK) and a 12 to 93% higher K apparent recovery efficiency (REK) than the other rates, although there was little difference in yield among different K rates (45, 90, and 180 kg K_2O ha^{-1}). In addition, our results of application timing showed that the later split application at peak bloom acquired the highest lint yield as well as a 35 to 103% higher AEK and 23 to 58% higher REK than the earlier split application at peak squaring and full dose at preplanting. In conclusion, KCl should be the preferred K source because of its lower cost and fair effect on yield compared with K_2SO_4. The 45 kg K_2O ha^{-1} of K rates is adequate for cotton in the NCP. The later split application of K at peak bloom is the best timing of K fertilizer for cotton yield and K use efficiency.

Yield Formation of Five Crop Species Under Water Shortage and Differential Potassium Supply

Schilling, G., H. Eißner, L. Schmidt, and E. Peiter. 2016. J. Plant Nutr. Soil Sci. 179(2):234-243. DOI: 10.1002/jpln.201500407.

Abstract: A long-term field experiment on a Haplic Phaeozem, established 1949 with four levels of potassium (K) supply (5, 69, 133, and 261 kg K ha^{-1}), was analyzed for the interaction between K supply and yield loss of five crop species by water shortage. The crop species were cultivated simultaneously side-by-side

in the following rotation: potato (*Solanum tuberosum* L.), silage maize (*Zea mays* L.), spring wheat (*Triticum aestivum* L.), beet (*Beta vulgaris* L.), and spring barley (*Hordeum vulgare* L.). The treatment with 133 kg K ha^{-1} supply had a nearly balanced K budget. In the treatments with lower supply, the soil delivered K from its mineral constituents. On the low-K plots (especially on those with only 5 kg K ha^{-1}), crops suffered yield depressions of nearly all main harvest products (cereal grains, potato tubers, beet storage roots, silage maize) and by-products (straw, beet leaves) by up to 40.7% of dry matter. Only wheat grains were an exception. Potassium concentrations in the harvested plant parts decreased nearly in parallel to the reduction of their dry matter yields, with the exception of cereal grains, which kept stable concentrations even in the treatment with only 5 kg K ha^{-1}. A comparison of four year-pairs with differing levels of precipitation in yield-relevant periods showed an average water shortage-induced depression of dry matter yields by 19.7% in the main harvest products. The severity of this yield depression was not mitigated by elevated K supply, with the exception of beet leaves, where the dry matter production was stabilized by high K supply. In this crop, the reduction of storage-root yield was associated with a decrease in harvest index and was therefore obviously caused by an inhibition of assimilate translocation from the leaves into these organs, in contrast to cereals, where water shortage primarily affected dry matter production in vegetative organs. It is concluded that the physiological causes of yield reduction by drought stress and the possibility of its amelioration by K supply differ between plant species and organs.

Fruiting Branch K^+ Level Affects Cotton Fiber Elongation Through Osmoregulation

Jiashuo Yang, Wei Hu, Wenqing Zhao, Binglin Chen, Youhua Wang, Zhiguo Zhou, and Yali Meng. 2016. Front. Plant Sci. DOI http://dx.doi.org/10.3389/fpls.2016.00013.

Abstract: Potassium (K) deficiency in cotton plants results in reduced fiber length. As one of the primary osmotica, K^+ contributes to an increase in cell turgor pressure during fiber elongation. Therefore, it is hypothesized that fiber length is affected by K deficiency through an osmotic pathway, so in 2012 and 2013, an experiment was conducted to test this hypothesis by imposing three potassium supply regimes (0, 125, 250 kg K ha^{-1}) on a low-K-sensitive cultivar, *Siza 3*, and a low-K-tolerant cultivar, *Simian 3*. We found that fibers were longer in the later season bolls than in the earlier ones in cotton plants grown under normal growth conditions, but later season bolls showed a greater sensitivity to low-K stress, especially the low-K sensitive genotype. We also found that the maximum velocity of fibre elongation (V_{max}) is the parameter that best reflects the change in fiber elongation under K deficiency. This parameter mostly depends on cell turgor, so the content of the osmotically active solutes was analyzed accordingly. Statistical analysis showed that K^+ was the major osmotic factor affecting fiber length, and malate was likely facilitating K^+ accumulation into fibers, which enabled the low-K-tolerant genotype to cope with low-K stress. Moreover, the low-K-tolerant genotype tended to have greater K^+ absorptive capacities in the upper fruiting branches. Based on our findings, we suggest a fertilization scheme for *Gossypium hirsutum* that adds extra potash fertilizer or distributes it during the development of late season bolls to mitigate K deficiency in the second half of the growth season and to enhance fiber length in late season bolls.

