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Editorial

Dear readers,

In 2019 we celebrate the 350th anniversary of the discovery of phosphorus (P) by the alchemist Hennig Brand. Phosphorus, along with nitrogen (N) and potassium (K) is one of the three plant macronutrients that are essential for plant life. It is key for both plant and human health.

Phosphorus was the first element to be chemically discovered when it was isolated by Brand in 1669 in Hamburg, Germany, while looking for the fabled philosophers stone to create gold. With its ability to glow in the dark and create a never-before-seen lightshow it quickly became a sensation in European courts and fairs.

By 1840 the pioneering plant scientist Justus von Liebig had confirmed that phosphorus played a crucial role in plant growth, resulting in huge demand for it as a fertilizer from the second half of the 19th century. Today, more than 46 million metric tonnes of P_2O_5 nutrient are consumed around the world each year. With almost three quarters of the world's soils deficient in phosphorus, using mineral fertilizers that contain phosphorus is vital for ensuring optimal crop health and yields.

Phosphorus is noted for its role in capturing and converting the sun's energy, but plants also need it for everything from cell growth and root development to increased disease resistance and early crop maturity. Phosphorus deficiencies can severely affect yields as well as fruit and seed development.

Why, as a potash institute, are we talking about the importance of phosphorus as a plant nutrient? Because P is one of the "big 3" pillars, and K fertilization without proper supply of P (and N) is useless. For a healthy crop and abundant yield, it is essential to ensure a healthy balance of all three macronutrients. Besides their individual effects on yield, P and K together can produce an extra positive yield interaction.

In this edition of the *e-ifc*, we present results from Brazil on the response of sugarcane to potassium fertilization. The paper from Turkey shows that application of polyhalite significantly enhanced cotton quality. The third paper comes from India and presents the results from 120 wheat and rice plots to potassium application in Vertisols.

I wish you an enjoyable read.

Dr. Patricia Imas
IPI Scientific and Communications Coordinator

Photo cover page: Photo by IPI.

Research Findings

Single sugarcane stalk from Ivinhema, Mato Grosso do Sul, Brazil. Photo by the authors.

Management Practices of Potassium Fertilization to Improve Sugarcane Yields in Central-South Brazil

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Abstract

Sugarcane (*Saccharum* spp.) demands high amounts of potassium (K) for profitable yields, but high K application rates could challenge agronomic K efficiency due to leaching and salinity damage to young roots. This study hypothesized that a split dose rather than just a basal K application could represent a better strategy, especially in soils with low cation exchange capacity (CEC). The objective was to evaluate sugarcane performance as a function of ascending K application rates, and the crop's response to split K application on soils varying in CEC and texture in Central-South Brazil.

Field trials were set up in three locations during 2016 to 2018: Chavantes, São Paulo (site 1, clay texture); Valetim Gentil, São Paulo (site 2, sandy-loam texture); and Ivinhema, Mato Grosso do Sul (site 3, sandy-loam texture). At each site, crop response was tested with potassium oxide (K_2O) rates ranging from 0-240 kg K_2O ha^{-1}. Additional treatments compared seven combinations of an intermediate K dose (120 kg K_2O ha^{-1}) split into basal (B) and

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a later top-dressing (TD) application 60-90 days after planting (0/120; 20/100; 40/80; 60/60; 80/40; 100/20; and 120/0, B/TD kg K_2O ha^{-1}, respectively). Tiller density, stalk yield and recoverable theoretical sugar content (RTSC) were determined in the plant-cane and first ratoon cycles. Sugarcane stalk yields ranged from 93-125 Mg ha^{-1}, and from 80-130 Mg ha^{-1}, across all sites for plant-cane and ratoon cycles, respectively.

Significant differences in sugarcane yields occurred between the three sites, and between crop cycles. Generally, crop response to K application dose was very weak, and significant only on the clay soil of site 1, indicating a more significant reliance on soil K reserves rather than on current K application. Split K dose affected sugarcane performance only at site 3 on sandy-loam soil, where yields significantly peaked under a B/TD combination of 40/80 kg K_2O ha^{-1} and tended to decline towards the two extreme combinations (0/120, and 120/0). However, no response to splitting could be observed at the two other sites.

The results of the present study highlight the need for precise determination of soil fertility in terms of texture, composition of the clay minerals, CEC, and total and available soil K status. Consequently, the design of K application management should be founded on crop requirements for target yields, and on the current need to maintain or replenish soil K status. Split K application appears a reasonable strategy on sandy soils; however, further research is required to determine the appropriate intensity of splitting during the crop cycle, taking into consideration the economic implications.

Keywords: Clay; leaching; *Saccharum* spp.; sandy-loam; split K application.

Introduction

Brazil is the world's largest sugarcane producer with an annual production of 633 million tonnes. In 2018, the total harvested area was 8.73 million hectares with a mean yield of 72.5 Mg ha^{-1} (CONAB, 2018). Recent expansion of sugarcane production in Brazil has led to a shift towards cultivation on sandy soils with low cation exchange capacity (CEC). Sugarcane potassium (K) requirements are very high and most of the K consumed in Brazil is imported. The consumption of nitrogen (N), phosphorus (P)

Fig. 1. Symptoms of K deficiency in a sugarcane field managed with low K rates on a high caption exchange capacity (CEC) soil from Belize, Central America. Photos by the authors.

and K fertilizers in Brazil totaled 15 million tonnes, with K fertilizers solely accounting for 5.7 million tonnes (IPNI, 2017).

Sugarcane crop demands for K are huge compared to other crop species such as maize (Kingston, 2014). Potassium plays a key role in osmoregulation, which is important for cell extension, stomata movement and enzyme activation (Epstein, 1972; Shukla *et al.*, 2009; Kingston, 2014). The K is particularly required for carbohydrate metabolism and translocation (Zörb *et al.*, 2014). Leite *et al.* (2016) recently estimated that 2.7 kg K is required to produce 1 Mg of stalk. Thus, about 325 kg ha^{-1} of K_2O can be required to produce 100 Mg ha^{-1} by highly demanding sugarcane varieties (FAOSTAT, 2017). This level of K requirement is in agreement with previous studies (Franco *et al.*, 2008; Kingston, 2014; de Oliveira *et al.*, 2016; da Silva *et al.*, 2018). In addition, K requirements change dramatically according to the crop development stage, peaking significantly during the period of sugar accumulation in the stalk (Kingston, 2014; Leite *et al.*, 2016).

The efficiency of K fertilization depends on K availability in the soil solution, on the soil capacity to retain K, and on the presence of K-containing crop residues (Ernani *et al.*, 2007). Total K uptake by sugarcane stalks ranges from 2.0 to 3.0 kg K_2O Mg^{-1}, while K accumulation in the stalks averages at 1.85 kg K_2O Mg^{-1} (Oliveira, 2011). Symptoms of K deficiency include chlorosis, which occurs first at the end of the young expanded leaves and gradually moves to the internal parts of the leaves. Symptoms of K deficiency are usually related to imbalances, such as inadequate K application on soils with low K level. In this situation, K deficiency can be observed on high CEC soils with a history of imbalanced K application (Fig. 1), as well as in sandy, low CEC soils, that have not received K application at planting (Fig. 2).

Sugarcane response to K application rates is usually positive, however, it varies depending on the amount of exchangeable K in the soil. Rosseto *et al.* (2004) verified a linear sugarcane response to K fertilization in seven of ten experiments. Reis Junior (2001), who observed a positive sugarcane yield response to K fertilization in 73 of 106 studies carried out on varying soil types with different K levels, suggested that interactions between K, calcium (Ca) and magnesium (Mg) might interfere with sugarcane response to K fertilization and should therefore be considered in K fertilization recommendations.

Due to operational and cost issues, sugarcane growers usually perform just a single application of K fertilizers during sugarcane crop establishment. In soils with low CEC, such as sandy soils, this application method presents a high potential for rapid K loss through leaching. In addition, there is a considerable risk of high-salinity damage to seedlings due to heavy K application at planting (Ernani *et al.*, 2007). For this reason, at sugarcane establishment, where high K rates are usually applied, it is recommended to split K dose into two applications; basal (B) at planting, and a later one as a top-dress (TD) (Alvarez and Freire, 1962; Spironello *et al.*, 1997). This practice has become more common in Central-South Brazil, where the TD fertilization usually accompanies a soil leveling operation performed to improve the operation of mechanical harvesting (Fig. 3).

Several previous studies have demonstrated significant yield gains of 10-15 Mg ha^{-1} when K fertilization is split, compared to a single application at planting (Casagrande *et al.*, 1983; Lana *et al.*, 2004). Nevertheless, less encouraging results have shown no significant yield gain from split K application, although maximum yields were obtained with lower K_2O rates when compared to a single application (Otto *et al.*, 2010).

Fig. 2. Symptoms of severe K deficiency in a sugarcane field managed with no K application at planting on a sandy soil in Lins, São Paulo, Brazil. Photos by the authors.

Fig. 3. Conventional practices for K fertilization in Brazilian sugarcane fields. Left: K application at planting at the bottom of the furrow. *Source:* Authors, 2019. Right: TD K application during soil leveling. *Source:* Canaonline, 2019.

Yield gains obtained from split application could be the result of lower leaching losses, reduction of root injury caused by salinity, or a better synchrony between the timing of K application and crop requirements. Despite this argument in support of split K application, most sugarcane growers in Brazil still perform a single K application at planting. However, the present trend of increasing K rates in order to compensate for the substantial K removal from soils – during sugarcane cropping – can intensify the negative economic and environmental consequences of heavy K fertilization.

The present study hypothesized that split K application is a better strategy than a single application at planting, especially in sandy soils with low CEC. The objective was to evaluate sugarcane yield and recoverable theoretical sugar content (RTSC) as related to K rates and split K application, in soils varying in CEC and texture, under Brazilian field conditions.

Material and methods

Experimental design

Three field trials were set up under field conditions during the 2016 to 2018 crop season: site 1 in Chavantes, São Paulo (23º3'54.56 ''S; 49º45'9.49''W); site 2 in Valetim Gentil, São Paulo (20°27'46,79"S; 50°06'15,60"W); and site 3 in Ivinhema, Mato Grosso do Sul (22°17'09.19''S; 53°40'30.50"W), Brazil (Fig. 4). These areas present a climate classification Cfa (site 1) and Aw (sites 2 and 3), according to the Köppen classification. The average temperature during the period of study was 21.2, 22.5 and 23.0 ºC with an average rainfall of 1,339, 1,194 and 1,534 mm in sites 1, 2, and 3, respectively.

Prior to establishment of the experiments, soil samples were randomly collected from six locations at each site at depths ranging from 0-100 cm, at 25 cm intervals. Soil samples were homogenized and submitted for chemical and physical analyses according to van Raij *et al.* (2001) and Camargo *et al.* (2009) (Table 1). Soil texture was classified as clay (site 1) and sandy clay loam (sites 2 and 3), with soil K levels ranging from 1.3-2.0 $mmol_c\ dm^{-3}$

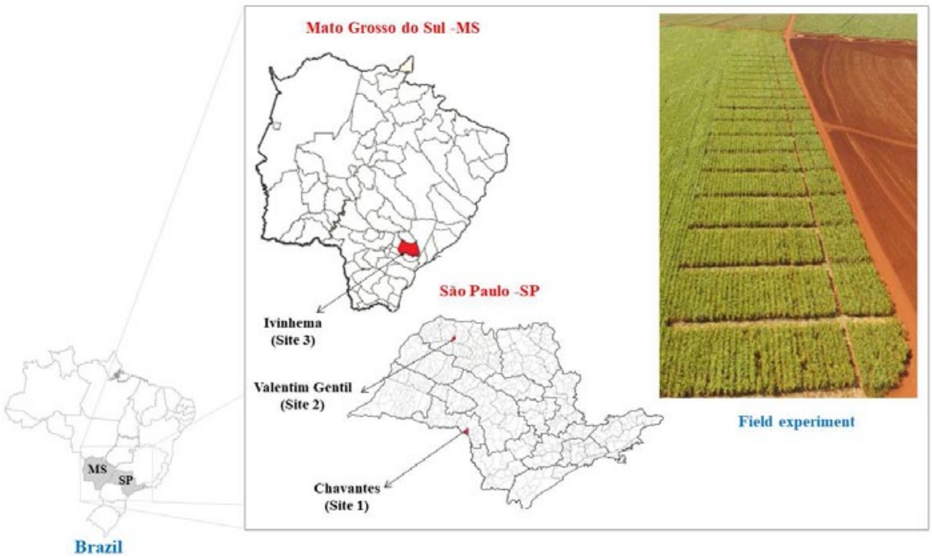

Fig. 4. Location of the field trials in Chavantes, São Paulo (Site 1), Valetim Gentil, São Paulo (Site 2) and Ivinhema, Mato Grosso do Sul (Site 3), in Brazil.

Table 1. Soil chemical and physical analysis of the experiment areas in Brazil[1].

Soil depth	pH ($CaCl_2$)	OM	P	S	K	Ca	Mg	Al	H+Al	CEC	SB	V	m	Sand	Silt	Clay
cm		*g dm*$^{-3}$	----*mg dm*$^{-3}$-----		-------------------*mmol*$_c$ *dm*$^{-3}$-------------------					*cmol*$_c$ *kg*$^{-1}$	-----------%-----------			------------*g kg*$^{-1}$-----------		
							Site 1									
0-25	5.0	23.0	8.0	9.0	2.0	34	8.0	0.0	38	82.0	44.0	54	2	118	173	709
25-50	4.7	26.0	6.0	14.0	1.5	26	9.0	2.0	42	78.5	36.5	46	5	113	172	715
							Site 2									
0-25	4.6	13.0	8.0	3.0	1.8	10	3.0	1.0	28	42.8	14.8	35	5	750	50	200
25-50	4.5	12.0	6.0	5.0	0.9	6	2.0	1.0	33	38.7	9.5	25	7	726	45	229
							Site 3									
0-25	4.8	14.0	5.0	7.0	1.3	10	7.0	1.0	34	52.3	18.3	35	0	724	23	253
25-50	4.5	12.0	0.3	5.0	0.6	5	4.0	2.0	42	51.6	9.6	19	17	676	21	303

[1]pH in $CaCl_2$ (0.01 mol L^{-1}); OM, soil organic matter by Walkley-Black; P, K, Ca, Mg by the exchangeable resin method; sulfur (S) by calcium phosphate extraction; CEC, cation exchange capacity; SB, sum of bases; V, base saturation; m, aluminum saturation.

at the upper soil level (0-25 cm). Soil K contents were classified as low to medium (0.7-3.0 mmol$_c$ dm^{-3}), according to van Raij *et al.* (1997).

The experiments were laid out in a randomized block design with five K rates (0, 60, 120, 180 and 240 kg K_2O ha^{-1}) applied through potassium chloride (KCl) directly into the furrow at planting (B) in four replications. Other treatments were carried out to evaluate six different combinations of B and TD K applied at a constant rate of 120 kg K_2O ha^{-1}: 0+120; 20+100; 40+80; 60+60; 80+40; and 100+20 kg K_2O ha^{-1}, respectively. TD was performed between 60 and 90 days after planting, following usual practices adopted by sugarcane growers. There was a total of 11 treatments comprising 44 experiment units; each experiment unit consisted of six sugarcane furrows, spaced 1.5 m apart and 15 m long.

Sugarcane (CTC4 variety) was planted using conventional soil tillage operations (disking or chiseling) in 2016. Lime was applied and incorporated (0.25 m deep) to increase the base saturation to 70% in all sites. After lime incorporation, furrows were opened, and applied with 150 kg phosphorus pentoxide (P_2O_5) ha^{-1} as mono-ammonium phosphate (11% N and 52% P_2O_5). Sugarcane was cultivated following usual agronomic practices of the sugarcane mills, including weed and disease control methods. In all sites, N and K were applied after the first harvest at a ratio of 1:1 kg Mg^{-1} biomass produced, and the residual effects were evaluated after the first ratoon.

Measurements and analysis

Evaluation of tiller density was performed 120 days after planting (DAP), by counting the number of tillers in the four central lines of each plot. Sugarcane yield (Mg ha^{-1} of stalk) was determined by mechanical harvesting of the four central rows of each plot, and after weighing the stalks in a truck equipped with a scale. Ten plants were collected per plot and the RTSC was analyzed according to Fernandes (2011).

Data were submitted for analysis of variance based on the F-test ($p<0.05$). When the F test showed significance, the effect of K rates was compared by regression analysis ($p<0.1$), while the effect of split application was compared using the LSD test ($p<0.1$).

Results and discussion

Effect of K rates

Significant differences in sugarcane performance occurred between the three experiment sites (Table 2). Tiller density and stalk yield of the plant cane cycle differed significantly in the order of site 1 (Chavantes) > site 2 (Valentim) > site 3 (Ivinhema). However, this order changed dramatically at the first ratoon harvest, where Ivinhema became the leading site. There was a significant positive relationship between tiller density and stalk yield ($p<0.005$), demonstrating that tiller density is a major factor in determining sugarcane yield. Nevertheless, these two parameters failed to predict the RTSC and the consequent sugar yield. Sugarcane ripening and sugar production are very sensitive to weather conditions and were possibly promoted by the drier conditions at Valentim compared to the other two sites. Potassium rates did not affect tiller density and RTSC at all sites and seasons, and a mean value of 15.8 tillers m^{-1} and 150.9 kg

Table 2. Sugarcane performance at the three experiment sites (site 1: Chavantes; site 2: Valetim Gentil; and site 3: Ivinhema) during the plant cane and first ratoon production cycles. Values show the average yield parameters for all K doses. Similar letters indicate no significant differences ($p<0.01$) between sites within a cycle.

	Plant cane			Ratoon		
	Site 1	Site 2	Site 3	Site 1	Site 2	Site 3
Tiller density (tillers m^{-1})	16.0a	14.1b	11.7c	15.8c	18.1b	19.6a
Stalk yield (Mg ha^{-1})	118.4a	104.5b	101.1c	107.5b	85.3c	120.5a
RTSC (kg sugar Mg^{-1} stalks)	131.7c	163.1a	143.9b	164.6	-	162.4
Sugar yield (Mg ha^{-1})	15.6	17.05	14.55	17.71	-	19.57

Mg^{-1} was achieved, respectively. The lack of tiller density response to K rate may indicate that the high-salinity effect anticipated from B KCl applications was not severe enough to reduce tiller density and sugarcane yield, at least in the sites evaluated herein. Alleoni and Beaclair (1995) also found no relationship between K rates and tillering in their study. In contrast, Otto *et al.* (2010) reported that tiller density was reduced where B applied K rates exceeded 130 kg K_2O ha^{-1}.

Rising K application doses from 0 to 240 kg K_2O ha^{-1} resulted in significant increases in stalk yield on the clay soil of Chavantes (site 1), which was accompanied by a significant rise in sugar yields (calculated). On the two other sites, stalk and sugar yields fluctuated randomly with no observable influence of K rates (Fig. 5). Nevertheless, even where a significant yield increase was identified, the contribution of K fertilizer was very low – less than 50 kg stalks, and 6-10 kg sugar per one kg K_2O applied. It is worth noting that the yield values obtained can be considered within the top range of worldwide sugarcane yields (FAOSTAT, 2017). It appears, therefore, that at all three sites, sugarcane performance was a function of the soil fertility during each cycle rather than the current K application dose. A consequent question would therefore regard the fate of the applied K.

All chemical interactions between plant and soil occur in the liquid soil phase, which maintains durable ion exchange with the soil particle surface. The greater the particle's specific surface area (SSA) the larger capacity it harbors for ion exchange. Therefore, soil texture, namely the ratio between clay, silt and sand, is a key determinant of soil fertility. Sand particles are considered inert due to their extremely low SSA, and hence, poor CEC. In contrast, clay minerals comprise the tiniest soil particles that consequently possess immense SSA with correspondingly high CEC. Therefore, clay minerals, and to a much lesser extent silt, are considered the most chemically active soil fractions.