Assessing Potassium Environmental Losses from a Dairy Farming Watershed with the Modified SWAT Model

Chunying Wang, Rui Jiang, Laurie Boithias, Sabine Sauvage, José-Miguel Sánchez-Pérez, Xiaomin Mao, Yuping Han, Atsushi Hayakawa, Kanta Kuramochi, Ryusuke Hatano. 2016. Agricultural Water Management. DOI 10.1016/j.agwat.2016.02.007

Abstracts: Potassium (K) was intensively used to optimize agricultural crop yield. Potassium losses should be accurately quantified for efficient nutrient management. However, no hydrologic model had been developed yet to quantify daily K losses at watershed scale. The Soil and Water Assessment Tool (SWAT) model was modified (named SWAT-K) by including the main K dynamic processes (solid–liquid distribution in soil and stream, plant uptake, and transportation with water flow and soil erosion) to simulate stream K load and K budget at the watershed scale. The SWAT-K was tested on the dairy farming Shibetsu River Watershed (672 km^2), Eastern Hokkaido, Japan. The solid–liquid distribution coefficient for K in suspended sediment was 10 ml g^{-1}. Langmuir equation was fitted to describe the solid–liquid distribution of K in soil, which derived an affinity constant of 0.046 L mg K^{-1} and was used directly in SWAT-K. The fitted Langmuir equation also derived an adsorption maximum for K in soil. The adsorption maximum for K in soil normalized for clay content ranged from 4 to 20 g K kg^{-1}, and the fitted value of 15.5 g K kg^{-1} was used in SWAT-K. The SWAT-K satisfactorily predicted the daily dissolved K load at watershed outlet, and estimated an annual dissolved K load of 27.3 kg K ha^{-1} year^{-1}. The simulated pasture K yield of 36.1 (±2.5) kg K ha^{-1} year^{-1} was close to the observed data of 38.0 (±3.1) kg K ha^{-1} year^{-1}. Then the model was used to quantify K budget at watershed scale. The simulated dissolved K leaching was 15.1 kg K ha^{-1} year^{-1}, and simulated soil K surplus of 75.1 kg K ha^{-1} year^{-1} was much higher than plant uptake of 28.4 kg K ha^{-1} year^{-1}. The large amount of leaching and soil storage indicated that agricultural K input might be excessive and reducing the K application was recommended.

External Potassium (K^+) Application Improves Salinity Tolerance by Promoting Na^+-Exclusion, K^+-Accumulation and Osmotic Adjustment in Contrasting Peanut Cultivars

Koushik Chakraborty, Debarati Bhaduri, Har Narayan Meena, Kuldeepsingh Kalariya. 2016. Plant Physiology and Biochemistry 103:143-153. DOI 10.1016/j.plaphy.2016.02.039.