When a soluble K fertilizer is applied and the soil wetted, the liquid soil phase is enriched with K^+ ions. The greater the sand soil fraction, the higher the risk of K leaching and loss, which was probably the case at Valetim Gentil and Ivinhema

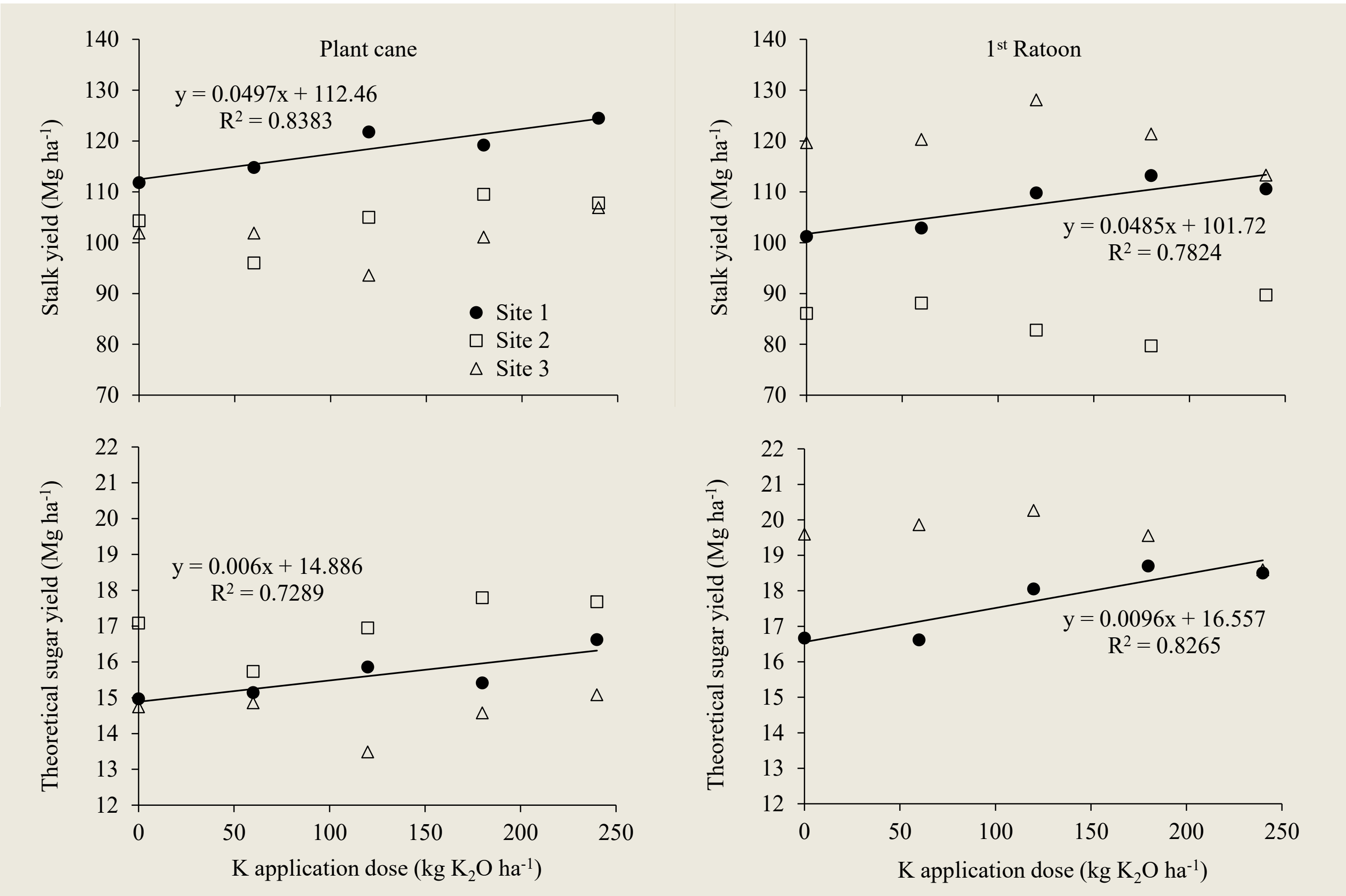

Fig. 5. Effects of K application dose on the stalk (upper figures) and on the theoretical sugar (lower figures) yields in two successive seasons (plant cane and first ratoon of sugarcane crops at three experiment sites in Brazil (site 1: Chavantes; site 2: Valetim Gentil; and site 3: Ivinhema). Significant correlation curves could be obtained for site 1 only.

experiment sites. However, the clay and silt fractions at these sites still seemed to bear considerable capacity to support an acceptable sugarcane performance, including the significant residual effect demonstrated at the first ratoon.

In addition to the vast on-surface chemical activity, clay particles retain significant long-term ion exchange capacity between external and internal mineral layers. This aspect of soil fertility largely depends on the mineral composition, spatial structure, and the history of the clay fraction of a given soil and its location (Zörb *et al.*, 2014). Generally, where a positive K balance has been maintained in the long-term, it may be assumed that the clay fraction is K-saturated, harboring significant K-residual potency. However, similar soil types that have experienced long periods of a negative K balance often display a considerable tendency to adhere K^+ ions in internal mineral layers, and hence reduce K availability to plant roots. This was more likely the situation at Chavantes (site 1), which may explain the unsatisfactory sugarcane response to the rising K application dose (Fig. 5).

Split K application

Splitting the K application dose may offer solutions for K losses through leaching on sandy soils or fixation on K-poor clay soils. Nevertheless, the splitting treatments, as carried out in the present study, failed to enhance sugarcane performance. The average yield parameters obtained from the splitting treatment (Table 3) did not differ from those of the B applied K experiment (Table 2), with similar significant differences between the three locations. Ivinhema (site 3) was the sole location at which a significant and consistent effect was observed as a result of the split combinations on sugarcane performance (Fig. 6).

At the Ivinhema site, the extreme treatment of applying the complete seasonal K dose through the B or TD application, gave rise to the lowest stalk yields. In contrast, the combination of 40 and 80 kg K_2O ha^{-1} as the B and TD application, respectively, resulted in the highest stalk yield (Fig. 6). Furthermore, there was a clear yield increase with the rise of the TD rate from 0-80 kg K_2O ha^{-1}; yet, the stalk yields started to decline once the B rate dropped below 40 kg K_2O ha^{-1} (Fig. 6). These results weakly support the split K application principle, however, the maximum yield increase did not exceed 10-15% – much less than expected and needed economically – and more importantly, the results were insufficiently consistent. Previous studies have shown that splitting the K dose into two applications on sandy soils could raise sugarcane stalk yields by 10-15 Mg ha^{-1} (Casagrande *et al.*, 1983; Lana *et al.*, 2004), but will fail to contribute on clay soils (Casagrande *et al.*, 1983).

Overall, based on the results shown here, it would be too difficult to recommend any specific K dose or practice to conclusively enhance sugarcane yields. A more careful analysis of the present study's circumstances may suggest directions for further evaluation of the split dose approach.

On sandy soils under humid tropical conditions, plant roots have an extremely narrow window of time to take up soil K – from the time of application to the impending rains – before it is leached away from the rhizosphere. Leaching could occur for any application of soluble fertilizer, the rate of which exceeds the uptake capacity during a given opportunity. Therefore, splitting the seasonal K dose into two applications is

Table 3. Sugarcane performance under split K application at the three experiment sites (site 1: Chavantes; site 2: Valetim Gentil; and site 3: Ivinhema) during the plant cane cycle. The average yield parameter values are provided for all split combinations within each site. Similar letters indicate no significant differences (p<0.01) between sites.

	Plant cane			
	Site 1	Site 2	Site 3	Mean
Tiller density (tillers m^{-1})	16.4a	14.2b	11.9c	13.4
Stalk yield (Mg ha^{-1})	120.1a	100.7b	100.2c	100.7
RTSC (kg sugar Mg^{-1} stalks)	131.0c	165.4a	144.1b	146.9
Sugar yield (Mg ha^{-1})	15.73	16.66	14.44	15.72

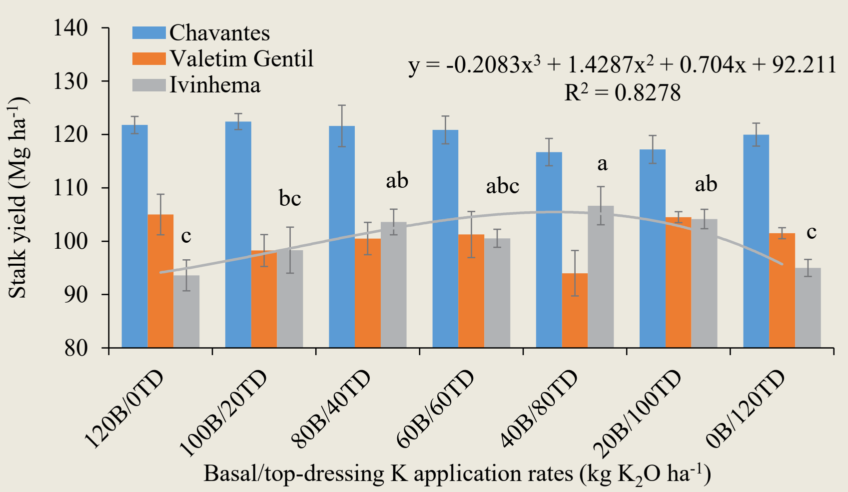

Fig. 6. Effect of seven combinations of split K application (totaling 120 kg K_2O ha^{-1} per treatment) at B and a single TD application, 60-90 days after planting on sugarcane stalk yields at three experiment sites in Brazil (site 1: Chavantes; site 2: Valetim Gentil; and site 3: Ivinhema). Bars indicate ± standard error. Similar letters indicate no significant differences (p<0.05) between combinations within Ivinhema site.

probably just a very small step forward, as indicated by the results of the present study. On the other hand, splitting the seasonal dose into many applications might significantly expand the number of opportunities for nutrient uptake during a crop cycle, boost K use efficiency, and lead to enhanced sugarcane performance. This approach is technically feasible in various ways, from hand application to fertigation, and the economic balance of each should be carefully considered.

An alternative approach may be the introduction of polyhalite, which beyond a relatively slower K release, is comprised of nutrients other than just K (Mg, Ca, and S), with the potential to deliver substantial benefits to poor acidic soils in Central-South Brazil (Vale and Sério, 2017; Bernardi *et al.*, 2018). Any alternative solution selected must include serious attempts to reduce soil acidity, as the soil pH values at the experiment sites were too low (Table 1). Low pH significantly confines K^+ access to soil particle surface, thus reducing short- and long-term interactions between the nutrient and the soil, and subsequently leading to declined soil fertility.

Conclusions

Generally, sugarcane performance and yields at all three experiment sites of the present study were reasonably high (100-120 Mg stalks ha^{-1}), above the recent yearly average in Brazil (75 Mg stalks ha^{-1}), and within the top range of worldwide yields. However, crop performance hardly responded to the K application dose, suggesting a reliance on residual soil resources rather than on current K supply. Moreover, crop response to split K dose into two applications (basal and a later top-dressing) was statistically significant only in one of the three locations.

On clay soils, careful pre-planting attention must be paid to the composition of the clay minerals and to the determination of both total and available K. Determining these parameters is necessary to calculate current soil K resources – both residual and exchangeable. Consequently, the seasonal K dose should be defined according to crop requirements upon a predetermined target yield, plus the K amount required to maintain or recuperate soil K reserves. Nutrient leaching is less critical on clay soils, and hence split application would be useful only where salinity problems might occur.

Sandy loam soils are more complex; the very low CEC, in addition to the rapid drainage imposed by the dominant sand fraction significantly curtail the opportunity of roots to take up nutrients. Still, the smaller clay fraction may harbor considerable nutrient stores. On sandy loam soils, splitting the K dose has great potential not only in expanding nutrient uptake opportunities during the crop cycle, but also in replenishing soil K reserves in the long-term. Nevertheless, further investigation is required to verify the intensity of splitting for maximum impact.

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Research Findings

Photo 1. Experiment site. Photo by the authors.

Effect of Different Potassium Fertilizers on Cotton Yield and Quality in Turkey

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Abstract

Cotton (*Gossypium hirsutum* L.) is an important cash crop in Turkey, which supports a long tradition of textile industry and trade. Aiming at enhancing cotton production and quality, the Turkish authorities are promoting a transition from traditional to modern agriculture practices, including the revision of advice regarding mineral nutrition. Beyond the common basal nitrogen (N) and phosphorus (P) application, potassium (K), which is usually ignored by Turkish farmers, is required to enhance yield and quality. There is also increasing awareness of sulfur's (S) significance as an essential macronutrient for cotton crop growth. Muriate of potash (KCl) and sulfate of potash (K_2SO_4) are very common fertilizers. Both are donors of soluble K, and the latter also supplies S. Polyhalite is a natural mineral, which occurs in sedimentary marine evaporates, and consists of a hydrated sulfate of K, calcium (Ca) and magnesium (Mg) with the composition of 14% potassium oxide (K_2O), 48% sulfur trioxide (SO_3), 6% magnesium oxide (MgO), and 17% calcium oxide (CaO).

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The objective of this study was to compare the effects of three different K sources – K_2SO_4, polyhalite, and KCl – on cotton yield, quality, and nutrient content and uptake. Standard N and phosphorus pentoxide (P_2O_5) rates of 250 and 184 kg ha^{-1}, respectively, were employed throughout all four treatments. The control treatment was applied with N and P only, while the other four treatments received an equal dose of 210 kg K_2O ha^{-1} in the forms of K_2SO_4, polyhalite, or KCl. Unequivocally, the results of the present study demonstrate the pivotal role of K in cotton production, highlighting the need to enhance its application practices. Results indicate KCl as the preferable K donor to obtain high cotton yields, with 6.3 Mg ha^{-1}, compared to 2.7, 5.6, and 4.8 Mg ha^{-1} for the control, K_2SO_4, and polyhalite, respectively. However, some of the quality properties, such as fiber fineness, length, and elongation performed better under polyhalite and K_2SO_4 fertilizers. The direct and indirect influences of nutrients such as S and Ca on lint development and quality remains to be revealed. Nevertheless, compromising between yield and quality, S containing fertilizers must be considered. While polyhalite appears too slow to stand alone as K donor, this fertilizer shows significant potential, on less calcareous soils, as a slow-release donor of S, Ca, Mg, and K. Basal polyhalite application, in combination with other NPK fertilizers and included in practices suited to meet crop requirements during the season, can provide the Turkish cotton industry with a significant step towards enhancing yields and quality.

Keywords: Gossypium hirsutum L.; MOP; SOP; polyhalite; potassium.

Introduction

Cotton (*Gossypium hirsutum* L.), also known as upland cotton, is a major row crop grown primarily for fiber and oil seed. Worldwide cotton lint production in 2018 was about 26 million tonnes (USDA, 2019). India and China are the leading world producers, with about 6 million tonnes each, followed by the USA, Brazil, Pakistan, and Australia with 4.55, 1.9, 1.8, and 1.05 million tonnes, respectively (Statista, 2018).

Turkey is the world's seventh largest cotton lint producer, with 870,000 tonnes in 2017/2018, produced from 540,000 ha. However, to maintain its significant textile industry, Turkey requires a continuous flow of cotton into the country and accordingly, imported about 650,000 tonnes cotton lint in 2017/2018. The Turkish government's current policy is to substitute expensive cotton imports with a consistent increase in local production (Karadas *et al.*, 2017). Achieving this goal requires an expansion of the cotton producing areas, which is promoted by the Turkish government through 'Fiber vs. Food Approach' to boost farmer incentives to grow cotton as a cash crop instead of staple food crops (e.g., corn) (Demirdöğen *et al.*, 2016). An alternative and more promising approach would be increasing lint yields in the country. Although Turkey is already ranked third in the world's average lint yields with 1,655 kg ha^{-1}, (Indexmundi, 2019), this value comes from wide-ranging agricultural methods – from rain-fed low-input to intensive modern high-input cropping systems. While the world's average lint yield stands at about 800 kg ha^{-1}, the estimated potential yield is 5,000 kg ha^{-1}, given the most favorable environmental conditions and cultural practices, and before genetic manipulations (Constable and Bange, 2015). Improving the standard cultural practices while optimizing the inputs may therefore be key to enhancing the Turkish cotton yields and production.

Classification is essential to the cotton pricing system and is required for high-level quality control in textile production. The major lint quality parameters include: 1) fiber fineness and maturity, measured by Micronaire (MIC); 2) fiber length (mm); 3) length uniformity index (LUI, %); 4) fiber strength (g Tex^{-1}); and, 5) fiber elongation, as the percentage of its initial length (Zhao *et al.*, 2013). All these parameters are directly influenced by environmental conditions and practices, including crop nutritional status.

The cotton plant is a perennial shrub with an indeterminate growth habit; however, its commercial cultivation is mostly annual. The growth and development of the cotton plant proceeds through a number of stages, which may practically be divided into four main stages (Oosterhuis, 2001): 1) germination, emergence and seedling establishment; 2) leaf area-canopy development; 3) flowering and boll development; and, 4) boll maturation. Nevertheless, as the vegetative growth continues, the indeterminate growth mode of the cotton shoots generates a consecutive leaf and flower formation on young shoots side-by-side with boll development and maturation on the older ones. Beyond the competition between vegetative growth, flower formation, and boll maturation on the plant resources, the upper floor of new foliage produces shade, which quite often limits the current carbon exchange rates at the older, sub-floors. This complex development habit might lead to significant yield losses, either through the shedding of flowers and bolls at diverse developmental stages or by interrupting boll maturation, leading to reduced lint quality. Associated with this complex growth habit is an extreme sensitivity to adverse environmental conditions, which is reflected in excess fruit abscission and poor lint quality (Oosterhuis, 2001).

Since cotton plants continue to grow vegetatively after fruiting is initiated, the vegetative to fruiting balance of the plant is critical. Excess vegetative growth from abundant fertility and water can delay maturity and increase problems with insects and boll rot. Excess fruiting, on the other hand, may cause seed abortion with associated early fruit shed and lessen yield potential (Oosterhuis, 2001). Beyond strict irrigation management, optimized mineral nutrition is a powerful tool to control the vegetative-reproductive balance. Nitrogen (N), which is the element needed in the greatest amount and is often limiting, is involved in numerous fundamental processes such as protein synthesis, photosynthesis, dry matter partitioning, as well as enzyme and hormonal activity (Marschner, 2012). Nitrogen deficiency results in short, stunted plants, with pale green leaves (Geng *et al.*, 2015). Excess N, on the other hand, promotes surplus vegetative growth, which might interfere with the optimum balance of boll production. Total seasonal N requirement ranges from 50-300 kg N ha^{-1}, depending on the growing season and the achievable yield potential. N drawn to the lint and seed accounts for 43-60% of total plant N. The developing fruit becomes the dominant sink for N in the plant and redistribution within the plant occurs. Peak daily N uptake in irrigated cotton crop ranges from 1.5-4.6 kg ha^{-1} day^{-1}, dependent on crop conditions and actual yield (Oosterhuis, 2001). Increasing N use efficiency is among the major challenges facing the cotton industry (Ali, 2015).

Potassium (K) is integrally involved in the plant's metabolism and in plant water status, although it is not a constituent of any known plant components. Its primary role is as an enzyme activator. Potassium has been implicated in over 60 enzymatic reactions, which are involved in many processes in the plant such as photosynthesis, respiration, carbohydrate metabolism, translocation and protein synthesis (Marschner, 2012; Zörb *et al.*, 2014; Shen *et al.*, 2017). Potassium balances charges of anions and influences their uptake and transport. Another important function is the maintenance of osmotic potential and water uptake. These two functions of K are manifest in its role in stomatal opening when stomatal conductance and turgor are coupled (Pettigrew, 2008; Wang *et al.*, 2013; Oosterhuis *et al.*, 2014). Another major role of K is in photosynthesis by directly increasing leaf growth and leaf area index, and therefore, CO_2 assimilation. Thus, K increases the outward translocation of photosynthate from the leaf (Hu *et al.*, 2015; 2017; 2018).

In cotton, K also plays a particularly important role in fiber development (Pettigrew, 2008) and a shortage will result in poorer fiber quality and lowered yields (Xiangbin *et al.*, 2012). Potassium deficiency occurs more frequently and with greater intensity on cotton than for most other agronomic crops (Pettigrew, 2008). Typical K deficiency symptoms occur in the leaves, the damage to which might be followed by shedding of flower buds (Loka *et al.*, 2019) and by ceased boll development (Pettigrew, 2003). Immature dwarfed fruit are a typical symptom of severe K deficiency in cotton. The K deficiency syndrome may be the outcome of numerous reasons that include low soil K status; K fixation in the soil; a greater demand for K by modern cultivars; less storage of K prior to flowering by modern cultivars; and, the inability of the root system to supply the needed K during boll development (Oosterhuis, 2001). Total seasonal K requirement ranges from 60-400 kg K_2O ha^{-1} for irrigated cotton, depending on crop conditions and on the achievable target yield (Constable and Bange, 2015). Potassium removal by the lint and seed accounts for 7.5-46% of total plant K, as a function of yield. Peak daily K uptake occurs during boll development and ranges from 1.8-5.2 kg K_2O ha^{-1} day^{-1} in irrigated crops.

Although often underestimated, sulfur (S) is an important nutrient influencing cotton plant growth, development and yield. Sulfur is an essential constituent of cysteine, the amino acid that initiates protein buildup (Haneklaus *et al.*, 2008). Sulfur activates many enzyme systems (Najafian and Zahedifar, 2015), as well as being a pivotal constituent of the enzymes involved in N metabolism, such as nitrate reductase and nitrite reductase (Swamy *et al.*, 2005). A positive interaction between N and S in increasing crop biomass and yield was observed by Salvagiotti and Miralles (2008). Sulfur application improved N use efficiency in wheat by increasing N uptake (Salvagiotti *et al.*, 2009). Likewise, a surge in leaf photosynthesis correlated with increased S supply (Terry, 1976).

While the worldwide use of S fertilizers was limited to cases of critical S deficiency, the sharp decline in S pollution during the last few decades (Kovar and Grant, 2011) has resulted in a consistently rising trend of S deficiency symptoms in many crops. Rates of S removal by crops have become greater than that of soils' ability to restore available S (Chen *et al.*, 2005), a phenomenon which calls for the employment of S fertilizers. Nevertheless, crop responses to S application have been found to vary widely due to differences in location, soil type, various S containing compounds in the soil and consequent S availability, crop genotype, environmental conditions and crop management (Björkman *et al.*, 2011).