Abstract: Achieving salt-tolerance is highly desirable in today's agricultural context. Apart from developing salt-tolerant cultivars, possibility lies with management options, which can improve crop yield and have significant impact on crop physiology as well. Thus present study was aimed to evaluate the ameliorative role of potassium (K^+) in salinity tolerance of peanut. A field experiment was conducted using two differentially salt-responsive cultivars and three levels of salinity treatment (control, 2.0 dS m^{-1}, 4.0 dS m^{-1}) along with two levels (with and without) of potassium fertilizer (0 and 30 kg K_2O ha^{-1}). Salinity treatment incurred significant changes in overall physiology in two peanut cultivars, though responses varied between the tolerant and susceptible one. External K^+ application resulted in improved salinity tolerance in terms of plant water status, biomass produced under stress, osmotic adjustment and better ionic balance. Tolerant cv. GG 2 showed better salt tolerance by excluding Na^+ from uptake and lesser accumulation in leaf tissue and relied more on organic osmolyte for osmotic adjustment. On the contrary, susceptible cv. TG 37A allowed more Na^+ to accumulate in the leaf tissue and relied more on inorganic solute for osmotic adjustment under saline condition, hence showed more susceptibility to salinity stress. Application of K^+ resulted in nullifying the negative effect of salinity stress with slightly better response in the susceptible cultivar (TG 37A). The present study identified Na^+-exclusion as a key strategy for salt-tolerance in tolerant cv. GG 2 and also showed the ameliorating role of K^+ in salt-tolerance with varying degree of response amongst tolerant and susceptible cultivars.

Solubilization of Potassium Containing Mineral by Microorganisms From Sugarcane Rhizosphere

Tri Candra Setiawati, Laily Mutmainnah. 2016. Agriculture and Agricultural Science Procedia 9:108-117. DOI 10.1016/j.aaspro.2016.02.134.

Abstract: Potassium solubilizing microorganisms (KSM) isolated from sugarcane rhizosphere and their capability on solubilization from some insoluble potassium were examined. Isolation of potassium solubilizer was carried out from three sugarcane plantations area, on Alexandrov's agar medium. From the 41 isolated microorganisms were selected 15 isolates potassium solubilizing microorganisms which exhibiting highest potassium solubilization (solubility index) on solid medium. All the KSM were found to be capable of solubilizing K from insoluble K-bearing minerals source, and the solubilization zone ranging from 0.15 to 4.5 cm. 13.3% isolate has Solubility Index (SI) more than four on solid medium. Quantitative test result of KSM conducted on liquid medium containing potassium mineral trachyte, feldspar, leucite (Pati and Situbondo), released water soluble-K (exchangeable-K) ranging from 0.13 to 12.25 mg.L^{-1} (Feldspar); 1.24 to 15.57 mg L^{-1} (Leucite pati); 1.01 to 4.,59 mg L^{-1} (Leucite Situbondo); and 0.16 to 6,34 mg L^{-1} (Trachyte). KSM strain Sbr3 caused maximum solubilization on feldspar (12.25 mg L^{-1}), KSM strain Asb3 on leucite Pati (18.17 mg L^{-1}), KSM strain Prj3 on leucite Situbondo (16.14 mg L^{-1}), whereas KSM strain Prj5 caused maximum solubilization on trachyte (6.92 mg L^{-1}). All isolates produced organic acid citric, ferulic and coumaric, some isolates also produced malic and syringic acid. Total organic acid produced by isolated ranging from 130.42 to 434.44 mg.L^{-1}. Ferulic acid was produced by all isolates on all of K sources higher than other organic acid.

Phytoextraction of Soil Phosphorus by Potassium-Fertilized Grass-Clover Swards

Timmermans, B.G.H., and N. van Eekeren. 2016. J. Environmental Quality 45(2):701-708. DOI 10.2134/jeq2015.08.0422.

Abstract: In the development of the Dutch National Ecological Network, many hectares of arable land are converted to nature areas to protect plant and animal species. This encompasses development of species-rich grasslands. On former agricultural land on sandy soils, this development is often hampered by relatively high phosphorus (P) levels, which also cause eutrophication. Standard practices to decrease the amount of P are either topsoil removal or long-term mowing of low-yielding established grassland. Both methods have disadvantages, and there is a need for additional techniques. As an alternative, phytoextraction ("mining") of soil P has been proposed. We tested a new technique of mining without mineral N fertilizer by cropping an intensively mown grass-clover with potassium (K) fertilization that could potentially be used as cattle feed. A long-term field experiment was conducted, comparing soil P removal by grass-clover swards with and without supplementary K fertilization on a sandy soil. During the experiment, which ran from 2002 to 2009, soil P levels and nutrient contents of grass-clover were measured, and P and K balances were calculated. Our results show that grass-clover with K fertilization removed excess soil P (also at lower P levels) at a relatively high rate (34 kg P ha^{-1} yr^{-1}, significantly higher than without K fertilization; $P < 0.05$) and produced reasonable yields of grass-clover. Our P balance suggested reduced leaching from the topsoil during this experiment. For nature restoration in agricultural areas, this tool opens many possibilities.

Modelling of K/Ca Exchange in Agricultural Soils

Schneider, A., and A. Mollier. 2016. Geoderma 271:216-224. DOI 10.1016/j.geoderma.2016.02.016.

Abstract: The exchange selectivity of soil toward K relative to Ca increases in the depletion profile near roots during plant uptake. The modelling of the soil K/Ca exchange is thus necessary for accurate soil–plant transfer modelling. The aims of this work were i) to study the change in the K affinity of 45 agricultural soil samples that came from 15 French K trials in the range of small K saturation ratios of the soil CEC (< 25%); ii) to test two multi-site models for their ability to represent the K/Ca exchange data, i.e., a low and infinitely high K-selective sites model (M2) with two adjusted parameters and a low and high K-selective sites model (M3) with three adjusted parameters; and iii) to propose a model of the exchange parameters. Compared to model M3, model M2 predicted the exchange data well despite its lower number of adjusted parameters. The two parameters of model M2 could be modelled, i.e. the Gapon selectivity coefficient for the low K-selective sites (G_n) and the cation exchange capacity of the infinitely high K-selective sites (S_i). For the Podzol G_n was lower (0.75) than G_n for the other studied soils, which had a higher mineral content, and G_n for these other soils linearly increased with an increase in the clay content of the soils. For all of the soils, S_i linearly increased with the clay content and with the initial exchangeable K content of the soil. Using this description of the two parameters of model M2, more than 97% of the variance of the exchange data could be explained. Thus, when exchange sites' heterogeneity is taken into account, the K/Ca exchange selectivity coefficient can be adequately and simply described. This conclusion can be drawn regardless of the formalism used to model the exchange data, including the Vanselow and the Gaines and Thomas formalisms.

Effects of Potassium Deficiency on Antioxidant Metabolism Related to Leaf Senescence in Cotton (*Gossypium hirsutum* L.)

Hu, W., X. Lv, J. Yang, B. Chen, W. Zhao, Y. Meng, Y. Wang, Z. Zhou, and D.M. Oosterhuis. Available online 4 March 2016. In Press. Field Crops Research. DOI:10.1016/j.fcr.2016.02.025.

Abstract: In order to explore the changes in antioxidant metabolism related to leaf senescence under potassium (K) deficiency, field experiments were conducted in 2012 and 2013 with contrasting two cotton (*Gossypium hirsutum* L.) cultivars in low-K sensitivity (Simian 3, low-K tolerant and Siza 3, low-K sensitive) under three K levels (0, 150 and 300 kg K_2O ha^{-1}). Results showed that K deficiency enhanced the early season flowering rate, earliness, shedding rate and yellow leaf rate, and decreased leaf number, leaf area, boll number, seed cotton weight per boll and lint percentage. The premature senescence of leaf subtending the cotton boll (LSCB) induced by K deficiency was characterized by early chlorophyll degradation and negative chlorophyll fluorescence. Despite higher activity of hydrogen peroxide (H_2O_2) scavenging enzymes (catalase and peroxidase) and higher content of ascorbic acid (ASC) existed in the K-deficient leaf, higher H_2O_2 content was observed, which caused higher malondialdehyde content. Although lower dehydroascorbate reductase activity was observed under K deficiency, high ASC content was attributed to lower ascorbate peroxidase activity. The differences between Siza 3 and Simian 3 in response to K deficiency were that: (1) the seed cotton weight per boll and lint percentage in Siza 3 decreased more obviously, (2) higher leaf K concentration was needed for maintaining chlorophyll content for Siza 3, (3) Chlorophyll fluorescence parameters was more easily damaged in Siza 3, especially non-photochemical quenching, and (4) superoxide dismutase and glutathione reductase activities decreased markedly only in Siza 3.