In cotton, experiments discovered that application of S coated urea gives rise to higher cotton yields compared with a polymer-coated urea, which indicates that the additional S supply increased the plant biomass Geng *et al.* (2015). Indeed, a more recent study demonstrated that S fertilizer application to soil resulted in significantly higher cotton yields compared to corresponding controls (Geng *et al.*, 2016). These studies indicate that the cotton industry might find benefits in the inclusion of S fertilizer in the crop management toolbox.

In Turkey, straight K fertilizers are not used much, since soils are traditionally conceived as rich in this nutrient. However, the authorities, aiming to enhance production and quality, and maintain sustained soil fertility, are currently focusing on measuring K requirements, N/K ratios, target yields, and crop quality. As a result, cotton growers in Turkey are gradually moving to fertilization practices that generally include 15:15:15 complex N-P-K fertilizers applied at sowing, and ammonium nitrate or calcium ammonium nitrate applied during the second half of the vegetative phase. Nevertheless, further accuracy is required concerning adequate K doses, timing of application, and K interactions with other nutrients before a reliable and widely accepted K fertilization recommendation can be established for cotton in Turkey.

Potassium sulphate (SOP, K_2SO_4) is rarely recommended as a cotton fertilizer. In the framework of enhancing the Turkish cotton industry, the means to improve nutrient use efficiency are considered, including the use of slow-release fertilizers and the introduction of S (Gormus and El-Sabagh, 2016). 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% sulfur trioxide (SO_3), 6% magnesium oxide (MgO), and 17% calcium oxide (CaO). In addition to being a natural, multi-nutrient fertilizer, polyhalite is much less soluble. Thus, with significantly slower nutrient release rates, basal application of polyhalite at sowing may provide extended K and S availability during cotton crop development.

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

The major objective of this study was to evaluate the effects of polyhalite, SOP, and potassium chloride (MOP) on cotton production in Turkey. Cotton yield, quality properties, and macro and micro nutrient content and uptake under these fertilizer treatments were examined and compared.

Materials and methods

Experiments took place in the Antalya region, located on the Mediterranean coast in southwestern Turkey (Map 1). The soil was sandy-loam, slightly alkaline, and poor in phosphorus (P) and K (Table 1). Net cotton water requirements range from 400-800 mm through the entire crop growth season in Turkey, from April-May to October. In most years, precipitation during this time is very low so the crop relies mainly on irrigation. Drip irrigation, which was employed in the present study, is still rare.

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

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

Seasonal macronutrient (NPK) doses were 250, 184, and 210 kg ha^{-1} of N, phosphorus pentoxide (P_2O_5) and K_2O, respectively, according to the official recommendations for cotton. The experiment included four fertilizer treatments: 1) control (N+P+no K); 2) K_2SO_4+N+P; 3) polyhalite+N+P; and, 4) potassium chloride (KCl)+N+P. All treatments received the mentioned doses of NPK, excluding the control, which lacked any K fertilizers. Nitrogen and P were supplied to all treatments through di-ammonium phosphate (DAP) and ammonium nitrate (AN), whereas K was supplied using K_2SO_4, polyhalite, and KCl. All fertilizers were applied basally, before sowing.

The experiment layout employed a randomized block design with four treatments and four replications. Each experimental unit (plot) was 5 m long and 2.8 m wide and consisted of 4 rows. Cotton cv. Gloria was sown on 9 May at a distance of 0.2 m apart and within rows spaced 0.7 m apart, giving rise to a density of 71,500 plants ha^{-1}. Drip irrigation was practiced according to the weekly current evaporative demands, supplying a total of 760 mm water over the entire cropping season.

An early harvest took place on 4 October and a final harvest on 27 October. Lint quality parameters were determined at the Cotton Research Institute, Aydin, Turkey. Lint and seed macro and micro nutrient contents were determined at the Plant and Soil Laboratories of the West Mediterranean Agricultural Research Institute in Antalya, Turkey.

Results and discussion

The highest early and total yields were obtained under the KCl treatment, although the yield of the K_2SO_4 treatment did not differ significantly (Fig. 1). Cotton yields above 5 Mg ha^{-1} are considered very high and beyond the recently defined potential of this crop (Constable and Bange, 2015). Polyhalite application gave rise to a high yield of 4.75 Mg ha^{-1}, which did not differ significantly from that of the K_2SO_4 treatment. The substantially lower yield obtained by the control, 2.7 Mg ha^{-1}, clearly demonstrates the production limits imposed by a lack of K (Fig. 1). Nevertheless, these results do not show any convincing evidence of the significance of S with regard to cotton yield levels.

Fiber fineness, maturity, length, strength and elongation are the most important physical parameters that describe lint quality. It is generally considered that concerning lint fineness, both too low and too high micronaire cottons should be avoided, the ideal range being between about 3.8 and 4.2 MIC for upland cotton (International Trade Center, 2019). In the present study, the control lint was very close to this 'premium range' at 3.74 MIC (Fig. 2). Lint fineness of cotton applied with K_2SO_4 or polyhalite displayed a much higher MIC value but still within the acceptable range (below 4.9). KCl application, on the other hand, promoted thicker fibers that fell into the discount range of above 5 MIC (Fig. 2). The thickness of these particular fibers might be one of the reasons why this treatment had the highest yield (Fig. 1).

Maturity, which is largely determined by growing conditions, can be defined as the relative wall thickness of the fiber (International Trade Center, 2019). Maturity generally has a greater effect on fabric appearance and defects than any of the other fiber properties. Measuring the maturity of a cotton sample in addition to its fineness is essential to whether the determined fineness is an inherited characteristic or is a result of immaturity. Percentage maturity (Pm) above 80% is desirable (International Trade Center, 2019). All treatments of the present study, including control, obtained a Pm greater than 85%, meaning the produce was classified among the 'high maturity' range (Fig. 2). Nevertheless, Pm values were significantly higher among K applied cotton, with or without S. Thus, K supply clearly improved this quality parameter, in agreement with previous studies that have demonstrated the role of K in sugar transport into the developing boll, and in cellulose buildup in the fiber cell wall (Xiangbin *et al.*, 2012; Hu *et al.*, 2015).

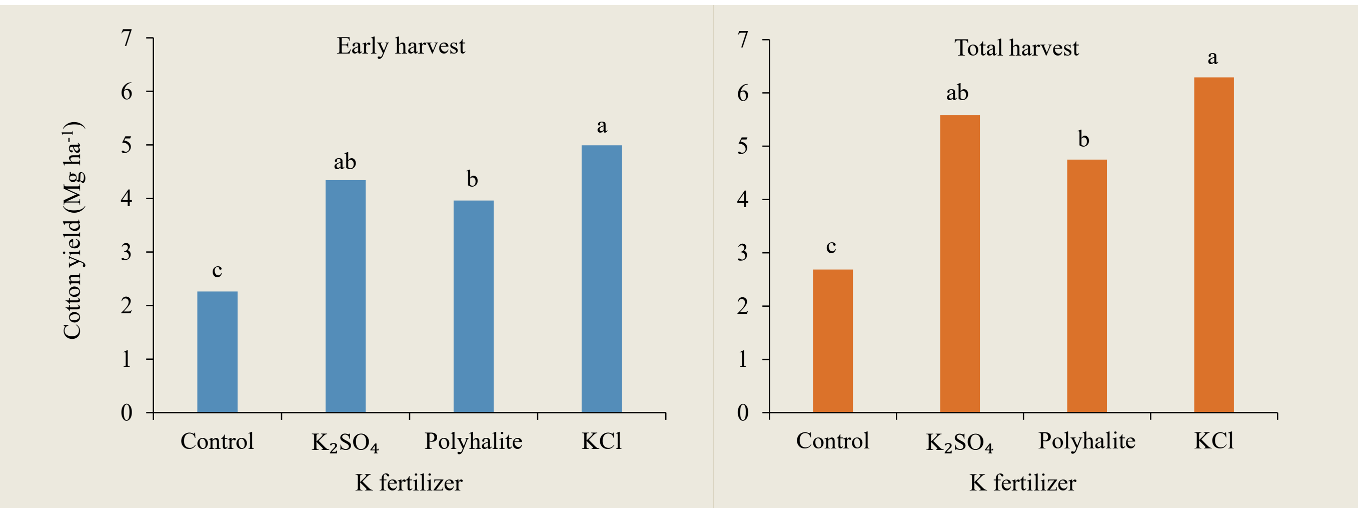

Fig. 1. Effects of different K and S fertilizer treatments on early and total cotton yields. Similar letters indicate no significant differences between treatments ($p<0.05$).

Length, length uniformity, and length distribution, including short fiber content, are probably the most important cotton fiber properties. An increase of 1 mm in fiber length increases yarn strength by some 0.4 g tex^{-1} or more. The staple length, upper half-mean length (UHML), and 2.5% span length, all provide similar but not identical measures, approximating the length of the fibers when carefully detached from the seed by hand. Fiber length characteristics are determined mainly by genetic (cotton variety) factors, however, the genetic potential requires suitable growing conditions to be pronounced.

A fiber length of above 28 mm is desirable in most cases, yet, longer fibers enable smoother and more efficient processing, thus facilitating the production of finer, stronger, more even and less hairy yarns, as well as stronger fabrics with better appearance (International Trade Center, 2019). All treatments, including the control, displayed a fiber length greater than 30 mm and within the desired range (Fig. 2). However, K applied and furthermore, K+S applied plants gave rise to significantly longer fibers. These results provide indications that, in addition to K significance in fiber construction, S may be strongly and positively involved in processes determining fiber length.

The strength of individual cotton fibers is largely determined by the fineness of the fibers, whereas the tenacity (i.e. fineness or cross section-corrected strength) of cotton is largely determined genetically. Cotton fiber tenacity is measured on standard fiber bundles (tex), and values above 30 g tex^{-1} are generally desirable (International Trade Center, 2019). Cotton bundle tenacity in the present study ranged from 36-38 g tex^{-1}, with no significant differences between treatments. A recent study under Mediterranean conditions showed that S applied at a modest range of 15-45 kg ha^{-1} through K_2SO_4 significantly enhanced lint length and strength (Gormus and Al-Sabagh, 2016).

Fiber elongation (extension at break) is a measure of fiber, and consequently, yarn elasticity; to be useful, textile products must conform to a certain level of elasticity. While the industry classifies fiber elongation above 8% as highly elastic and beyond the desired optimum, recent studies claim that elasticity should be further increased through breeding and genetic manipulations (Kelly *et al.*, 2019).

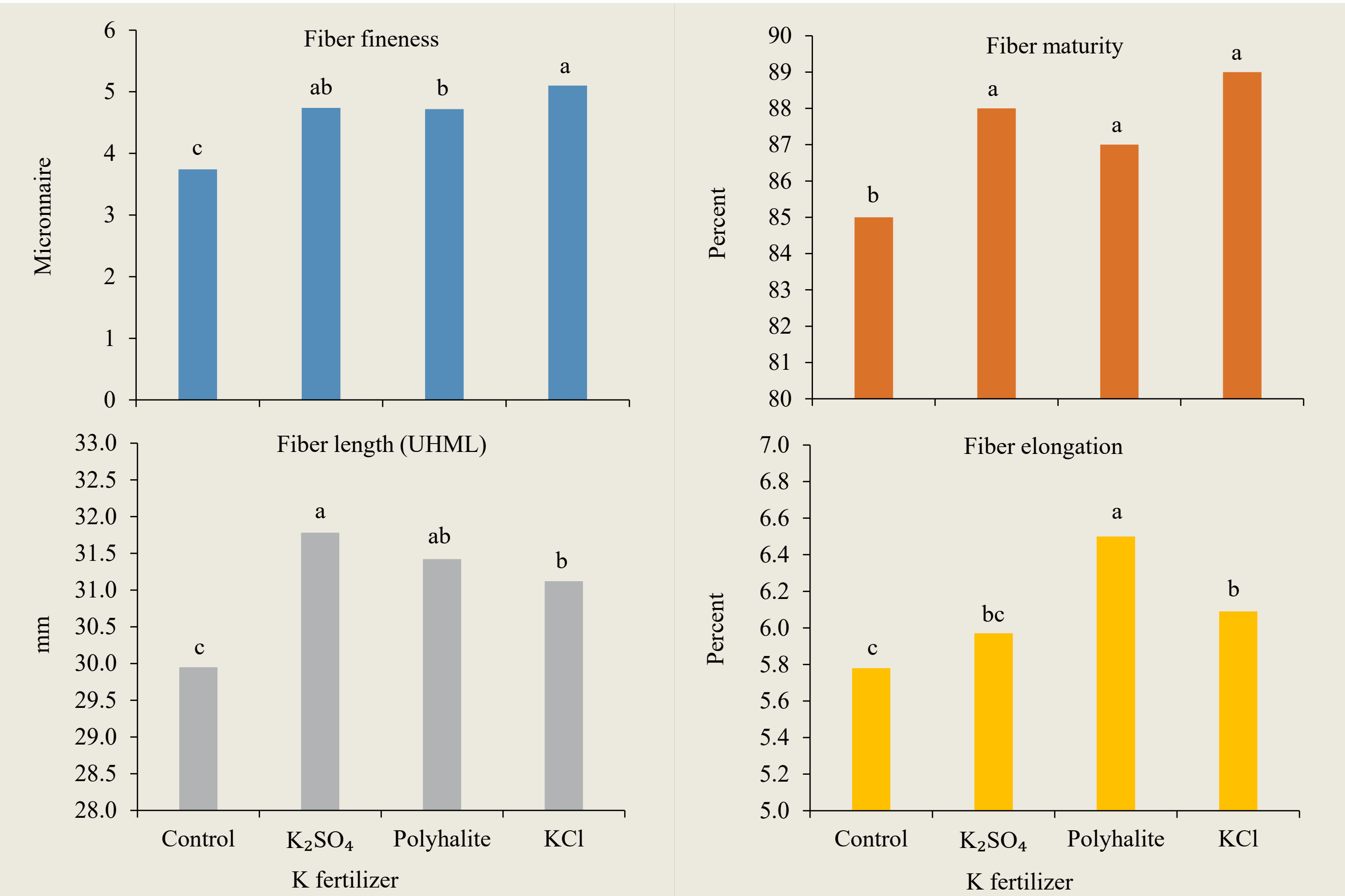

Fig. 2. Effects of different K and S fertilizer treatments on lint quality parameters. Similar letters indicate no significant differences between treatments ($p<0.05$).

In the present study, polyhalite applied cotton displayed a significantly higher value of fiber elongation than other treatments at 6.5%, followed by KCl and K_2SO_4, which were within the elastic category range of 5.9-6.8%. The control cotton fell into the low elasticity range (Fig. 2). These results indicate that in addition to S, other nutrients donated by polyhalite, such as Ca and Mg, may enhance fiber elasticity.

Lint N and P contents were slightly higher in both the control and K_2SO_4 applied plants at 0.21 and 0.35% N and P, respectively, compared to polyhalite or KCl applied plants (0.12 and 0.31% N and P, respectively). Lint K content was significantly lower in control plants, compared to that of the other treatments, which were quite similar (Fig. 3). As anticipated, lint Ca content was significantly higher in polyhalite applied plants, as this treatment was the only one to include the nutrient (Fig. 3). Similarly, lint S content was the highest under polyhalite and significantly lower under KCl. Control was the exception, with lint S content relatively higher than presumed (Fig. 3).

No differences in the macronutrient content of seeds was observed between treatments, suggesting that seeds are always first to fulfill their nutritional requirements, regardless of current nutrient availability. Seed nutrient contents were 5.75, 0.88, 0.9, 0.12, 0.37, and 0.37% for N, P, K, Ca, Mg, and S, respectively.

Macronutrient uptake by the cotton yield (lint + seeds) was significantly lower in control plants, articulating the lower yield rather than the nutrient content (Table 2). Consequent to the increasing yields (Fig. 1), K application boosted bolls' N and P uptake by about 100% compared to control. Among the three treatments supplied with K, polyhalite plants displayed slightly but significantly lower N and P uptake rates. Of note is that N uptake to the cotton yield of the K applied treatments reached 65-88% of the total N dose supplied, demonstrating the interaction between the two nutrients and the significant role of K in supporting yield buildup.

A similar pattern occurred with K uptake; however, in this case, only 17-22% of the K dose applied reached the cotton bolls (Table 2). This makes sense, as K is not incorporated to the plant structures but remains as a soluble cation, facilitating plant water relations and biochemical processes throughout all plant tissues and organs (Marschner, 2012). Although not supplied to the control, K uptake by the bolls of this treatment was as high as 18 kg ha^{-1}, suggesting that cotton plants drag remarkable amounts of K even from poor soils. Plants applied with polyhalite obtained significantly lower K uptake compared to those applied with KCl or K_2SO_4, indicating a relatively lower K availability where this fertilizer stands alone as a K donor.

Uptake of Ca, Mg, and S to cotton bolls was significantly higher under the KCl and K_2SO_4 treatments, whereas polyhalite applied plants displayed considerably lower Mg and S uptake rates (Table 2). These results indicate that on calcareous soils, the relative advantage of polyhalite as a Ca and Mg donor might decline.

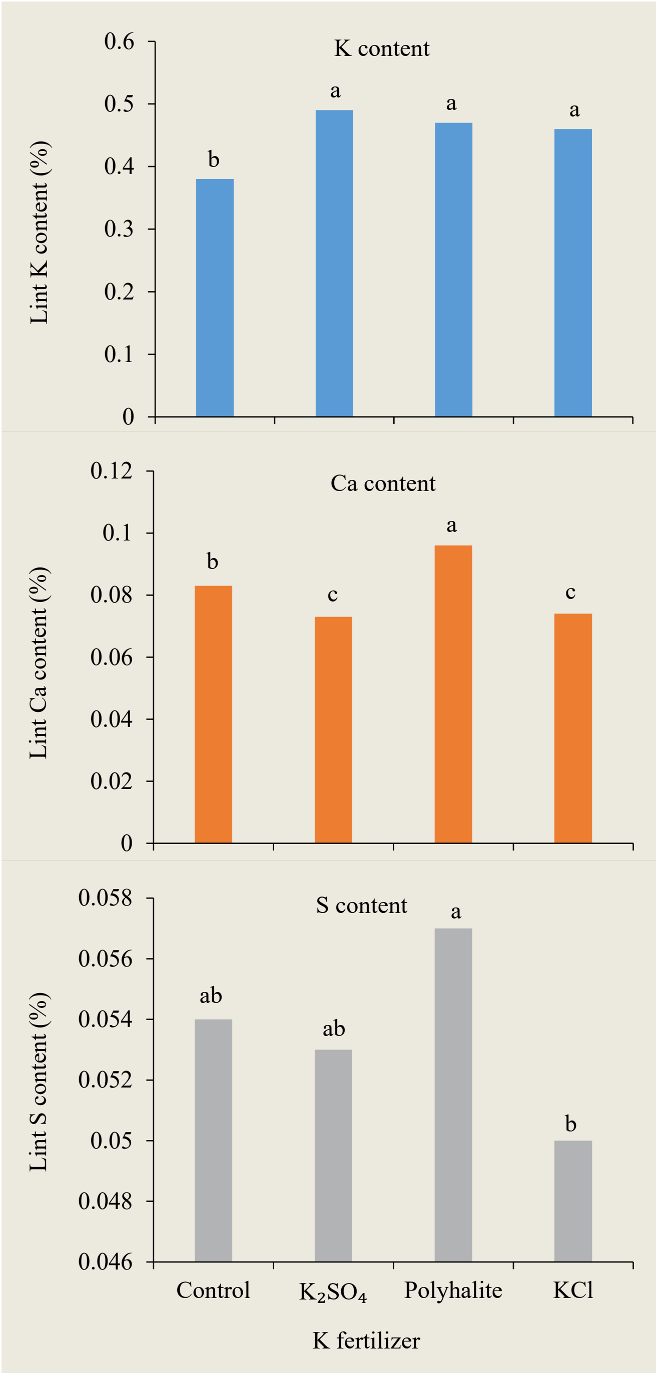

Fig. 3. Effects of different K and S fertilizer treatments on lint Ca, Mg, and S contents. Similar letters indicate no significant differences between treatments ($p<0.05$).

Table 2. Effects of fertilizer treatments on the macronutrient uptake by the total (lint + seeds) yield.

Treatment	N	P	K	Ca	Mg	S
	--------	--------	--------	*kg ha*$^{-1}$ --------	--------	--------
Control	95.1c	14.7c	17.7c	2.8c	6.6c	6.2c
K_2SO_4	191.7a	29.6a	40.8ab	5.5b	13.6a	13.5ab
Polyhalite	161.3b	24.5b	35.6b	5.5b	11.4b	12.0b
KCl	218.5a	31.8a	45.5a	6.3a	14.7a	15.0a
Significance level	*	*	*	*	*	*
LSD	11.4	1.6	2.5	2.5	0.63	0.72

* $p \geq 0.001$.

Table 3. Effects of fertilizer treatments on the micronutrient uptake by the total (lint + seeds).

Treatment	Fe	Zn	Mn	Cu
	--------	-------- *g ha*$^{-1}$	--------	--------
Control	121.9c	78.1d	30.1c	28.6c
K_2SO_4	210.2ab	174.7b	61.6a	54.1ab
Polyhalite	179.2b	144.4c	50.7b	43.7b
KCl	228.7a	201.9a	69.0a	63.8a
Significance level	**	**	**	*
LSD	0.72	8.7	0.72	4.9

* $p \geq 0.01$; ** $p \geq 0.001$.