What Do We Not Know About Mitochondrial Potassium Channels?

Laskowski, M., B. Augustynek, B. Kulawiak, P. Koprowski, P. Bednarczyk, W. Jarmuszkiewicz, and A. Szewczyk. Available online 4 March 2016. In Press. Biochimica et Biophysica Acta (BBA) - Bioenergetics. DOI 10.1016/j.bbabio.2016.03.007.

Abstract: In this review, we summarize our knowledge about mitochondrial potassium channels, with a special focus on unanswered questions in this field. The following potassium channels have been well described in the inner mitochondrial membrane: ATP-regulated potassium channel, Ca^{2+}-activated potassium channel, the voltage-gated Kv1.3 potassium channel, and the two-pore domain TASK-3 potassium channel. The primary functional roles of these channels include regulation of mitochondrial respiration and the alteration of membrane potential. Additionally, they modulate the mitochondrial matrix volume and the synthesis of reactive oxygen species by mitochondria. Mitochondrial potassium channels are believed to contribute to cytoprotection and cell death. In this paper, we discuss fundamental issues concerning mitochondrial potassium channels: their molecular identity, channel pharmacology and functional properties. Attention will be given to the current problems present in our understanding of the nature of mitochondrial potassium channels. This article is part of a Special Issue entitled 'EBEC 2016: 19th European Bioenergetics Conference, Riva del Garda, Italy, July 2–6, 2016', edited by Prof. Paolo Bernardi.

Soybean Yield Components and Seed Potassium Concentration Responses among Nodes to Potassium Fertility

Parvej, Md. R., N.A. Slaton, L.C. Purcell, and T.L. Roberts. 2016. Agron. J. 108(2):854-863. DOI 10.2134/agronj2015.0353.

Abstract: Soybean [*Glycine max* (L.) Merr.] yield loss by K deficiency has been reported extensively, but very little research has evaluated how the yield loss is distributed among nodes. We evaluated soybean seed yield, individual seed weight, pod and seed numbers, seed abortion, and seed-K concentration among nodes of an indeterminate and determinate cultivar grown under three K fertility levels (low, medium, and high represented by 0, 75, and 150 kg K ha^{-1} yr^{-1}, respectively). Chlorosis along upper leaf margin was observed during seed-filling period in every low K fertility plot. Soybean grown with medium and high K fertility averaged 28 and 43%, respectively, greater predicted seed yield on the top seven (of 10) node segments for the indeterminate soybean and 72 and 101% greater seed yield on the node segments 2, 3, 4, and 7 (of seven) for the determinate soybean than plants having low K fertility. Yield loss was attributed to reduced individual seed weight, fewer pod and seed numbers, and increased seed abortion. The seed-K concentration of soybean grown with low K fertility was lowest (11.6 [indeterminate] and 15.2 [determinate] g K kg^{-1}) for seeds located on the top nodes and increased (17.8 g K kg^{-1}) quadratically to the bottom of the plant. The largest proportion of seed yield and the greatest yield loss from K deficiency come from the middle and upper nodes of indeterminate plants and the combination of the bottom nodes, due to branching, plus the upper-middle nodes of determinate plants.

Site-Specific Nutrient Management for Cassava in Southern India

Byju, G., M. Nedunchezhiyan, A.C. Hridya, and Sabitha Soman. 2016. Agron. J. 108(2):830-840. DOI 10.2134/agronj2015.0263.

Abstract: Cassava (*Manihot esculenta* Crantz.) yield in the major growing environments of India has been stagnating despite the development of high yielding varieties and increasing use of chemical fertilizers. On farm experiments were conducted to evaluate the performance of site-specific nutrient management (SSNM). Field and crop specific NPK rates were calculated using quantitative evaluation of fertility of tropical soils (QUEFTS) model. The average 2-yr yield advantage of SSNM over farmer fertilizer practice (FFP) was 7 Mg ha^{-1}. The N agronomic efficiency increase of SSNM over FFP was 32 kg kg^{-1}, the N recovery efficiency of SSNM was 0.14 kg kg^{-1} greater than that of FFP and the N physiological efficiency of SSNM was 54 kg kg^{-1} greater than that of FFP, whereas the partial factor productivity of SSNM was 148 kg less than that of FFP. Use of SSNM led to a reduction of fertilizer costs by an average of US$10 ha^{-1} $crop^{-1}$ and an increase in gross return above fertilizer costs by $254 ha^{-1} $crop^{-1}$ compared with FFP. Zone NPK recommendation maps and customized fertilizer blends were also developed. The results showed the potential of SSNM in significantly increasing yield and nutrient use efficiency of cassava. Future research is needed to validate the customized fertilizer blends and fine tune zone NPK recommendation maps which will help reduce the need for field specific modeling and intensive crop monitoring.

Uneven HAK/KUP/KT Protein Diversity Among Angiosperms: Species Distribution and Perspectives

Nieves-Cordones, M., R. Ródenas, A. Chavanieu, R.M. Rivero, V. Martinez, I. Gaillard, and F. Rubio. 2016. Front. Plant Sci. DOI http://dx.doi.org/10.3389/fpls.2016.00127.

Abstract: HAK/KUP/KT K^+ transporters have been widely associated with K^+ transport across membranes in bacteria, fungi, and plants. Indeed some members of the plant HAK/KUP/KT family contribute to root K^+ uptake, notably at low external concentrations. Besides such role in acquisition, several studies carried out in *Arabidopsis* have shown that other members are also involved in developmental processes. With the publication of new plant genomes, a growing interest on plant species other than *Arabidopsis* has become evident. In order to understand HAK/KUP/KT diversity in these new plant genomes, we discuss the evolutionary trends of 913 HAK/KUP/KT sequences identified in 46 genomes revealing five major groups with an uneven distribution among angiosperms, notably between dicotyledonous and monocotyledonous species. This information evidenced the richness of crop genomes in HAK/KUP/KT transporters and supports their study for unraveling novel physiological roles of such transporters in plants.

The Art of Splitting Nitrogen Applications to Optimise Wheat Yield and Protein Content

Levy, L., and C. Brabant. 2016. Recherche Agronomique Suisse 7(2):80-87.

Abstract: The cereals trade association has set up a harvest payment system based on the protein content of 'TOP' class wheats. Agroscope has implemented tests to study the impact of splitting the application of nitrogen fertiliser on wheat yield and quality. In Swiss soil and weather conditions, a 20-40-80 kg N/ha split - the third input being made at the CD-37 stage (flag-leaf sprouting) - yielded excellent results, both in terms of grain yield and protein content. Producers keen to produce grains with a high protein content may be tempted to choose the varieties highest in protein, and to manage them very intensively, with a significant third input at flowering; however, this strategy carries a very high risk of non-assimilation of the nitrogen by the plant,

and of loss of grain yield. From an economic perspective, the most productive varieties are also the most profitable, even if they belong to lower quality categories. The study also highlighted the fact that in situations of low nitrogen availability, a high-straw variety developing a large number of spikes per m² has the edge. By contrast, the size of the plant militates against grain formation in the more intensive systems.

Influence of Splitting the Application of Nitrogenous Fertilisers on the Baking Quality of Wheat

Brabant, C., and L. Häner. 2016. Recherche Agronomique Suisse 7(2):88-97.