Micronutrient uptake by the cotton bolls also reflected fertilizer influence on the boll yield rather than on element content. Thus, micronutrient uptake under the control treatment was significantly low; under KCl, uptake rates were the highest; and under K_2SO_4 and polyhalite it was intermediate (Table 3). Among four microelements examined, zinc (Zn) was the most responsive, as its uptake rates were 2-3 fold higher in K applied than in control plants, compared with iron, manganese, and copper, which increased 1.5-2 fold by comparison.

Photo 2. Basal polyhalite application can benefit cotton yield. Photo by the authors.

Conclusions

Unequivocally, the results of the present study demonstrate the pivotal role of K in cotton production, highlighting the need to enhance practices of its application. Overall, results indicate KCl among the fertilizers examined as the preferable K donor to obtain high cotton yields. However, the global cotton and textile industries currently tend to focus on lint quality enhancement rather than yield levels. Some of the quality properties, such as fiber fineness, length, and elongation performed better under polyhalite and K_2SO_4 fertilizers.

The direct and indirect influence of nutrients such as S, Ca, and Zn on lint development and quality remains to be revealed. Nevertheless, S containing fertilizers must be considered to achieve good results for both yield and quality. While polyhalite appears too slow to stand alone as a K donor, this fertilizer shows significant potential on less calcareous soils as a slow-release donor of S, Ca, Mg, and K. Basal polyhalite application, used in combination with other NPK fertilizers and included in practices suited to meet crop requirements during the season, can provide the Turkish cotton industry with a significant step forward.

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Research Findings

Rice field in India. Photo by the authors.

Wheat and Rice Response to Potassium in Vertisols
Results from 120 Plot Pairs Across Bhopal, Jagtial, Jabalpur, and Raipur Districts, India

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Abstract

The soil quality and fertility in the country are of utmost importance. Declining soil fertility is one of the primary factors that directly affect crop productivity, and fertilizer use is a key factor in order to ensure soil fertility and productivity. Potassium (K) depletion in soil is also a major factor in declining soil fertility. Degradation of soil due to significant nutrient demands by crops and imbalanced fertilizer application is common in the arable lands of India. While practices of nitrogen (N) and phosphorus (P) application have been established and disseminated, K crop and soil requirements are largely ignored.

Rice and wheat are among the most important crops in India both from the perspective of food security and export. However, productivity of these crops in India is low compared to their yield levels. To evaluate the K response in these two critical crops, and to demonstrate to farmers the increased yield and profitability with application of muriate of potash (MOP) on K depleted soils,

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a project – the Potash for Life (PFL) project – was launched. This study aimed to evaluate and demonstrate the principal contribution of K application in increasing wheat and rice yield and profitability, and to raise the awareness of stakeholders and growers towards vital need to adopt balanced and K-inclusive fertilization regimes. Three identical plots were grown with the selected crops side by side. Besides optimum level of N and P, three levels of K, i.e. 0, 40 or 80 kg ha^{-1} were applied. A significant and positive effect of K levels was observed in both wheat and rice crop. The average yield increase was statistically significant and was around 571-599 kg ha^{-1} (11-15%) in wheat, and 286-728 kg ha^{-1} (4-11%) in rice. It was concluded that the plant available K in the soil K is significantly lower than the plant demand for wheat and rice production indicating the necessity for which means that K fertilization to improve agricultural productivity.

Keywords: Potassium response, rice, wheat, Vertisol, critical limit.

Agriculture forms the backbone of the Indian economy in spite of concerted efforts towards industrialization over the last three decades. As such, agriculture contributes a high share (15%) of the net domestic product in India (FAO, 2018). India's economy has experienced remarkable progress during recent decades. In spite of that, 70% of the population still live in rural areas and are dependent on agriculture (FAO, 2018). The ever increasing demand for food, feed, and fibers, and the limitation of arable land, necessitate not only the practices of conserving, managing, and enriching the natural resources, but also up-scaling of land-use efficiency. Soil forms the basis for any crop production activity and is the most precious natural resource. Therefore, soil fertility management is crucial in order to ensure productivity and nutritional security, while maintaining soil health and sustainability (Prasad and Power, 1997). Subsequently, fertilizer use is a key factor in order to ensure soil fertility and productivity. Though, fertilizers are one of the most costly inputs in agriculture but if used correctly, they turn to be the most profitable (FAO, 2005).

It is a fact that imbalanced and incorrect use of fertilizers not only impact nutrient use efficiency, but it can also cause deterioration in soil quality (Wallace, 2008). Therefore, balanced fertilizer use must be promoted as it is an absolutely essential way to prevent both soil fertility decline or soil quality deterioration from over-use or imbalanced use.

Rice and wheat are among the most important crops in India from the aspect of both food security and export. The annual production of 168.5 million tons of rice and 98.5 million tons of wheat makes India the second largest producer of rice and wheat in the world after China (FAOSTAT, 2019).

Rice is arguably the most important crop in Asia and is considered one of the central staple foods in most Asian countries, and India is no exception. In India, rice is grown as both a *kharif* and *rabi* crop, although more than half of total rice production is grown during the summer monsoon season (*kharif*) (Auffhammer *et al.*, 2012). *Rabi* production is made possible by expanding irrigation infrastructure. Top rice producing states in India are Andhra Pradesh, West Bengal, Uttar Pradesh, Punjab and Odisha, although the production in other states is also very significant (OGD, 2019).

The rice-wheat cropping system is a very common practice in India (Mohanty *et al.*, 2007). This system became popular in the 1960s with the emergence of short-duration and high-yielding varieties of rice and wheat, and today it is practiced on around 11 million hectares (Joshi *et al.*, 2007; Kumar *et al.*, 1998). Wheat, together with rice, plays a critical role in the Indian food economy. During the green revolution, area under wheat greatly increased but, currently, the area seems to have stabilized at around 27 million hectares (Joshi *et al.*, 2007). Most of the wheat in India is produced in the states of Uttar Pradesh, Punjab, Haryana, Rajasthan, Madhya Pradesh (M.P.), Gujarat, and Bihar (OGD, 2019; Joshi *et al.*, 2007). The rice-wheat cropping system is very intensive and has been a topic of many studies that have evaluated its sustainability, and which have pointed out the importance of good soil fertility management in ensuring optimal yields and long-term sustainability (Joshi *et al.*, 2007; Mohanty *et al.*, 2007; Kumar *et al.*, 1998).

While the importance of these crops is unquestionable, the average yield levels of 3.85 t ha^{-1} and 3.22 t ha^{-1}, for rice and wheat respectively, are not as impressive. These substantially lag behind the optimum levels (FAO, 2019). The production of these two critical crops is crippled by low yields, inadequate irrigation, poor infrastructure, and outdated fertilizer practices. However, the country can overcome these constraints through optimization of different aspects of production such as: mechanized sowing and harvesting; improved market access for farmers; improved irrigation; and, by ensuring sufficient and balanced plant nutrient supply, through correct and updated fertilizer practices.

Imbalance in nutrient supply to plants is a big limitation in agricultural production. Most notably in India, long-term application of only diammonium phosphate (DAP) and urea can lead to potassium (K) depletion in the soil, as the crop take up substantial amounts of K. This practice of omitting K from regular fertilization is particularly common in Vertisols, probably originating from the fact that Vertisol is classified as K-rich soil. However, even K-rich soils can be depleted after years of intensive agricultural production. Numerous studies have recorded positive crop response to applied K in Vertisols in India (Singh and Wanjari, 2012; Dwivedi *et al.*, 2007; Chen *et al.*, 2000). The present study has suggested an increase in the critical value for K in Indian Vertisols from the currently used level of 280 kg K ha^{-1} to 330 kg K ha^{-1} (Singh *et al.*, 2019).

To test these recommendations, and to quantify yield and profit benefits of a K-inclusive fertilization regime to farmers, a multi-location study on rice and wheat was performed.

Objectives

The trials had two main objectives:

- Evaluate the MOP response of rice and wheat on Vertisols in India
- To demonstrate to farmers the increased yield and profitability obtained as a result of applying MOP, in addition to the conventional use of DAP, urea and manure.

Materials and methods

Experimental design

Trials for K response in rice and wheat were conducted in India in the states of Madhya Pradesh (M.P.), Chhattisgarh, and Telangana, for two years during 2016-2018 under three cropping systems: (1) soybean-wheat in Bhopal and Jabalpur districts of M.P.; (2) rice-wheat systems in Bhopal district, M.P., and Raipur district, Chhattisgarh; and, (3) rice-rice system in Jagtial district, Telangana (Table 2). The location of each studied district is shown in Fig. 1, Fig. 2, and Fig. 3. The experiment was conducted in a randomized block design, with a minimum of five replicates. Due to severe drought, the yields of soybean at both locations in M.P., and the yields of wheat at Raipur, were not included.

Kharif crops were sown at the onset of the monsoon and irrigated in the case of an early withdrawal of monsoon, or in the case of prolonged dry periods. The *rabi* crop was grown exclusively under irrigated conditions. All recommended agronomic practices were followed. Crops were harvested at maturity, grain yields were measured, and are reported here at 11% moisture content.

Soil analysis

The soil analysis was performed according to the methodology described by Kumar *et al.* (2018). Assessment of the effect of wetting on K availability in the soil was performed on four soil samples, with six replicates for each sample. Five gram soil was weighed in a flask and 5 ml of water were added. The flasks were kept at room temperature for 24 hours after which 20 ml of neutral normal ammonium acetate was added to displace cations from the exchange sites. The K content in the extract was then determined using flame photometer. The soil nutrient status and other soil properties at the beginning of the experiment are presented in Table 1.

Treatments

There were three treatments abbreviated as K_0, K_{40} and K_{80}, corresponding to the levels of applied K. The levels of N and P were constant at estimated optimum levels for each crop and location (Table 2). In addition, data was also collected from the plots where farmers previous fertilizer regime was applied and is labeled as K_{FP} treatment (farmers' practice).

Statistical analysis

The statistical analysis was performed using pairwise t-tests. Data analysis was conducted on all data points using pairwise t-tests (paired two sample for mean), in order to compare the control plots (K_0) with the K_{40}, K_{80}, and K_{FP} plots, for each location and season, for both crops tested in this study.

The yield levels, and the yield increase levels, were further compared between the locations and seasons. For these non-paired comparisons, an F-test was first performed to test for the equality of variances. This information was then used to select between two different variants of two-sample t-tests, in order to correctly assume equal or unequal variances. In all tests, the confidence level was at 95 percent.

In addition, linear regression analysis was used to explore the effect of initial K status of the soil on the yields of control plot, as well as on the response to two applied levels of K. The same analysis was

Fig. 1. Map of Madhya Pradesh state. Bhopal and Jabalpur districts, where experimental plots of soybean-wheat and rice-wheat cropping systems were located are indicated with red ellipses. *Source:* https://d-maps.com/continent.php?num_con=13&lang=en.

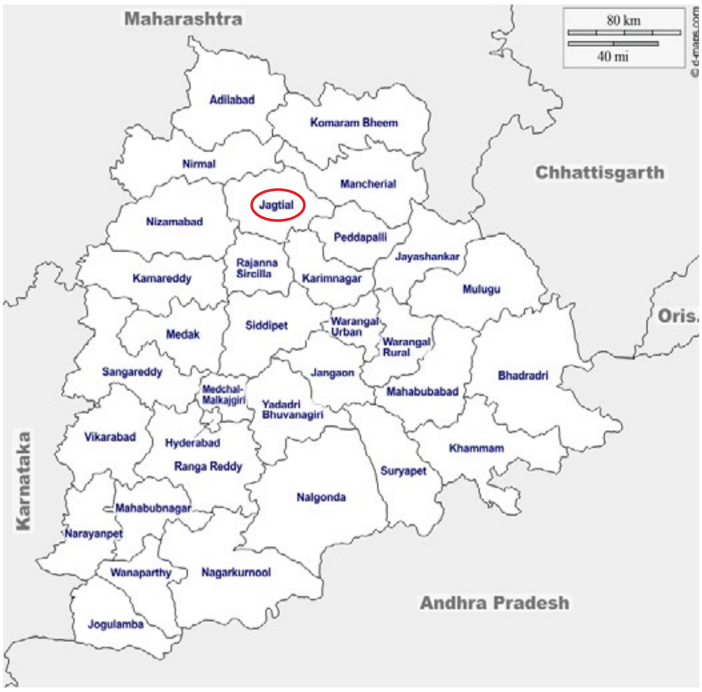


Fig. 2. Map of Telangana state. Jagtial district where experimental plots of rice-rice cropping system were located is indicated with a red ellipse.
Source: https://d-maps.com/continent.php?num_con=13&lang=en.

performed to evaluate the relationship between control yield, the absolute yield increase, and the relative yield increase.

Results: Wheat

Potassium, applied as MOP (KCl), in addition to the common fertilizer application of urea, DAP, and manure resulted in a significant increase in wheat yield (Table 3). With an average yield increase in K_{80} treatment of 599 kg ha^{-1} and 571 kg ha^{-1}, in Bhopal and Jabalpur, respectively, and an average additional net profit of about 7,500 INR ha^{-1}, the benefits arising from K application to wheat producers are clear. The average control yields in the districts of Bhopal and Jabalpur were 5,257 kg ha^{-1} and 3,804 kg ha^{-1}, respectively; while in K_{80} plots, it was 5,855 kg ha^{-1} and 4,375 kg ha^{-1}, respectively (Table 3). In the K_{40} treatment, the yields at both locations were between the control and those in the K_{80}. The difference between control yield, with regards to both the K_{40} and the K_{80} yields, was statistically verified to be significant. Furthermore, the yield in K_{80} treatment was also statistically higher than the yield in K_{40} treatment.

Fig. 3. Map of Chhattisgarh state. Raipur district where experimental plots of rice-wheat cropping system were located is indicated with a red ellipse.
Source: https://d-maps.com/continent.php?num_con=13&lang=en.

Absolute yield increase

Mean yield levels at both locations show a clear increase as a result of K application

Table 1. Initial soil properties and nutrient status at the study locations.

Location	Soil type	pH	EC	OC	Available nutrients status		
					N	P	K
			dS m^{-1}	*g kg^{-1}*	-----------*kg ha^{-1}*------------		
Bhopal (Madhya Pradesh)	Typic Chromustert	7.43	0.24	6.00	235	22.47	355
Jabalpur (Madhya Pradesh)	Typic Chromustert	7.45	0.16	6.61	252	15.95	476
Raipur (Chhattisgarh)	Typic Haplustert	7.46	0.19	4.59	154	7.51	366
Jagtial (Telangana)	Typic Tropaquept	7.78	0.37	7.80	185	45.48	382

Note: EC = electric conductivity; OC = soil organic content.

Table 2. Fertilizer regimes applied across the three treatments (K_0, K_{40} and K_{80}), and farmers' practice dose indicated as K_{FP}.

Location	Crop	Fertilizer rate											
		K_0			K_{40}			K_{80}			K_{FP}		
		N	P	K	N	P	K	N	P	K	N	P	K
		----------kg ha⁻¹----------											
Bhopal (Madhya Pradesh)	Rice	120	26	-	120	26	40	120	26	80	112	22	-
Bhopal (Madhya Pradesh)	Wheat	120	26	-	120	26	40	120	26	80	116	22	-
Jabalpur (Madhya Pradesh)	Wheat	120	35	-	120	35	40	120	35	80	80	26	10
Raipur (Chhattisgarh)	Rice	100	26	-	100	26	40	100	26	80	100	26	20
Jagtial (Telangana)	Rice	170	39	-	170	39	48	170	39	96	170	39	20

Table 3. Mean wheat yields for control and +K plots, as well as mean yield increase levels for wheat harvested in the 2016-2018 period in Bhopal and Jabalpur districts.

Treatment	Bhopal	Jabalpur
K_0 – Control (kg ha^{-1})	5,257	3,804
K_{40} (kg ha^{-1})	5,563	4,004
K_{80} (kg ha^{-1})	5,855	4,375
K_{FP} (kg ha^{-1})	4,717	3,488
Increase in K_{40}, absolute (kg ha^{-1})	307	200
Increase in K_{80}, absolute (kg ha^{-1})	599	571
Increase in K_{40}, relative (%)	6.1	5.3
Increase in K_{80}, relative (%)	11.3	15.0

at 40 kg ha^{-1}, and an even higher increase in the treatment where the K dose is doubled to 80 kg ha^{-1} (Fig. 4). Yield levels in farmers' practice plots were slightly lower than the control.

Looking at the distribution of absolute yield increase across the farms, we see a uniform distribution of yield responses at Jabalpur with consistently higher response to higher K doses (Fig. 6). Furthermore, the increase is linear with R^2=0.9805. Increasing the K dose from 40 to 80 kg ha^{-1} increased the yield 2-3 times. At Bhopal, although the increase is uniform in both treatments, there is an inconsistency between K_{40} and K_{80} responses (Fig. 5). For instance, in some fields, a negative response was observed at 40 kg K ha^{-1}, while in K_{80} the response is positive, and very high. This suggests that the yields were affected by other factors not considered or investigated in this study. Nevertheless, a stronger response to higher K dose is apparent and has a linear increase with only a slight curve (R^2=0.9743).

The K-response range to the MOP application at the K dose of 40 kg per ha ranged from -241 to 1,280 kg ha^{-1} in Bhopal, and from 138 to 263 kg ha^{-1} in Jabalpur (Fig. 7). The average value in Jabalpur was found to be stable, which is indicated by a very low standard error of the mean, and the identical values of the mean and the median (Fig. 9) and are thus representative of the data set. As observed in the distribution plot (Fig. 5), external factors affected the response in Bhopal, which is also indicated by wider standard error of the mean, and larger difference between the mean and the median (Fig. 8).

In the K_{80} treatment, the yield response in Bhopal ranged from -153 to 1,457 kg ha^{-1} (Fig. 7). The wide range of responses again points to other factors affecting the experiment. In Jabalpur, the response ranged from 469 to 670 kg ha^{-1}. With the higher dose of K, the average value in Bhopal was found to be more stable, as indicated by much closer proximity of the mean and the median (Fig. 8). Due to the mentioned wide range of responses, the standard errors of the mean remained relatively high. In Jabalpur, the average value was found to be stable, which is indicated by a very low standard error of the mean, and again the values for the mean and the median were virtually identical (Fig. 9), which make all the values representative of the dataset.

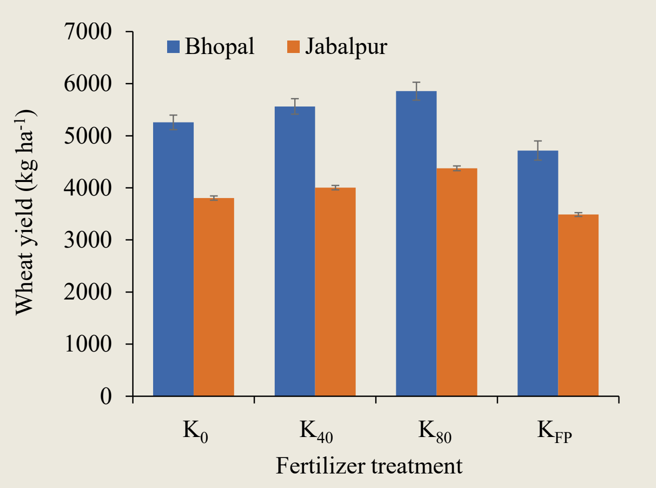


Fig. 4. Mean wheat yield for control and two +K treatment plots harvested in Bhopal and Jabalpur in the 2016-2018 period. Additionally, yield levels of plots where fertilizer regime was applied according to the previous farmers' practice is also shown (K_{FP}). The error bars signify the standard error of the mean. The differences between all levels were confirmed to be significantly different using t-test with α = 0.95.

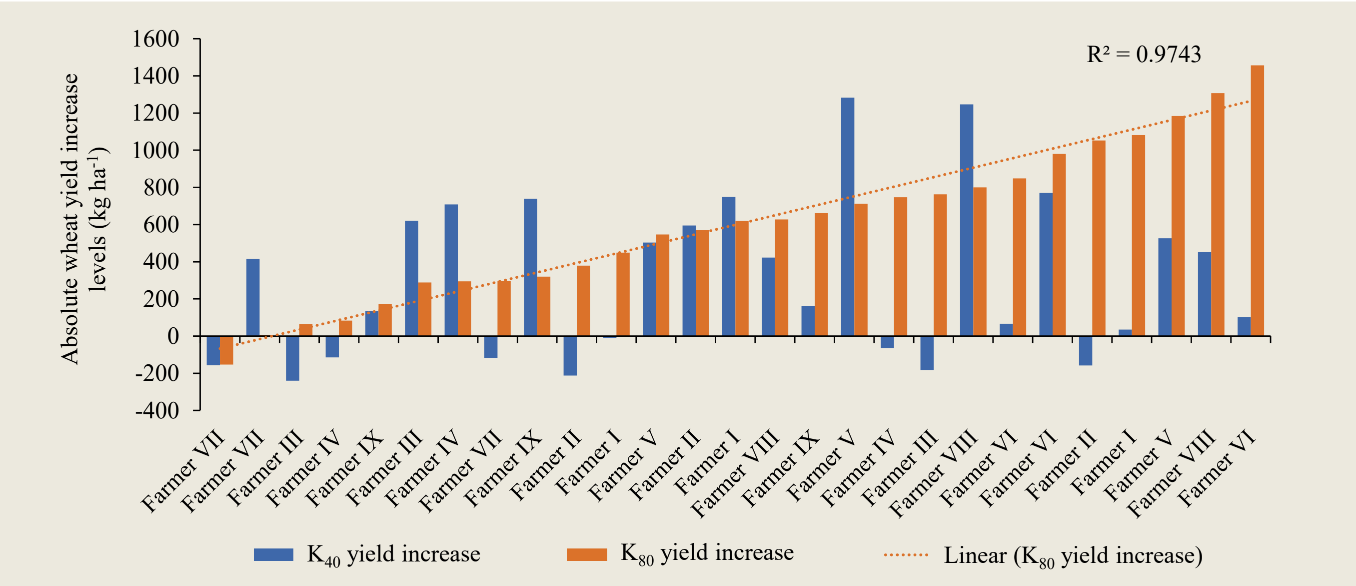


Fig. 5. Absolute wheat yield increase in plots fertilized with MOP in comparison to control plots with no MOP fertilization in 27 plot pairs across Bhopal district and 9 farms harvested in the 2016-2018 period. The data is sorted according to the response in K_{80} treatment. The orange line represents linear regression of K_{80} yield response.

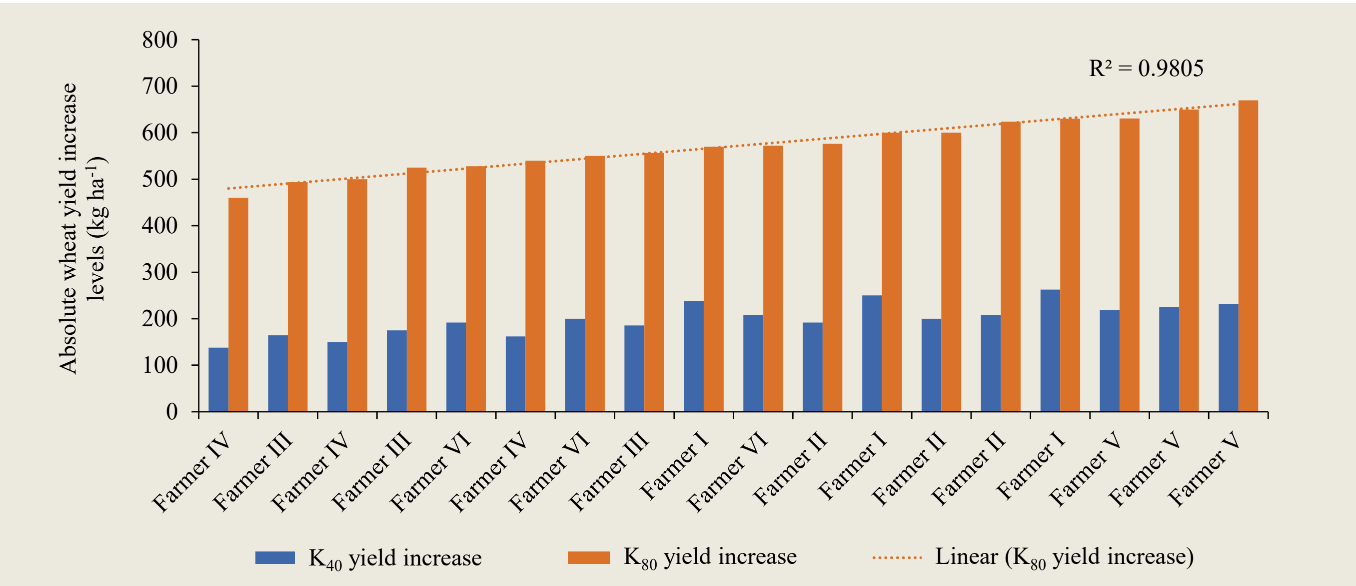


Fig. 6. Absolute wheat yield increases in plots fertilized with MOP in comparison to control plots with no MOP fertilization in 18 plot pairs across Jabalpur district and 6 farms harvested in the 2016-2018 period. The data is sorted according to the response in K_{80} treatment. The orange line represents linear regression of K_{80} yield response.

Looking at the plot of the relationship between control yield level and absolute yield increase, no definite pattern was ovserved at both locations, indicating that the control yield level was not an influencing factor for absolute yield increase (Fig. 10). The scatter plot illustrates the much more consistent response to K application in Jabalpur.

Relative yield increase

In relative terms, the application of 80 kg K ha^{-1} added to the common fertilizer practice of urea, DAP and manure, gave rise to an average wheat yield increase of 11% and 15%, in Bhopal and Jabalpur, respectively. This corresponded to an average benefit cost ratio of 6:1 in terms of local MOP input costs and net profit increase, based on the 2016 report of the Fertilizer Association of India (Chanda *et al.*, 2016). This means that, for every rupee

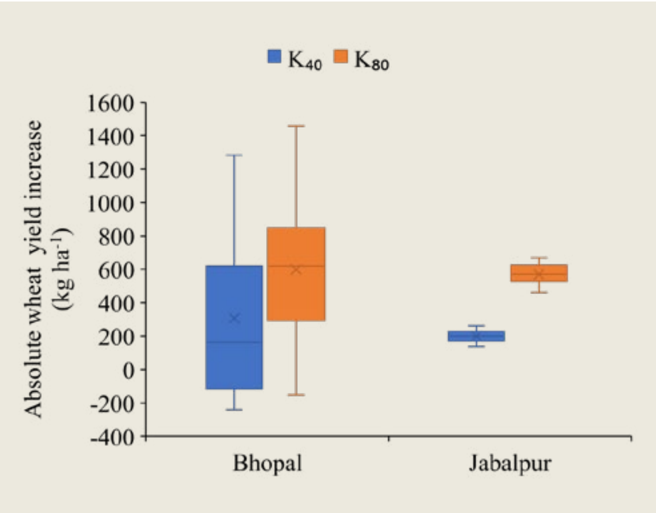


Fig. 7. Box plot diagram illustrates the distribution of the same data as in Fig. 5 and Fig. 6. In the box plot, the middle line represents the median, the upper and lower edge of the box represent the 25th and the 75th percentiles, respectively. The mean is signified by the x-marker. The bars reach the maximum and minimum values.

invested in fertilizer, 3 rupees are returned through increased yields. In the K_{40} treatment, the increase was 6% and 5% in Bhopal and Jabalpur, respectively, with the same B:C ratio of 6:1 in Bhopal, and a lower B:C ratio of 4:1 in Jabalpur.

The distribution of the relative yield increase (Fig. 12) followed the same pattern as the absolute yield increase, with a very consistent and clear linear response in Jabalpur (R^2=0.9508 in K_{80} treatment), narrow standard errors of the mean, and close proximity of the mean and the median (Fig. 9). In Bhopal, the same variation caused by factors other than fertilizer regime is observed (Fig. 11). The response in Bhopal was also close to linear with R^2=0.9658.

In Bhopal, the K-response to the K_{40} application ranged from -4% to 25%, while in the K_{80} treatment, the response ranged from -4% to 30% (Fig. 13).

In Jabalpur, the yield increase response to the K_{40} application ranged from 4% to 7%, while in the K_{80} treatment, the response ranged from 13% to 17% (Fig. 13).

The plot of the relationship between control yield level and relative yield increase shows no identifiable patterns distinguished at both locations, indicating that the control yield level was not an influencing factor in relative yield increase (Fig. 14). The scatter plot again illustrates the much more consistent response to K application in Jabalpur, represented by the orange points.

Results: Rice

Potassium, applied as MOP (KCl), in addition to the common fertilization practices of urea, DAP, and manure, resulted in a significant increase in rice yield (Table 4). With an average yield increase in K_{80} treatment ranging from 255 to 728 kg ha^{-1} across locations, and an average additional net profit of about 4'471 INR ha^{-1}, the benefits arising from K application to the rice producers are clear. The average control yield in Bhopal and Jagtial districts (*kharif* season), Jagtial (*rabi* season), and Raipur were 5,202 kg ha^{-1}, 6,559 kg ha^{-1}, 7,010 kg ha^{-1} and 3,350, respectively; while in K_{80} plots the yield levels were 5,458 kg ha^{-1}, 7,288 kg ha^{-1}, 7,296 kg ha^{-1}, and 3,704 kg ha^{-1}, respectively (Table 4). In the

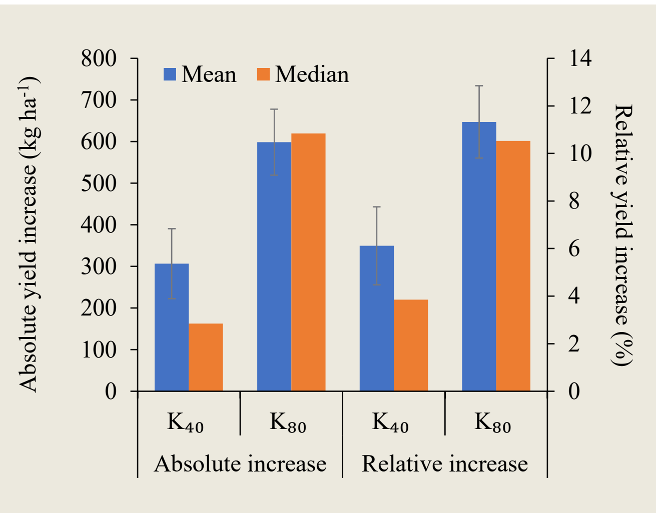


Fig. 8. Absolute and relative yield increases, illustrated both as mean and median, for wheat harvested in Bhopal in the 2016-2018 period. The error bars signify the standard error of the mean.

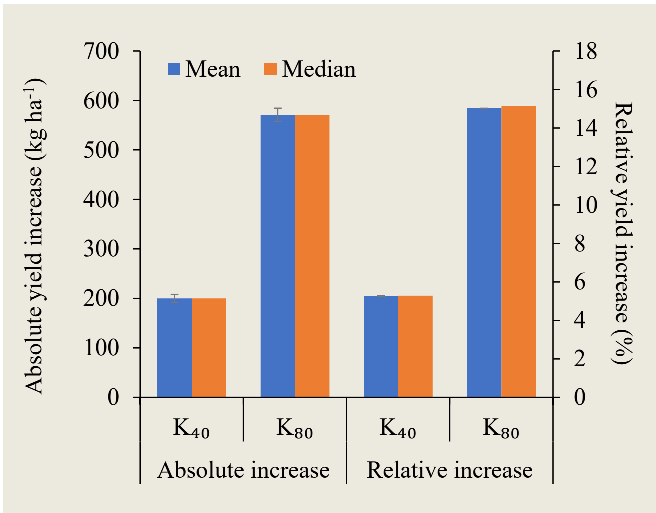


Fig. 9. Absolute and relative yield increases, illustrated both as mean and median, for wheat harvested in Jabalpur in the 2016-2018 period. The error bars signify the standard error of the mean.

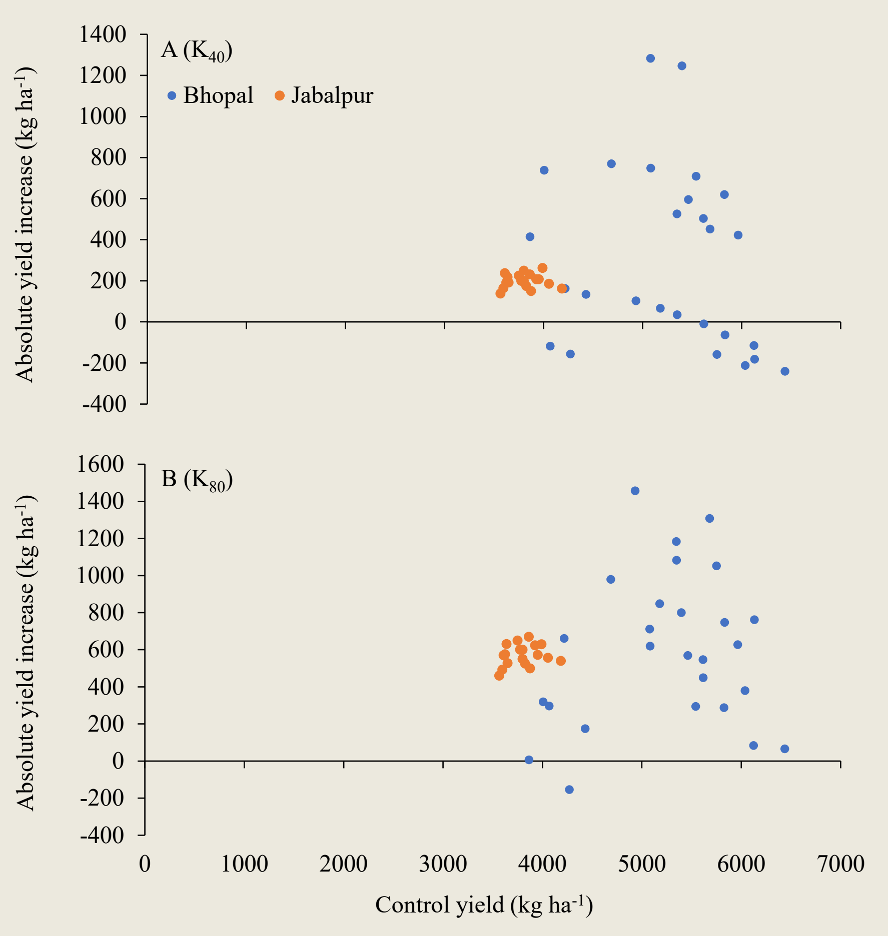


Fig. 10. Absolute yield increase in (A) K_{40} and (B) K_{80} treatments as a function of the control yield of wheat crop. Linear regression analysis identified no significant linear regression equation. Blue and orange points represent experimental plots at Bhopal and Jabalpur, respectively.

Table 4. Mean yield levels for control and +K plots, as well as mean yield increase levels for rice harvested in Bhopal and Jagtial districts, and Raipur.

Treatment	Bhopal	Jagtial (Kharif)	Jagtial (Rabi)	Raipur
K_0 – Control (kg ha^{-1})	5,202	6,559	7,010	3,350
K_{40} (kg ha^{-1})	5,338	6,930	7,270	3,690
K_{80} (kg ha^{-1})	5,458	7,288	7,296	3,704
K_{FP} (kg ha^{-1})	4,820	6,624	7,091	3,611
Increase in K_{40}, absolute (kg ha^{-1})	136	371	259	340
Increase in K_{80}, absolute (kg ha^{-1})	255	728	286	354
Increase in K_{40}, relative (%)	3	6	4	10
Increase in K_{80}, relative (%)	5	11	4	11

K_{40} treatment, the yields at both locations are between the control and those at K_{80}. The difference between control yield and K_{80} yield was statistically verified to be significant at all locations.

Absolute yield increase

Mean yield levels across the treatments and farmers' practice fertilizer regime show a clear increase in yield as a result of K application at 40 kg ha^{-1}, and further higher increase when the K dose is doubled to 80 kg ha^{-1} (Fig. 15). This holds true for all locations and seasons. Furthermore, the fields that received fertilizer treatment according to farmers' previous practice all had lower yields than the fields with applied K. This was also statistically verified to be significant, with the exception of *rabi* rice in Jagtial where the same trend is clear, but not statistically verifiable with the studied number of replicates.

Looking at the distribution of absolute yield increase across the locations we see a uniform distribution of yield responses at all locations except Raipur, which had much lower yield variability resulting in most of the Raipur data points being grouped in the distribution graph (Fig. 16). The yield increase is linear with the exception of five fields that had much higher yield increase, resulting in overall R^2=0.9436. Comparing the response in K_{40} to that in the K_{80} treatment, the inconsistency is observed, with some plots even showing a negative response to 40 kg K ha^{-1}, while the same plots show very high responses in the K_{80} treatment (Fig. 16). This implies that the yields were also affected by factors that were not considered in this study, since such inconsistencies are extremely unlikely to be caused by the fertilizer regime.

The K response range to the MOP application at the K dose of 40 kg ha^{-1} ranged from -252 to 756 kg ha^{-1} in Bhopal, from -406 to 1,318 kg ha^{-1} in *kharif* season in Jagtial, 359 to 1,236 kg ha^{-1} in *rabi* season in Jagtial, and from 0 to 648 kg ha^{-1} in Raipur (Fig. 17). The average value in Bhopal was found not to be stable, with high standard error of the mean, and a large difference between median and the mean, signifying again the influence of external factors (Fig. 18A). At other locations, the mean values are more stable, with the mean being within the error interval of the mean. The response in Raipur was the most consistent and the most normally distributed (Fig. 17 and Fig. 18D).

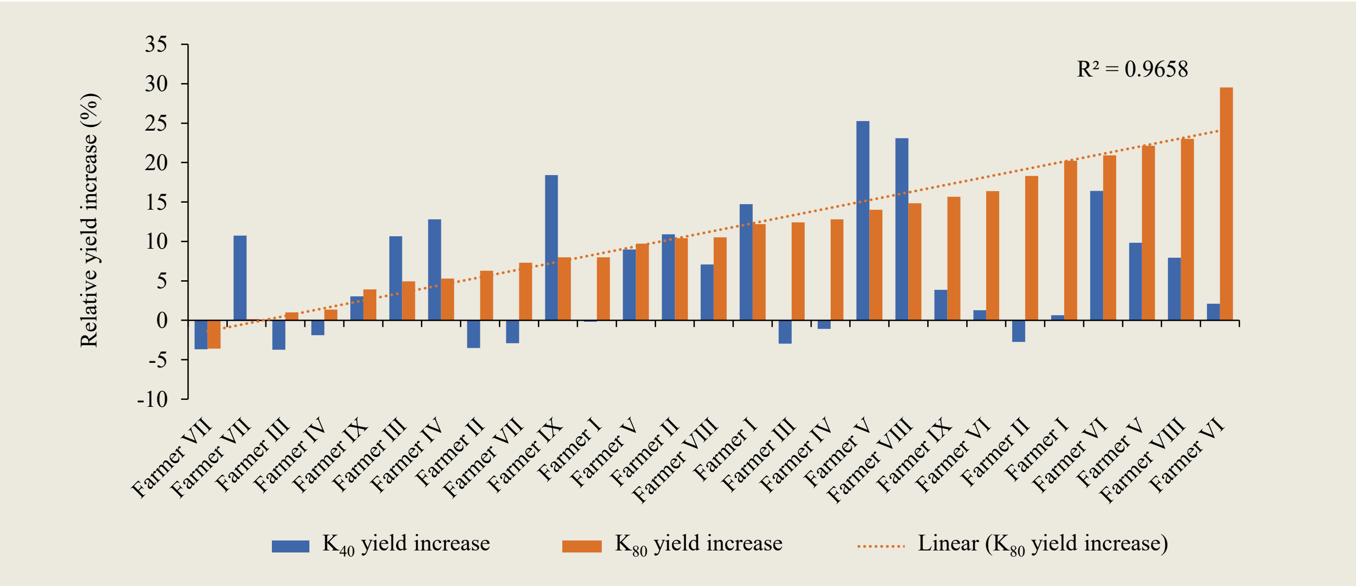


Fig. 11. Relative wheat yield increases in plots fertilized with MOP in comparison to control plots with no MOP fertilization in 27 plot pairs across Bhopal district and 9 farms harvested in the 2016-2018 period. The data is sorted according to the response in the K_{80} treatment. The orange line represents linear regression of K_{80} yield response.

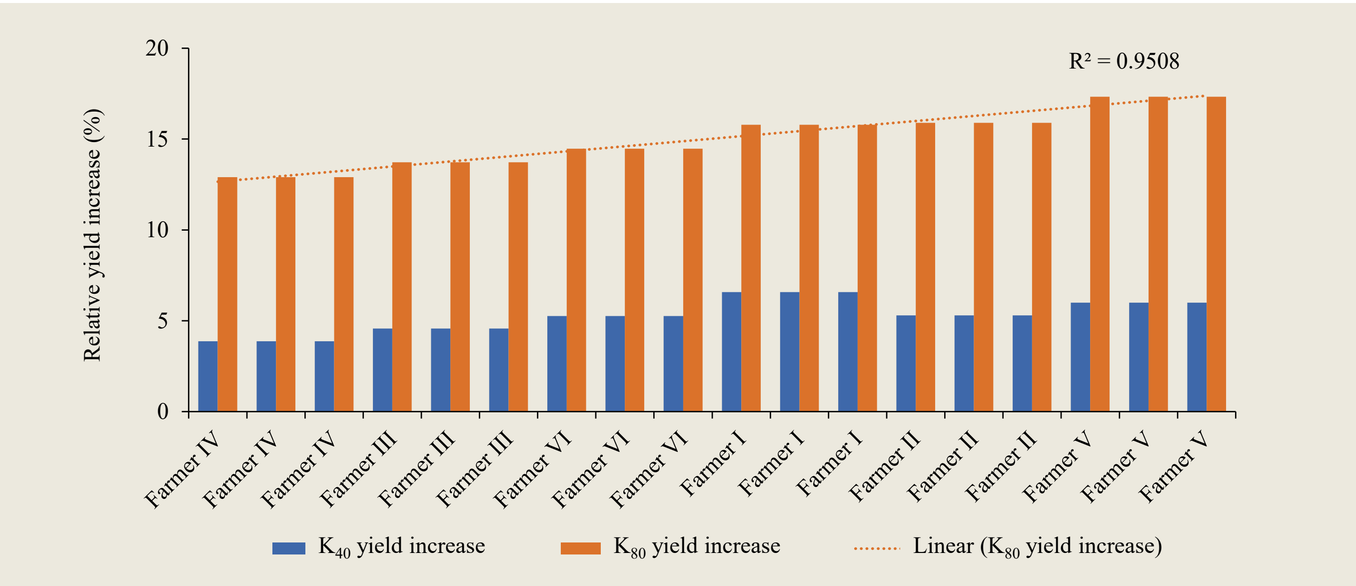


Fig. 12. Relative wheat yield increases in plots fertilized with MOP in comparison to control plots with no MOP fertilization in 18 plot pairs across Jabalpur district and 6 farms harvested in the 2016-2018 period. The data is sorted according to the response in K_{80} treatment. The orange line represents linear regression of K_{80} yield response.