Abstract: Certain types of bread products require a high protein content and well-defined rheological qualities. Although Swiss wheat varieties have a high protein content, said content fluctuates a great deal, and in some years is too low for breadmaking. From 2011 to 2013, a study was carried out on four varieties of wheat and seven nitrogen fertiliser application methods. The aim was on the one hand to analyse the influence of the nitrogen fertiliser (dose and splitting of application) on protein levels, and on the other to examine the relationship between the protein levels of the varieties and their rheological and baking qualities. The splitting of nitrogenous fertiliser applications into three rather than two doses not only significantly increases wet gluten content, but also substantially improves qualitative properties. A 20-40-80 kg N/ha split with a final dose when the flag-leaf appears is ideal for increasing wet gluten content without affecting either rheological quality or yield. This split can be recommended when cultivating 'Top' class varieties. The results also show that an increase in protein content does not necessarily improve gluten quality, since several parameters stagnate or decrease when nitrogen fertilisation is intensified. This observation can be explained by the stagnation in the proportion of glutenins, as well as by a decrease in gliadins in favour of albumins and globulins. No matter what nitrogenous fertilisation method is used, the variety 'Runal' always achieves the best protein levels. Despite its lower protein content, the variety 'CH Claro' obtains equivalent results to Runal in the rheological and baking tests.

Potato Losses in Switzerland from Field to Fork

Willersinn, C., G. Mack, P. Mouron, and M. Siegrist. 2016. Recherche Agronomique Suisse 7(2):104-111.

Abstract: This study ascertains potato losses in Switzerland along the value chain from field to fork on the basis of questionnaires. The results show that 41-46% of all processing potatoes and 53–56% of all table potatoes are not eaten by consumers. These losses do not represent a complete waste, however. Threequarters of table-potato losses and 90% of processing-potato losses are used as animal feed. Another 3-8% of potato losses is used to generate energy in biogas plants. Only about 5% of processing potato losses and 28% of table potato losses in total wind up as waste. In addition to harvest surpluses, quality standards exert a strong influence on quantities lost. Over 50% of all losses are due to quality defects in the potatoes. Around one-third of all potatoes with quality defects are rejected owing to their potential harmfulness to human health, whilst two-thirds of these potatoes are rejected because they fail to meet the freshness and quality criteria of trading partners and consumers.

Fertiliser Response of Cassava Cultivars as Measured by Leaf Colour, Chlorophyll Content, Nitrate Reductase Activity and Tuberous Root Yield

Hridya, A.C., and G. Byju. 2015. Indian J. Fert. 11(11):57-63.

Abstract: Response of cassava (*Manihot exculenta* Crantz) cultivars to applied NPK was studied on the Ultisols of the Central Tuber Crops Research Institute, Sreekariyam, Thiruvananthapuram. Parameters evaluated included LCC scores, SPAD values, chlorophyll contents (Chl *a*, Chl *b* and Chl *a*+*b*), nitrate reductase activity and tuberous root yield. The experiment was laid out in a split-plot design with three NPK rates (control - 0 NPK, 100% NPK and 150% NPK) in the main plots and four cultivars of cassava, namely H-165, H-226, Sree Jaya and M-4 in subplots in the sub-plots. Each treatment was replicated thrice. Site-specific nutrient management approach using the modified Quantitative Evaluation in Fertility of Tropical Soils (QUEFTS) model was used for computing the 100% NPK and 150% NPK rates. These have subsequently been referred to as the 100% SSNM-NPK and 150% SSNM-NPK, respectively. The study revealed on par results between 100% SSNM-NPN and 150% SSNM-NPN treatments on LCC scores, SPAD values, chlorophyll contents, nitrate reductase activity and tuberous root yield. The cassava cultivars significantly varied among themselves in influencing the leaf colour, chlorophyll content and tuberous root yields. The cultivars H-165 (25.52 t ha^{-1}) and H-226 (25.19 t ha^{-1}) produced significantly high tuberous root yield compared to Sree Jaya (20.86 t ha^{-1}) and M-4 (18.12 t ha^{-1}).

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