In the K_{80} treatment, the yield response ranged from -220 to 893 kg ha^{-1} in Bhopal, -1 to 1,412 kg ha^{-1} in *kharif* season in Jagtial, -680 to 1,210 kg ha^{-1} in *rabi* season in Jagtial, and 0 to 835 in Raipur (Fig. 17). With the higher K dose, the average value in Bhopal was found to be more stable as indicated by much closer proximity of the mean and the median (Fig. 18). On the other hand, in Raipur, the mean value was less stable in K_{80} than in K_{40}, further pointing to inconsistencies and factors that are out of the scope of this study.

Looking at the plots of the relationship between control yield level and absolute yield increase, no patterns can be distinguished within one location, which indicates that the control yield level was not an influencing factor for absolute yield increase (Fig. 19).

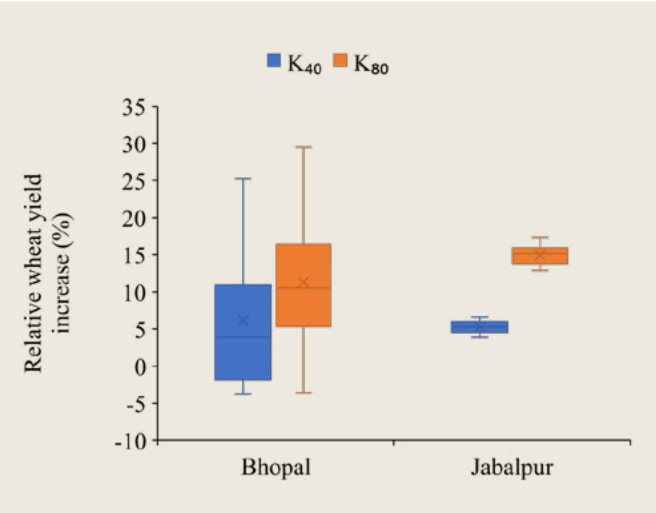


Fig. 13. Box plot diagram illustrates the distribution of the same data as Fig. 11 and Fig. 12. In the box plot, the middle line represents the median, the upper and lower edge of the box represent the 25th and the 75th percentiles, respectively. The mean is signified by the x-marker. The bars reach the maximum and minimum values.

The scatter plot again indicates the much more consistent response to K application in Raipur, which is represented by yellow points, and differences in control yields, which are discussed in detail in the section on "Effect of location and background fertilizer treatment" and presented in Fig. 23.

Relative yield increase

In relative terms, the application of 40 kg K ha^{-1} – added to the common fertilizer practice of urea, DAP and manure - gave rise to an average rice yield increase of 3%, 6%, 4%, and 10% at Bhopal, Jagtial *kharif* season, Jagtial *rabi* season, and Raipur, respectively (Table 4). This corresponded to an average benefit:cost ratio of 4:1 in terms of local MOP input costs and net profit increase, based on the 2016 report of the Fertilizer Association of India (Chanda *et al.*, 2016). This means that, for every rupee invested in fertilizer, 4 rupees are returned through the increased yields.

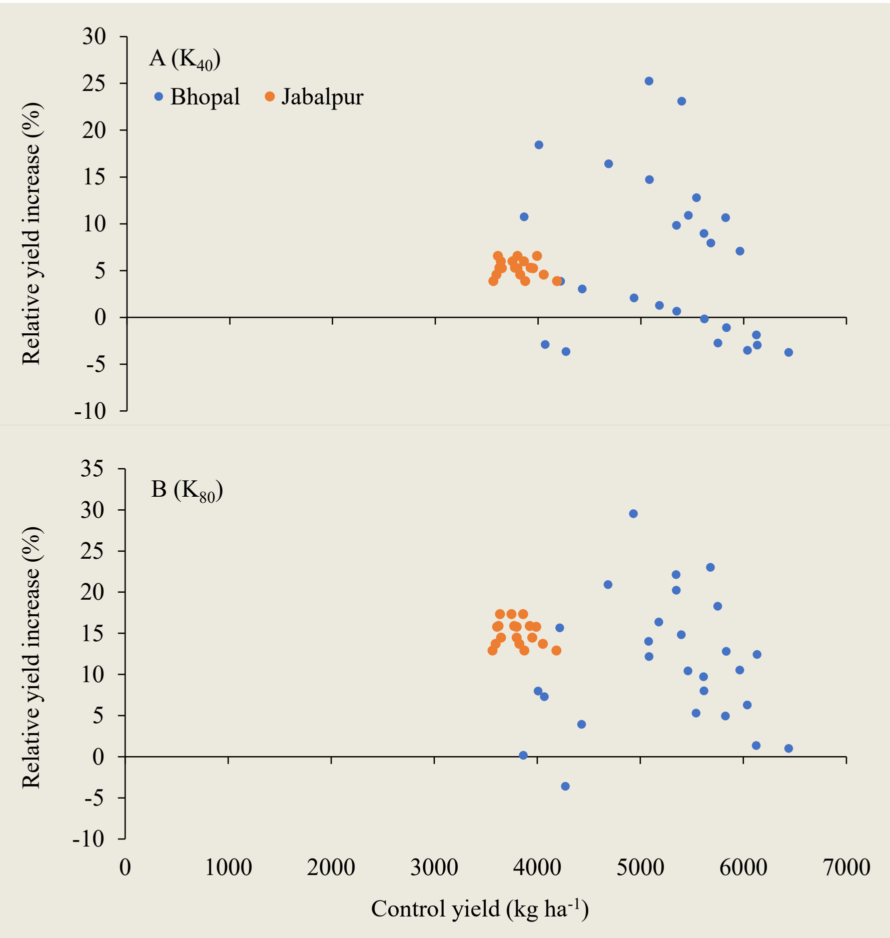


Fig. 14. Relationship of control yield and relative yield increase level. Linear regression analysis identified no significant linear regression equation. Blue and orange points represent experimental plots at Bhopal and Jabalpur, respectively.

The distribution of the relative yield increase has a similar pattern as the absolute yield increase, with even more linear distribution (R^2=0.9778) compared to the absolute increase (Fig. 20). Distribution of responses in Raipur and Bhopal are less evenly distributed than those in Jagtial.

At Bhopal, the yield increase response to the K_{40} application ranged from -4% to 14%, while in the K_{80} treatment the response ranged from -4 to 16% (Fig. 21). At Jagtial, the yield increase response of *kharif* rice to the K_{40} application ranged from 4% to 7%, while in K_{80} treatment, the response ranged from 0% to 23%. In the *rabi* season, relative response in K_{40} ranged from -5% to 20%, and from -9% to 18% in the K_{80} treatment. At Raipur, the relative response in K_{40} treatment ranged from 0% to 18%, while in K_{80} treatment it ranged from 0% to 25%.

Looking at the plots of the relationship between control yield level and relative yield increase, no patterns can be distinguished at any of the locations, which indicates that the control yield level was not an influencing factor for absolute yield increase (Fig. 22).

Effects of location and background fertilization

The experiments were performed at three locations, with varying levels of background fertilizer treatment, and possible microclimate differences that can affect the control yield. Fig. 23 shows the control yield level and background fertilizer amounts across three locations. The differences were statistically verified to be significantly different. The data implies that the varying nitrogen rates are responsible for the differences in control yield. Interestingly, the soil analysis shows that Raipur, which had the lowest control yield, had the lowest amount of nitrogen and P of the three locations (Table 1). Further, the amount of plant available P in Jagtial was the highest, and more than double that in Bhopal, which had the second highest P level. Considering the results of soil testing (Table 1), and applied amounts of N and P across three districts (Table 2 and Fig. 23), we can safely conclude that the background fertilization was not optimized to equalize the effects of N and P levels on the rice yields.

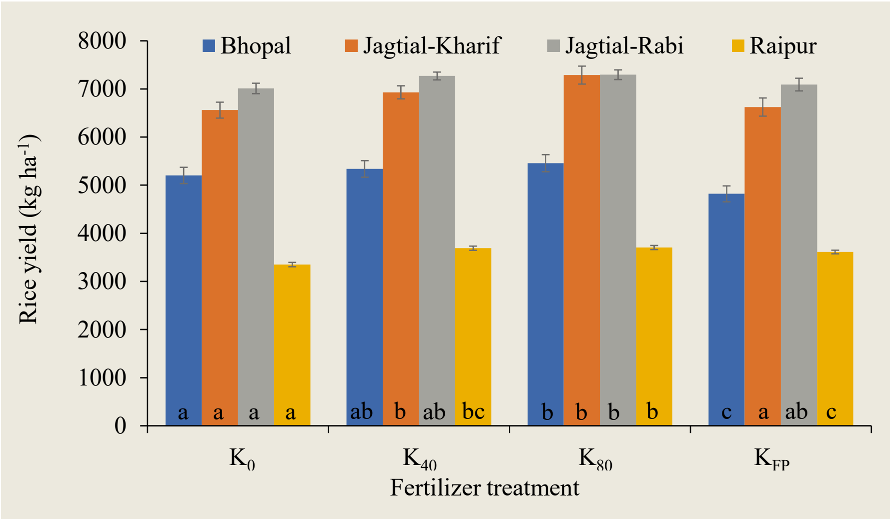


Fig. 15. Mean rice yield for control, two +K treatment plots, and plots with fertilizer regime according to the previous farmers' practice (K_{FP}), harvested in Bhopal, two seasons in Jagtial, and Raipur. The error bars signify the standard error of the mean. The differences between the treatments at each location/season were statistically evaluated using a t-test with α = 0.95 and are represented using the letter groupings displayed in the graph. The values with the same letter are not significantly different.

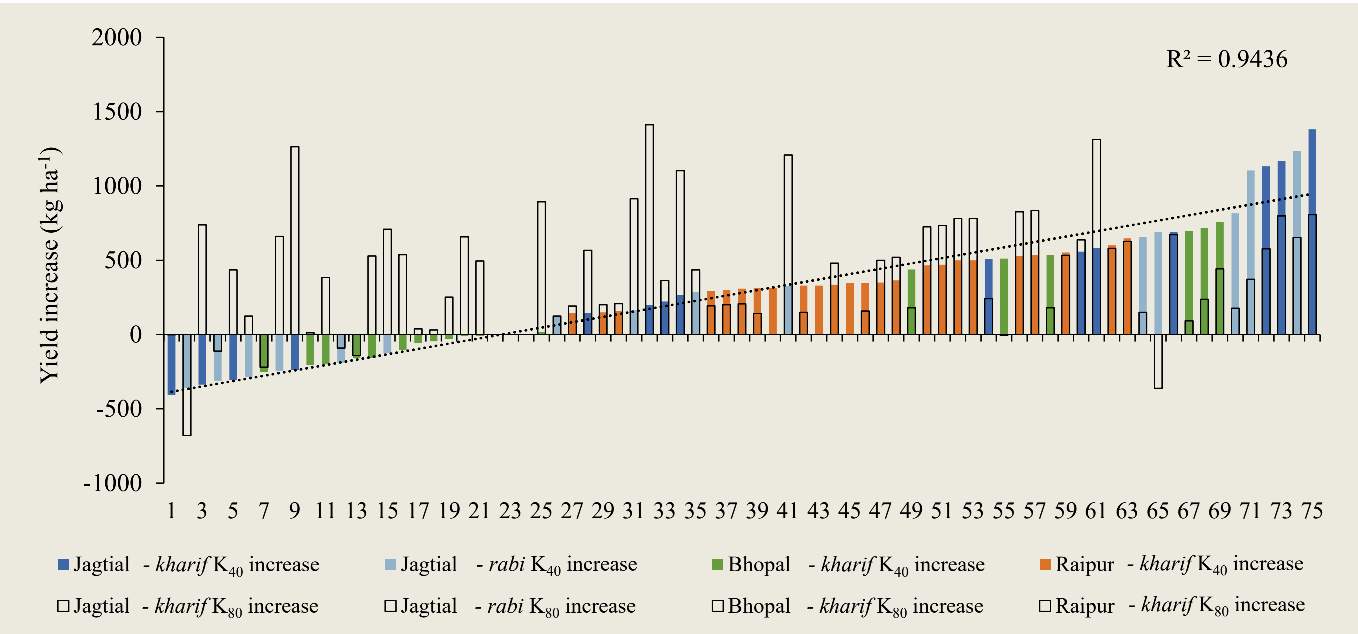


Fig. 16. Absolute rice yield increases in plots fertilized with MOP in comparison to control plots with no MOP fertilization in 75 plot pairs across three districts. The data is sorted according to the response in K_{40} treatment. Transparent outlined bars represent the absolute yield increase in K_{80} treatment at the same plot. Dotted line represents linear regression of K_{40} yield response.

Discussion

The results of this study clearly demonstrate the benefits of K-inclusive fertilizer regimes. The additional MOP resulted in a significant rise in yield levels. These results imply that the soils in the experimental locations have undergone nutrient depletion and therefore lack enough plant available K. The idea to disseminate MOP fertilizer application was thus shown to have a potential to increase wheat and rice productivity and profitability in M.P., Chhattisgarh and Telangana states. The average yield increase levels are moderate, but profitable nevertheless.

An average yield increase of 11-15% in wheat and 4-11% in rice reveals the importance and potential of K-inclusive

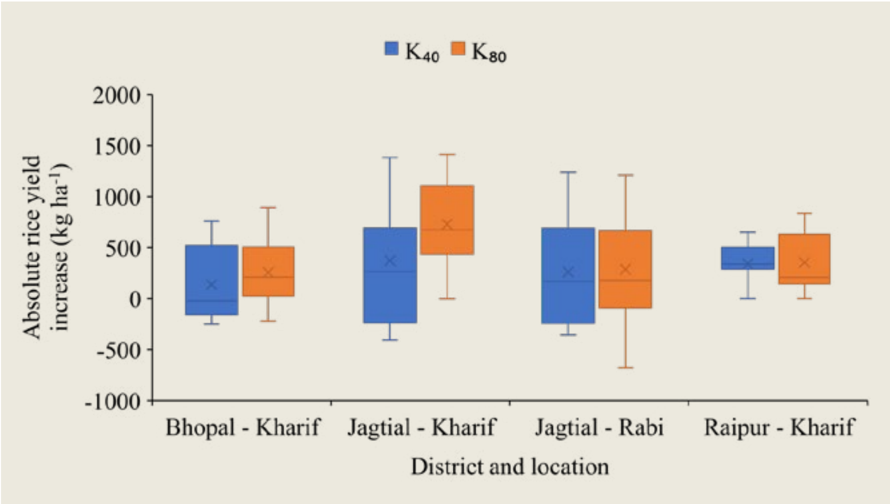
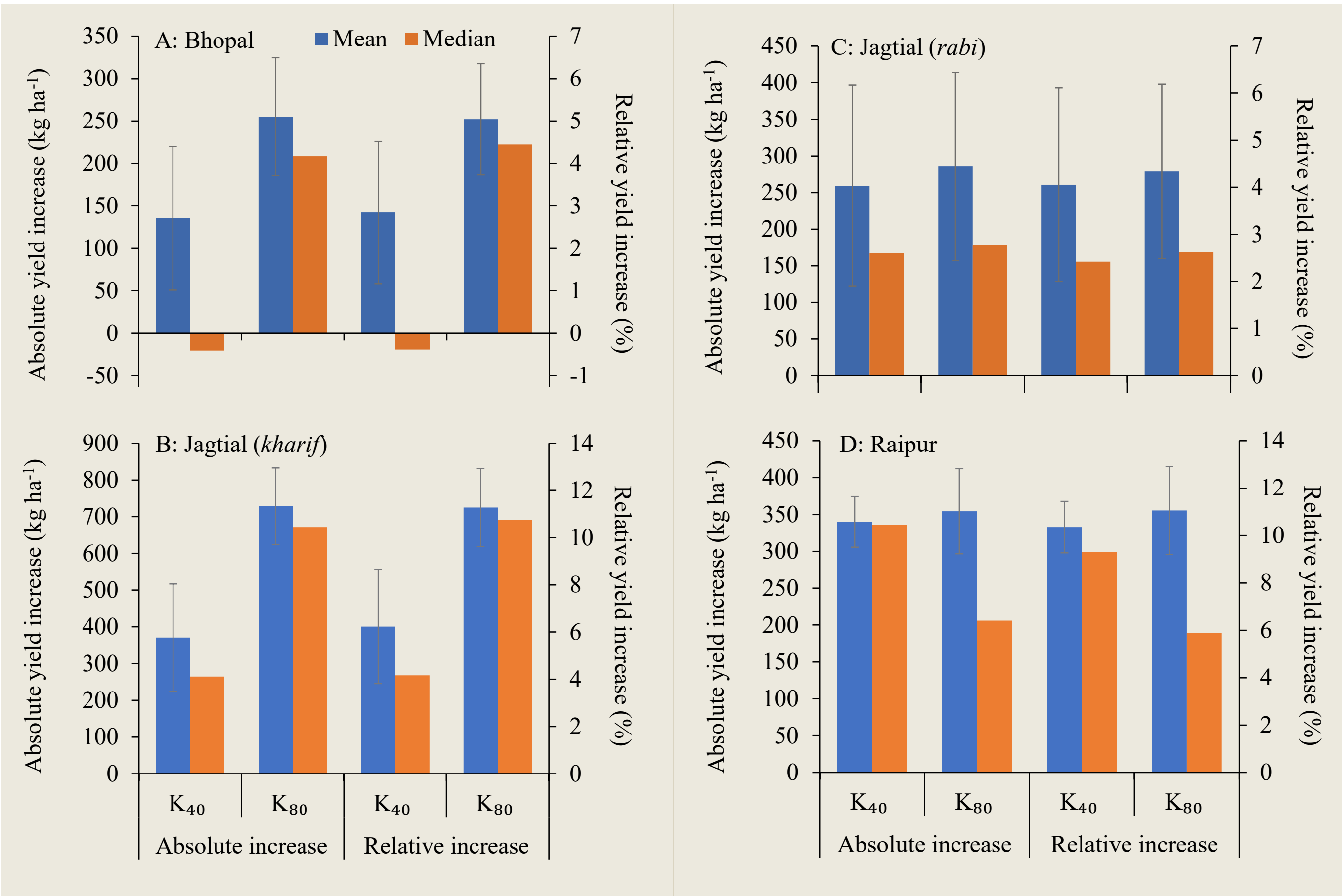


Fig. 17. Box plot diagram illustrates the distribution of the same data as Fig. 16. In the box plot, the middle line represents the median, the upper and lower edge of the box represent the 25th and the 75th percentiles respectively. The mean is signified by the x-marker. The bars reach the maximum and minimum values.



Figs. 18A-D. Absolute and relative yield increase, illustrated both as mean and median, for rice harvested in Bhopal, two seasons at Jagtial, and in Raipur. The error bars signify the standard error of the mean.

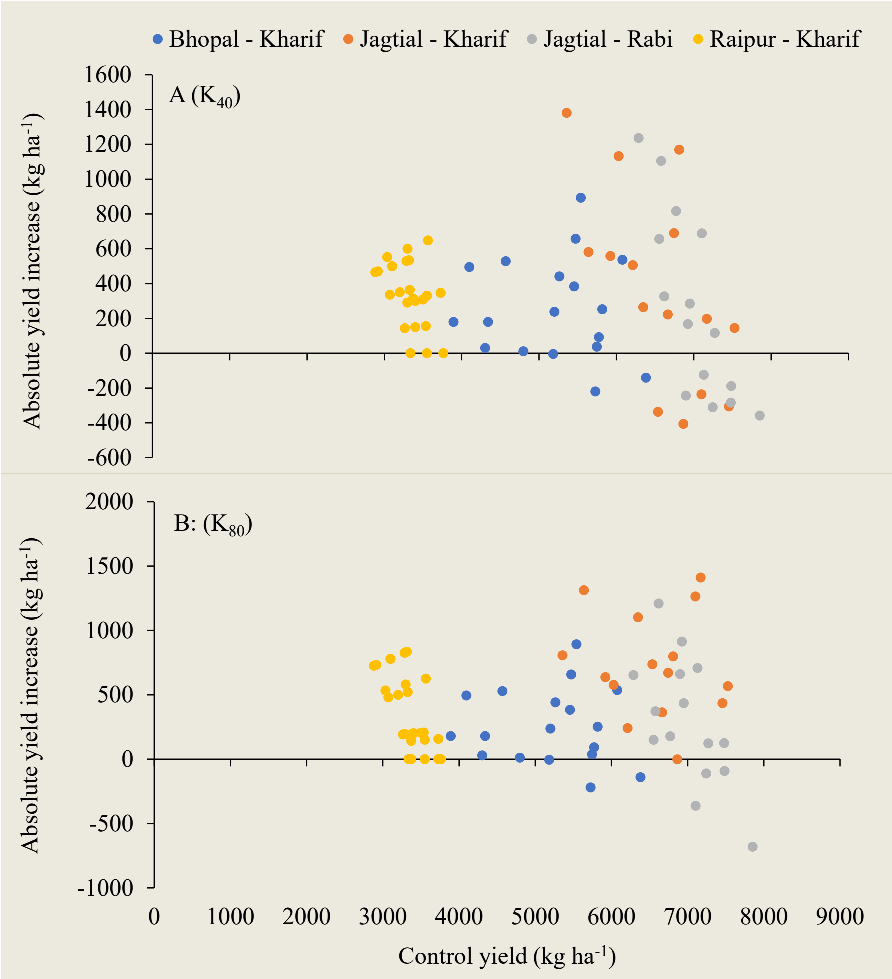


Fig. 19. Absolute yield increase in (A) K_{40} and (B) K_{80} treatments as a function of the control yield of rice crop. Linear regression analysis identified no significant linear regression equation. Different locations are represented by different colors according to the legend.

fertilizer regimes, although it is not the only constraint in wheat and rice production in the states under study, and India as a whole. It is clear that crop demand for K is higher than the available amounts in the soil. Cost to benefit analysis further supports that there is a quantifiable benefit in including MOP fertilizers even without changing any other production aspect.

The results also highlight that other external factors can have a great impact on yield interactions with the benefits of fertilization. It is important to keep in mind that the trials were set up on farmer-managed fields, and not in the highly controlled, researcher-managed conditions, which inherently adds unpredictable, but very real sources of variation. The benefit of this experimental design is that the results are more representative of the scenario an average farmer in India might observe upon applying MOP.

The variation in response shows there are cases where MOP application can result in only a minor yield increase in wheat and rice. This is to be expected considering the variability of available K in the soil between locations, as well as other limiting factors that were out of the

Impact of K (MOP) application on growth and density of rice panicles at Khamkheda village, Bhopal district, Madhya Pradesh, India. Photos by the authors.

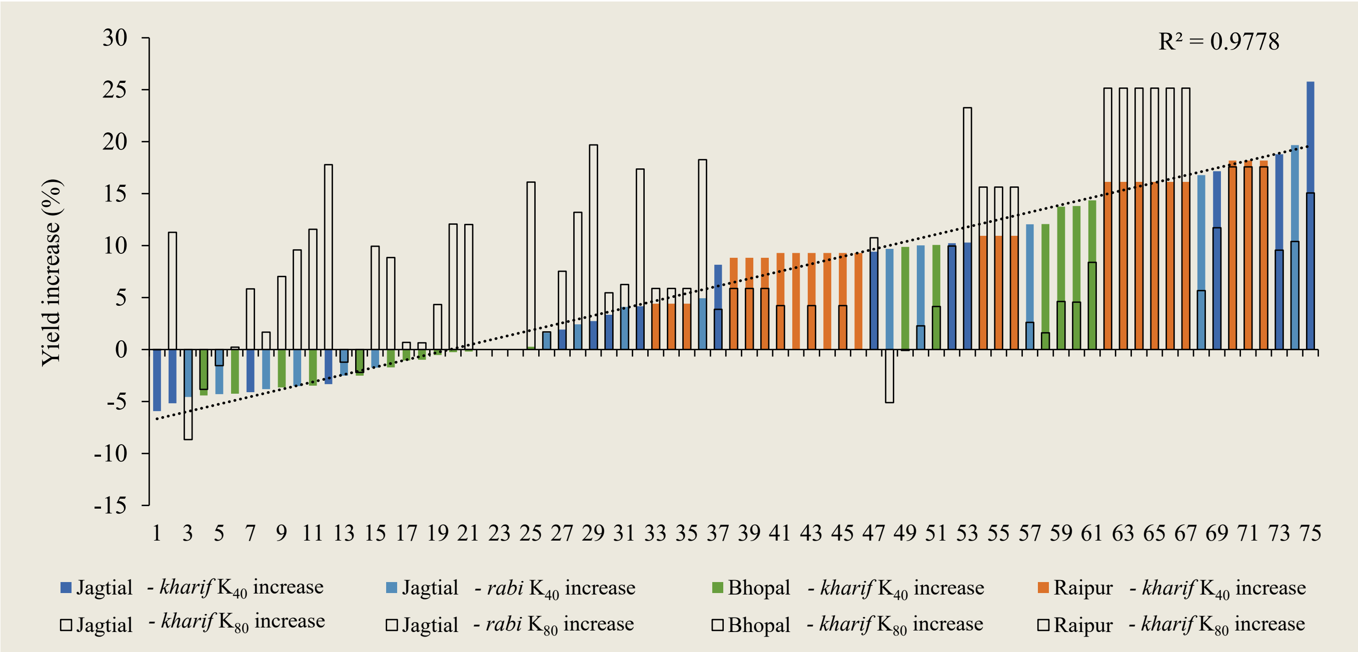


Fig. 20. Relative rice yield increases in plots fertilized with MOP in comparison to control plots with no MOP fertilization in 75 plot pairs across three districts. The data is sorted according to the response in K_{40} treatment. Transparent outlined bars represent the relative yield increase in K_{80} treatment at the same plot. Dotted line represents linear regression of K_{40} yield response.

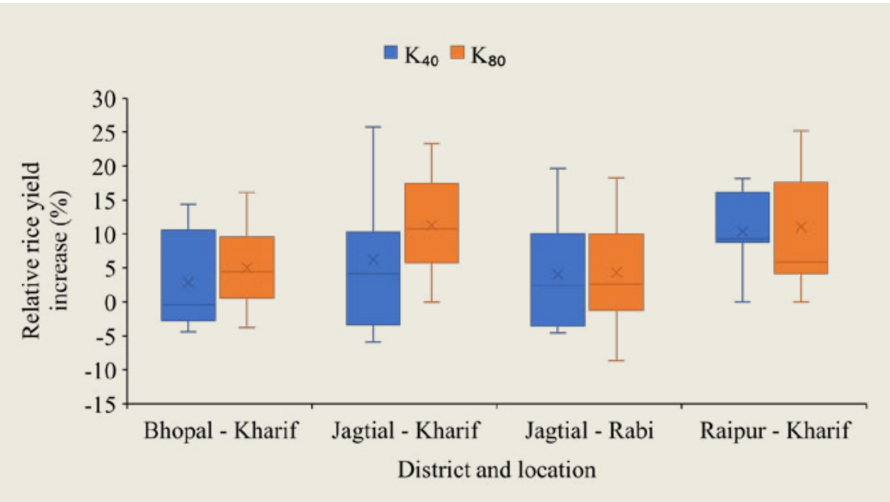


Fig. 21. Box plot diagram illustrates the distribution of the same data as in Fig. 20. In the box plot, the middle line represents the median, the upper and lower edge of the box represent the 25th and the 75th percentiles, respectively. The mean is signified by the x-marker. The bars reach the maximum and minimum values.

scope of this study, such as characteristics and quality of the seed material, crop protection measures, and availability of other nutrients. The seemingly negative response to K application in certain plots shows that other factors in the field can have much stronger impact on the yield at the end of the season than the fertilizers applied. We can safely conclude this since it is very unlikely that K application decreased the yields. This is further confirmed by the observed negative response in K_{40} treatment, but very high positive response in K_{80} treatment in the same field. There were also examples of the opposite situation. If K application was the cause of decreased yields, higher doses would be expected to proportionally decrease the yield, and the control plot would have the highest yield, which was not observed.

Despite variation, the linear distribution trend of the yield increase response from MOP suggests a moderate average natural variability of K depletion within the response range. The specifics of this trend provide evidence that the response patterns are due to the regional specific soil K status. Regardless, the diversity in yields for both control and '+K treatment', require a further investigation before any final recommendations can be disseminated.

Differences between the districts and seasons

The difference in K-response between the districts can have several explanations, such as difference in geography, practices, and levels of K depletion. We know that

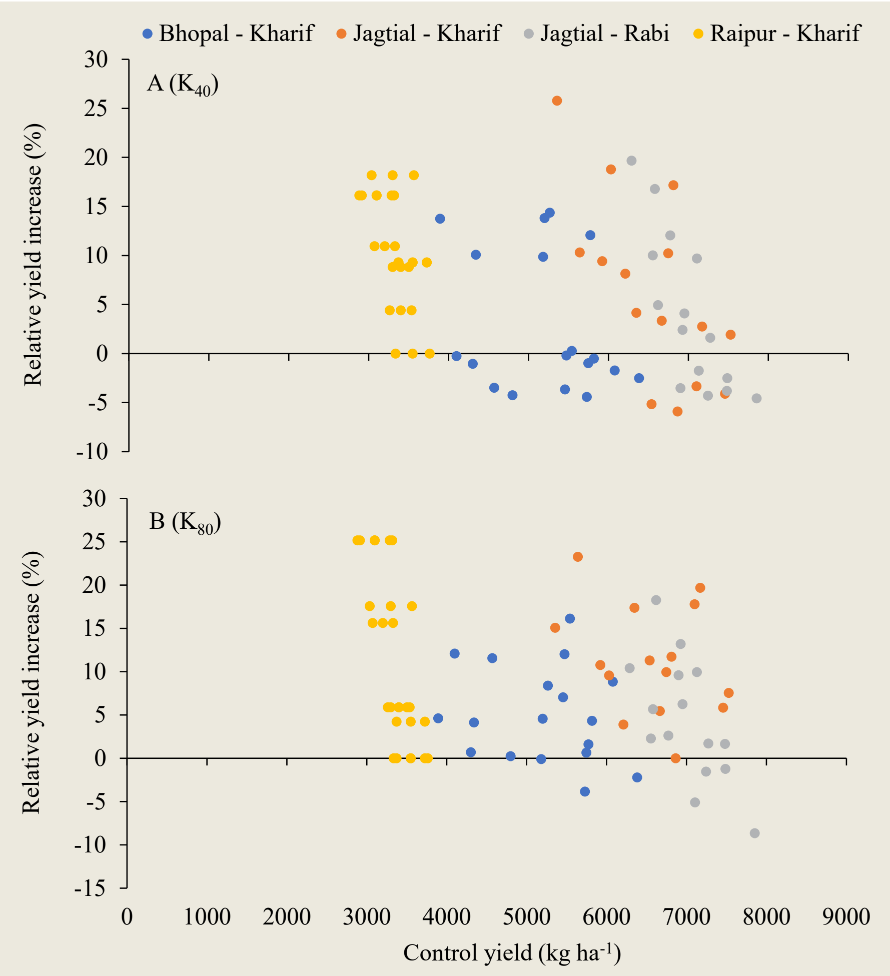


Fig. 22. Relative yield increase in (A) K_{40} treatment and (B) K_{80} as a function of the control yield of rice crop. Linear regression analysis identified no significant linear regression equation. Different locations are represented by different colors according to the legend.

there are different factors between the districts under study that affect yield levels, such as microclimate and fertilizer regimes etc. Therefore, these factors need to be disseminated.

Control yield levels and MOP response

Before we go into the details of different management practices, there is need to analyze the correlation between control yield levels and MOP response. We can confidently exclude the control yield level as a major governing factor for differences in yield increases between the districts for both crops, as the differences in control yields were not reflected in the yield increases (Fig. 10, Fig. 14, Fig. 19, and Fig. 22).

Effects of the different fertilizer regimes and seasonal variation

In the wheat experiment plots, a statistically significant difference in control and both K treatments was observed between two districts. The initial status of N at both locations was similar, however, levels of plant available P in Bhopal were higher by 70%. Yet, the applied amount of P fertilizer was identical at both locations, which points to P as a potential yield constraint at Jabalpur. Interestingly, the soil K level did not correlate with the observed yield differences between two locations. Finally, differences in levels of other factors, such as microclimate differences, could have had an additional influence on observed yields.

In the rice experiment plots, all three districts had statistically significant difference in control yields (Fig. 23). This is not very surprising considering significantly different background fertilizer levels and different soil nutrient status, especially nitrogen. It can be assumed that background fertilizer amounts were not optimal. The effect of plant available K in the soil was evaluated, and control yield, and absolute and relative yield increase was evaluated based on the soil analysis, and no identifiable effects could be determined. This further reinforces the theory that differences in N and P levels were affecting the yields. Additionally, regional microclimate could be another influencing factor.

Difference in distribution

In wheat, the distribution was very uniform and linear at Jabalpur, in both K_{40} and K_{80} treatments. Furthermore, the control yield was consistently the lowest, K_{40} treatment increased the yield by 5% on average, and doubling of applied K to 80 kg ha^{-1} increased the yield by an additional 10% (Fig. 12). This represents a very typical crop response to K on soils with strong K depletion.

The wheat response to applied K at Bhopal was linearly distributed and positive, which implies that the soil available K is lower than the plant demand. Compared to Jabalpur, on the other hand, response was more variable and inconsistent at the lower K dose in K_{40} treatment. This again shows that improved fertilizer practices, while providing direct productivity increase and economic benefits will not overcome other constraints and factors in all conditions. Production can still be affected by the climate, management practices, pest and disease pressure and other factors that were not controlled in this field study.

A similar situation is observed in rice experimental plots. While the K application had productivity and economic benefits across all locations and seasons, the distribution of responses was

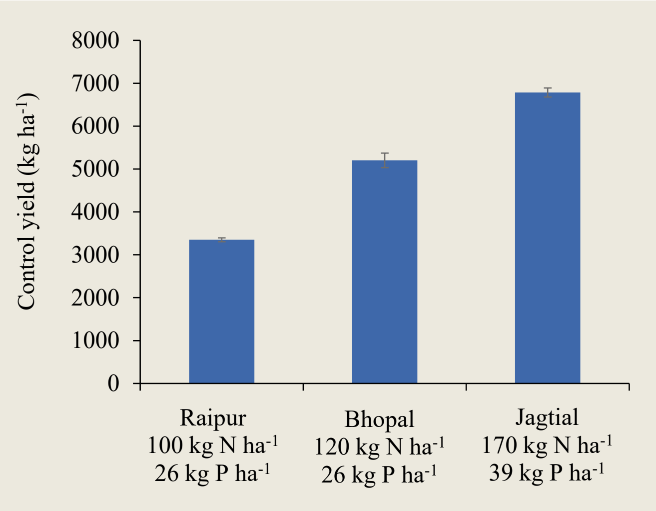


Fig. 23. Control rice yields across three locations. Error bars represent standard error of the mean. Amounts of applied background N and P are shown for each location.

not perfectly even at all locations. Responses in the Bhopal and Raipur districts were not evenly distributed, and the distribution was skewed from the expected normal distribution as indicated by the discrepancy between the median and the mean. Influencing factors remain elusive to this study and are here to show that in real-world environments the response to any treatment is under the influence of many external factors. Lower yields in K_{40} and K_{80} treatments compared to the control are normally considered as outliers in fertilizer experiments since such a response is caused by some other external factors. However, this study shows that, even without excluding these anomalies from the data, the benefits of K application are still clear and very significant.

Reasonable predictions and statistical inferences

The statistical inference drawn from the data is that if a wheat farmer in M.P. would apply MOP at 80 kg ha^{-1}, he would likely make a yield increase of about 294 to 848 kg ha^{-1}, or 5-16%. Given that the average B:C ratio was 5:1, this implies a profitable outcome, even if the MOP cost and the price of wheat would change significantly. Statistically this is very convincing.

In rice production, we can infer that MOP application at a rate of 80 kg ha^{-1} would provide a yield increase of up to 1,103 kg ha^{-1}, or up to 17%, with a B:C ratio of 3:1. Interestingly, applying K at a lower rate of 40 kg ha^{-1}, the farmer would obtain slightly lower yield increase (up to 689 kg ha^{-1}), but at a higher B:C ratio of 4:1 on average. This implies that at a K dose of 80 kg ha^{-1}, we are reaching the point of diminishing returns for the soil in question. Therefore, it can be concluded that the optimal amount lies in between the two levels tested in this study.

However, there is no way to accurately predict crop response to MOP application at a given location with certainty, other than by conducting comprehensive soil and K crop response tests. A relevant approach can then be tailored accordingly and include a whole package of solutions. On the other hand, the average values of wheat and rice yield increase within predictable ranges provides a high probability for the overwhelming majority of the farmers to obtain significantly higher yields as a result of following the MOP application practices in these demo plot trials. At the same time, to finalize nutrient balances at field scale by means of comprehensive soil testing would likely be unfeasible for smallholder farmers. Instead, raising the awareness of balanced fertilizer use and correct suggestions of MOP application rates, based on empirically verified large-scale trials, could gradually improve existing practices within the farming system of local smallholders. Then the fine tuning of dosage and nutrient balancing at local field level would be cost and resource effective and could provide a clear, simple and straight-forward path to productivity, profitability as well as achieve sustainability at a regional scale.

Conclusions

MOP application, in addition to commonly applied N and P fertilizer, had an unequivocal effect, significantly increasing wheat and rice yields resulting in higher profitability.

The soil status of plant available K is moderately lower than plant demand in order to meet the need for optimal production. Therefore, K-inclusive fertilizer regimes are necessary in order to improve agricultural practices and optimize yields. These results strongly indicate a critical need for the development of K fertilization practices aimed at increasing yields and profit in M.P., Chhattisgarh, and Telangana. In the short-term, the K_{40} dose successfully employed in this study should be recommended to farmers in the state, as a transient means to obtain higher yields and profits in two of the most important crops in India.

Nevertheless, the variation in the MOP response gives reason to evaluate a higher MOP dose in wheat, to study the optimal K dose for rice at a greater resolution, as well as to investigate ways to fine-tune the recommendations at a local field scale. Therefore, further research is recommended in order to determine appropriate MOP doses and application practices to ensure balanced crop nutrition, optimal fertilizer use, sufficient K availability whenever needed, and sustainable soil fertility.

Acknowledgement

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Singh, M., R.H. Wanjari, U. Kumar, and S.K. Chaudhari. 2019. AICRP on Long-Term Fertilizer Experiments: Salient Achievements and Future Directions. Indian Journal of Fertilisers 15(4):356-372.

The paper "Wheat and Rice Response to Potassium in Vertisols: Results from 120 Plot Pairs Across Bhopal, Jagtial, Jabalpur, and Raipur Districts, India" also appears on the IPI website.

Events

IPI event

November 2019

The 13th IPI-CAU-ISSAS International Symposium will take place in Kunming, China, 6-8 November 2019. This symposium on "Potash and Polyhalite: Potassium, Sulphur, Magnesium and Calcium for Efficient Balanced Plant Nutrition" is organized by International Potash Institute (IPI), China Agricultural University (CAU), Institute of Soil Science of Chinese Academy Science (ISSAS), and co-organized by National Agro-Tech Extension and Service Center (NATESC) and China Inorganic Salts Industry Association (CISIA).

It will address the issues related to the role and benefits of potash and polyhalite fertilizers for Chinese agriculture, including soil fertility, plant nutrition, efficient use of fertilizers and balanced fertilization practices.

This symposium will be of interest to soil and plant nutrition scientists, agronomists, and extension officers from universities and research organizations, government offices, and agribusinesses who share an interest in improving food production and quality.

The symposium will be chaired by Prof. Fusuo Zhang, academician of the Chinese Academy of Engineering and Director of the National Institute of Green Agricultural Development at China Agricultural University.

Main Themes:

- Potassium Management in Different Cropping Systems
- Polyhalite as a Multi-Nutrient Fertilizer
- Effect of Polyhalite Application on the Yield and Quality of Different Crops
- Role of S, Mg and Ca Nutrients in Plant Nutrition
- Potassium and Biotic and Abiotic Stresses
- Loss of Soil Fertility and Stagnation of Agricultural Production
- Nutrient Mining and Input-Output Balances at Farm and Regional Levels
- Crop Management Techniques for Efficient Fertilization

The symposium speakers:

- Surinder K. Bansal, Potash Research Institute of India, India
- Alberto C. de Campos Bernardi, Brazilian Agricultural Research Corporation (Embrapa), Brazil
- Michael Castellano, Iowa State University, USA
- Fang Chen, Chinese Academy of Sciences, Wuhan Botanical Garden, China
- Xinping Chen, Southwest University, Chongqing, China
- Zhenling Cui, China Agricultural University, Beijing, China
- Mingshou Fan, Inner Mongolia Agricultural University, Hohhot, China
- Shiwei Guo, Nanjing Agricultural University, Nanjing, China
- Ping He, Chinese Agricultrual Academy of Sciences, China
- Patricia Imas, IPI, Switzerland
- Chunjian Li, China Agricultural University, Beijing, China
- Guohua Li, ICL, China
- Ti Li, Sichuan Agricultural University, China
- Ruixian Liu, Jiangsu Academy of Agricultural Sciences, Nanjing, China
- Jianwei Lu, Huazhong Agricultural University, Wuhan, China
- Hillel Magen, IPI, Switzerland
- Guohua Mi, China Agricultural University, Beijing, China
- Jiwan P. Palta, University of Wisconsin, USA
- Tao Ren, Huazhong Agricultural University, Wuhan, China
- Jianyun Ruan, Tea Research Institute, Chinese Academy of Sciences, Hangzhou, China
- Mollie Sacks, Ministry of Agriculture, Israel
- Xiaojun Shi, Southwest University, Chongqing, China
- Guangyu Sun, Northwest A&F University, China
- Trinh Cong Tu, Central Highlands Soil, Fertilizer and Environmental Research Center, Vietnam
- Fabio Vale, IPI, Switzerland
- Huoyan Wang, Institute of Soil Science, Chinese Academy of Sciences, Nanjing, China
- Min Wang, Nanjing Agricultural University, Nanjing, China
- Xiaofeng Wang, China Inorganic Salts Industry Association, China
- Yi Wang, China Agricultural University, Beijing, China
- Zhengyin Wang, Southwest University, Chongqing, China
- Lilian Wanjiru Mbuthia, IPI, Switzerland
- Philip J. White, The James Hutton Institute, UK
- Zhijian Wu, Chinese Academy of Sciences Qinghai Institute of Salt Lakes, China
- Guohua Xu, Nanjing Agricultural University, Nanjing, China
- Minggang Xu, Institute of South Asian Tropical Crops, Chinese Academy of Tropical Agricultural Sciences, China
- Tian Youguo, NATESC, China
- Baige Zhang, Guangdong Academy of Sciences, Guangdong, China, Southwest University, Chongqing, China
- Chaochun Zhang, China Agricultural University, Beijing, China

Events (cont.)

- Fusuo Zhang, Chinese Academy of Engineering, College of Resources and Environmental Sciences, CAU, China
- Hongyan Zhang, China Agricultural University, Beijing, China
- Huimin Zhang, Chinese Agricultural Academy of Sciences, China

For more information and updates please go to the symposium website https://events.ipipotash.org/ or contact IPI's Coordinator for China, Mr. Eldad Sokolowski (eldad.sokolowski@icl-group.com) or IPI's Scientific and Communications Coordinator, Dr. Patricia Imas (patricia.imas@icl-group.com).

Publications

NEW: IPI funded research

Potassium Fractions and Availability for Chickpea (*Cicer arietinum*) in Vertisols of North-West Ethiopia

Misskire, Y., T. Mamo, A.M Taddesse, and U. Yermiyahu. 2019. South African Journal of Plant and Soil, DOI: 10.1080/02571862.2019.1579003

Abstract: For a critical appraisal of the supplying power of potassium (K) and to predict bioavailable K, it is necessary to have knowledge on the fractions of K and evaluate soil test methods for plant nutrition. This research aimed to assess the forms of K and select a suitable extractant for chickpea (*Cicer arietinum* L.) nutrition on Vertisols of East Gojjam, north-west Ethiopia. Potassium fractions and bioavailable K extracted by chemical solutions was measured using flame photometry. The mineralogy of Vertisols was assessed by X-ray diffraction. The results showed that the fractions of K were significantly correlated to each other and regression analysis showed that 97.6% of the variability of NH_4OAc-K was accounted by the HNO_3-K and total K fractions, signifying their existence in dynamic equilibrium. The forms of K were correlated to K uptake by chickpea, suggesting the contribution of the fractions of K to plant nutrition. The high level of K in each form was associated with the illite-smectite clay mineral. The availability of K by ammonium bicarbonate-DTPA was best predicted ($R^2 = 0.61$, $p < 0.05$) by chickpea uptake in comparison with Mehlich 3 and NH_4OAc ($R^2 = 0.48$ and 0.47, respectively). The weaker prediction of NH_4OAc-K may be due to the presence of high fixing clays. Further research is necessary on a wide variety of soils and crop types to verify this result and select a suitable extractant for crops in local conditions.

Publications by the PDA

Potassium for the Soil and Crop: The Importance of Getting it Right

Forrestal, P.J., M. Plunkett, C. Redmond, and M. Bourke.
POTASH News, May 2019

Crops including spring barley require high levels of potassium (K) to support yield, often at similar levels to nitrogen (N). Potassium has traditionally received much less focus compared with nitrogen. Nevertheless, K can play an important role in improving nitrogen use efficiency (NUE) bringing environmental benefits in addition to yield, plant vigour and lodging resistance benefits. A recent Teagasc trial showed that application of K fertiliser increased NUE from a low of 31% where the soil K was low and no K was applied to 85% at the highest K application rate on the same soil (Forrestal *et al.*, unpublished). 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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Follow our Facebook on: https://www.facebook.com/IPIpotash?sk=wall

Effects of *Ascophyllum Nodosum* Seaweed Extracts on Lettuce Growth, Physiology and Fresh-Cut Salad Storage under Potassium Deficiency

Antonios Chrysargyris, Panayiota Xylia, Myria Anastasiou, Iakovos Pantelides, and Nikos Tzortzakis. 2018. J. Science of Food and Agriculture 98(15):5861-5872.

Background: Potassium (K) deficiency in leafy vegetables such as lettuce is a major concern regarding quality. Seaweed (SW) extracts, as biostimulants, are biodegradable materials and have become increasingly popular as they are reported to enhance crop growth and yield.
Results: In order to overcome K deficiencies (i.e. 375 vs 125 mg L^{-1}), alternative foliar applications with extracts of *Ascophyllum nodosum* SW or K were examined using lettuce plants which were grown hydroponically. Potassium deficiency (at 125 mg

L^{-1}) reduced plant biomass, photosynthetic rate, leaf stomatal conductance, lettuce potassium content and tissue antioxidant capacity as compared with the higher K level (375 mg L^{-1}). Application of SW increased the relative growth of lettuce in the low-K treatment. The K level and/or SW application altered the plant's enzyme protective activity (superoxide dismutase, SOD; catalase, CAT; peroxidase, POD) against oxidative stress and hydrogen peroxide (H_2O_2) production. Spray applications of SW mitigated the effects of K deficiency on indicators of enzyme activity and plant damage, back to levels of high K content (375 mg L^{-1}). The high K level, but also SW application, increased the antioxidant activity of the processed lettuce before storage. Foliar application of the SW extract increased the quality of cut lettuce grown in 125 mg L^{-1} K conditions by reducing the rate of respiration and increasing consumer preference.
Conclusion: The SW application could alter the detrimental effects of K deficiency during lettuce growth and storage of processed products.

Co-Incorporation of Rice Straw and Green Manure Benefits Rice Yield and Nutrient Uptake

Lu Yang, Xing Zhou, Yulin Liao, Yanhong Lu, Jun Nie, and Weidong Cao. 2019. Crop Sci. 5(2):749-759. DOI:10.2135/cropsci2018.07.0427.

Abstract: Rice (*Oryza sativa* L.) straw is commonly incorporated into paddy soil after harvest, although it is not fully understood how the straw return strategy and its co-incorporation with legumes affect soil productivity and rice performance. A 5-yr experiment was conducted in a rice-rice-fallow or rice-rice-Chinese milk vetch (Mv, *Astragalus sinicus* L.) rotation in South China. Six treatments were included (i) a control with no fertilization and residue return, (ii) 100% of fertilizer recommendation (F_{100}), (iii) 80% of F_{100} plus conventional return of rice straw (F_{80}Rs), (iv) F_{80} plus Mv planting and incorporation (F_{80}Mv), (v) co-incorporation of F_{80}Rs and F_{80}Mv (F_{80}RsMv), (vi) similar to F_{80}RsMv except late rice straw was retained as high stubble (~35 cm, F_{80}RhMv). The results showed that, under reduced inorganic fertilizer input, grain yields in treatments with straw and/or Mv return were similar with those of F_{100}. However, N uptake in early and late rice markedly increased by 8 to 14% and 30 to 53% in the co-incorporation treatment F_{80}RsMv compared with F_{100}, respectively, as well as in the F_{80}RhMv treatment for late rice. Significantly greater fertilizer use efficiency was obtained in the co-incorporation practices. Although negative cumulative effects were observed for soil organic matter, total N, and available N after 5-yr rotation, the magnitude of decline in the co-incorporation treatments was much smaller than in others. Soil available P and K were accumulated in co-incorporation practice, whereas pH was less affected. Overall, the study suggested that the combination of rice straw and leguminous green manure is a promising practice to produce more grain yield with less fertilizer inputs in subtropical double-rice production.

Regulation of K^+ Nutrition in Plants

Ragel, P., N. Raddatz, E.O. Leidi, F.J. Quintero, and J.M. Pardo 2019. 2019. Front. Plant Sci. DOI: https://doi.org/10.3389/fpls.2019.00281.

Abstract: Modern agriculture relies on mineral fertilization. Unlike other major macronutrients, potassium (K^+) is not incorporated into organic matter but remains as soluble ion in the cell sap contributing up to 10% of the dry organic matter. Consequently, K^+ constitutes a chief osmoticum to drive cellular expansion and organ movements, such as stomata aperture. Moreover, K^+ transport is critical for the control of cytoplasmic and luminal pH in endosomes, regulation of membrane potential, and enzyme activity. Not surprisingly, plants have evolved a large ensemble of K^+ transporters with defined functions in nutrient uptake by roots, storage in vacuoles, and ion translocation between tissues and organs. This review describes critical transport proteins governing K^+nutrition, their regulation, and coordinated activity, and summarizes our current understanding of signaling pathways activated by K^+ starvation.

Wheat Grain Yield and Grain-Nitrogen Relationships as Affected by N, P, and K Fertilization: A Synthesis of Long-Term Experiments

Lollato, R.P., B.M. Figueiredo, J.S. Dhillon, D.B. Arnall, and W.R. Raun. 2019. Field Crops Research 236:42-57. DOI: https://doi.org/10.1016/j.fcr.2019.03.005.

Abstract: Nutrient management can reduce crop yield gaps, but available literature is mostly restricted to studies limited in time, geography, or in the number of nutrients evaluated. Our objective was to synthesize long-term experiments evaluating wheat (*Triticum aestivum* L.) yield and grain-N concentration (GNC) response to N, P, and K fertilizer rates and their interactions. We used data from three long-term (1966-2016) experiments conducted in Oklahoma (USA) comprising 155 site-years for yield (n = 8035) and 90 site-years for GNC (n = 4580). The last year of the experiments was the baseline to de-trend yield and GNC data. We first explored relationships between grain yield and GNC, grain N removal, apparent recovery of applied N in the grain (N recovery), and N-use efficiency (NUE) as affected by the presence and rate of N, P, and K across the entire dataset. Then, we subdivided the dataset into yield-environments based on the different data quartiles, and analyzed it using descriptive statistics, multi-level modeling, differences from the control, and conditional inference trees. Our main findings were: i) wheat yield was negatively related to GNC, but positively associated with N

removal, N recovery, and NUE. ii) The co-application of P and, to a lesser extent, K, increased N removal and NUE but decreased GNC. iii) The proportion of variability in yield and GNC explained by fertilizer management increased with an increase in yield-environment. iv) Wheat yield response to N and to P were typically quadratic, although response to P was restricted to high yielding environments. v) Wheat GNC increased linearly with increases in N rate, but decreased with increases in P and K rate. vi) Conditional inference trees suggested that the co-application of P and K improved yields but decreased GNC. The co-application of P and K can increased wheat yield, N removal, and NUE, but the increases in yield were greater than those in N removal, thus decreasing GNC.

Nutrient Flows and Balances in Intensively Managed Vegetable Production of Two West African Cities

Akoto-Danso, E.K., D. Manka›abusi, C. Steiner, S. Werner, V. Haering, D. J.-P. Lompo, G. Nyarko, B. Marschner, P. Drechsel, and A. Buerkert. 2019. J. Plant Nutr. Soil Sci. 182(2):229-243. DOI: https://doi.org/10.1002/jpln.201800339.

Abstract: This study reports and analyzes nutrient balances in experimental vegetable production systems of the two West African cities of Tamale (Ghana) and Ouagadougou (Burkina Faso) over a two-year period comprising thirteen and eleven crops, respectively. Nutrient-use efficiency was also calculated. In Tamale and Ouagadougou, up to 2% (8 and 80 kg N ha^{-1}) of annually applied fertilizer nitrogen were leached. While biochar application or wastewater irrigation on fertilized plots did not influence N leaching in both cities, P and K leaching, as determined with ion-absorbing resin cartridges, were reduced on biochar-amended plots in Tamale. Annual nutrient balances amounted to +362 kg N ha^{-1}, +217 kg P ha^{-1}, and –125 kg K ha^{-1} in Tamale, while Ouagadougou had balances of up to +692 kg N ha^{-1}, +166 kg P ha^{-1}, and –175 kg K ha^{-1} y^{-1}. Under farmers' practice of fertilization, agronomic nutrient-use efficiencies were generally higher in Tamale than in Ouagadougou, but declined in both cities during the last season. This was the result of the higher nutrient inputs in Ouagadougou compared to Tamale and relatively lower outputs. The high N and P surpluses and K deficits call for adjustments in local fertilization practices to enhance nutrient-use efficiency and prevent risks of eutrophication.

World Potassium Use Efficiency in Cereal Crops

Dhillona, J.S., E.M. Eickhoff, R.W. Mullen, and W.R. Raun. 2019. Agron. J. 111(2):889-896. DOI: 10.2134/agronj2018.07.0462.

Abstract: Worldwide potassium (K) fertilizer use has grown, while the expected fertilizer use efficiency has decreased. The objective of this paper was to estimate potassium use efficiency (KUE) for cereal crops and report on methods that will most likely lead to improved KUE. World KUE was calculated using the total area under cereal production, total cereal grain production, percent K content in cereal grains and K fertilizer consumed from 1961 to 2015. All data was obtained from FAOSTAT except percent K grain content, which was acquired from the USDA. The reported KUE estimate included assumptions established in prior literature. The percent K coming from the soil was estimated at 71%, while previous year K fertilizer-residual-effects were offset by knowing that similar amounts of fertilizer K will be applied in following years. At current consumption rates, existing K reserves as K_20 are estimated to last 100 yr meaning that mining operations will need to expand to meet expected market demands. Results showed that cereal production increased by a factor of 3.2 from 1961 to 2015 and that was accompanied by a threefold increase in fertilizer K consumed. Estimated KUE from 1961 to 2015 for world cereal crops using the difference method was 19%. Combined with findings from this paper, estimates of N, P, and K use efficiency for cereal production in the world stand at 33, 16, and 19%, respectively.

Possibility of Recommending Potassium Application Rates Based on a Rapid Detection of the Potato Petiole K Status with a Portable K ion Meter

Xiaohua ShiXin ZhangWenqin KangYang ChenMingshou Fan. 2019. American Journal of Potato Research 96(1):48-54.

Abstract: Because of the variations in the K amount required to produce 1 t potatoes and the poor relationship between soil potassium content and potato yield, recommended K-fertilizer rates based on soil tests are unreliable for potato production. This research was set to test the possibility of establishing a potato plant K diagnosis method with a portable K ion meter. The results confirmed the luxury absorption of K by potato. Moreover, the potato petiole K content by a portable K ion meter was linearly related to the vine and tuber K contents as well as the plant accumulated K level. Therefore the petiole K concentration is a good indicator of plant K status. Furthermore, the relationship between the relative potato yield and the petiole K content fits a quadratic equation, thus the threshold petiole K content could be calculated based on the minimum petiole K content at the highest relative yield.

Potassium Requirements for Corn in North Dakota: Influence of Clay Mineralogy

Brekera, J.S., T. DeSutterb, M.K. Rakkarc, A. Chatterjeed, L. Sharmae, and D.W. Franzen. 2019. SSAJ 83(2):429-436. DOI:10.2136/sssaj2018.10.0376.

Abstract: Due to initially high soil test K values, K soil

test correlation and calibration for corn in North Dakota has previously not been intensely investigated. Potassium fertilizer rate experiments were conducted on 25 sites from 2014 to 2016. The previously published soil test K critical value of 150 mg kg^{-1} predicted crop response correctly at 16 of the sites. Alternative soil test methods, including a resin-based extraction at two timings, sodium tetraphenylboron extractions at two timings, and 1 mol L^{-1} NH_4OAc extraction using moist soil were conducted; however, the currently used 1 mol L^{-1} ammonium acetate extraction using dry soil was most predictive. Mineral analysis of soil from all sites was determined for potassium feldspar content of whole soil, and clay species, particularly smectite, illite, and kaolinite, were determined on the clay fraction. Cluster analysis revealed that a smectite/illite ratio of 3.5 separated the sites into two unique K response data sets. Sites with a smectite/illite ratio >3.5 had a K critical level of ~200 mg kg^{-1}, whereas sites with a smectite/illite ratio <3.5 had a K critical level of ~130 mg kg^{-1}. For soils with K soil tests between 130 and 200 mg kg^{-1}, consideration of clay chemistry improves the predictability of crop yield response with K fertilization.

The Impact of Cover Crops and Foliar Application of Micronutrients on Accumulation of Macronutrients in Potato Tubers at Technological Maturity Stage

Gaj, R., B. Murawska., E. Fabisiak-Spychaj, A. Budka, and W. Kozera. 2018. Eur. J. Hortic. Sci. 83(6):345-355. DOI: https://doi.org/10.17660/eJHS.2018/83.6.2.

Abstract: The aim of the study was to assess the effect of mineral fertilization (NPK) in combination with manure and stubble crops (white mustard, pea, phacelia) and foliar application of micronutrients on the content and accumulation of macro-elements (N, P, K, Mg and Ca) in potato tubers at the of stage technological maturity. The tested plant was a potato cultivar 'Bila'. The experiment was carried out in 2010–2012, at the Wierzchucinek Research Station of the Bydgoszcz University of Technology and Life Sciences. The experimental factors were (I) fertilizer variants (n=5): the control (NPK), NPK + manure (FYM + NPK), NPK + white mustard (NPK + WM), NPK + pea (NPK + P), NPK + blue phacelia (NPK + PH), and (II) foliar fertilization with micronutrients (n=2): no fertilization with microelements (M0) and applications of fertilizer (M1). Micronutrients were applied twice a vegetation season in the form of a chelated fertilizer. The content and accumulation of nutrients in potato tubers at the stage of technological maturity were analyzed. It was found that the applied mineral NPK fertilization (the control), when in combination manure treatment and the three intercrops, significantly differentiated the content of all the studied nutrients in potato tubers. The highest concentration of nitrogen and calcium in tubers was found in the control plants, while highest concentrations of P, K and Mg were observed in tubers grown after manure application. Significantly higher nitrogen content (exclusive of 2011) as well as that of phosphorus were observed in the treatments with no foliar fertilization. In the case of magnesium and calcium, the relationship was reversed (exclusive of Ca content recorded in 2010). The experimental factors significantly differentiated the uptake values of all the nutrients analyzed and, irrespective of the study year, the largest accumulation of nutrients in potato tubers was found in the experimental variant with manure and micronutrient fertilizer application. The highest uptake of nutrients was recorded in tubers grown after pea intercrop as compared with other two intercrops tested. The correlation analysis as regards tuber yields, dry mass and starch as well as the total accumulation of nutrients, showed that regardless of the experimental variant analyzed, there was a highly significant correlation between yield/starch content and uptake of all the macronutrients under the study.

Citrus Fruit Yield Response to Nitrogen and Potassium Fertilization Depends on Nutrient-Water Management System

Quaggioa, J.A., T.R.Souza, F.C.B.Zambrosi, D. Mattos Jr., R.M. Boaretto, and G. Silva. 2019. Scientia Horticulturae 249:329-333. DOI: https://doi.org/10.1016/j.scienta.2019.02.001.

Abstract: The objectives of the present study were to investigate the influence of water supply combined with different rates and methods of nitrogen (N) and potassium (K) application on fruit yield and nutrient use efficiency (NutUE) of citrus by monitoring plant nutritional status and soil solution dynamic. The experiment was carried out with 4-yr-old Natal sweet orange trees on Rangpur lime over 4 consecutive growing seasons. Treatments were composed of 2 rates of N and K (NK): 50% and 100% of the recommended rates for maximum yield in rain-fed environments and 3 nutrient-water management systems: non-irrigation + broadcast granular fertilizer, irrigation + broadcast granular fertilizer and fertilizer application via irrigation (fertigation). Fruit yield was maximum under fertigation with application of 50% of the NK rate, and fertigation improved NutUE by 22% compared to non-irrigated trees. However, no difference in productivity and NutUE occurred across nutrient-water management systems under 100% of the NK rate. Differences in plant nutritional were not consistent across treatments and did not contribute to explain variations in fruit yield and NutUE. Soil solution analysis of fertigated trees receiving 100% of the NK rate revealed the lowest pH value and the highest concentration of $N\text{-}NH_4$. It is concluded that fruit yield responses of citrus trees treated with established NK rates for rain-fed environments might be limited by soil solution acidification and $N\text{-}NH_4$ toxicity when fertilizers are applied via fertigation, being necessary further adjustments on fertilization management of fertigated citrus groves.

How Potassium Deficiency Alters Flower bud Retention on Cotton (*Gossypium hirsutum* L.)

Loka, D.A., D.M. Oosterhuis, D. Baxevanos, D. Vlachostergios, and W. Hu. 2018. Archives of Agronomy and Soil Science 65(4):521-536. DOI: https://doi.org/10.1080/03650340.2018.1511894.

Abstract: Potassium (K) is fundamental for plant growth and development but despite the increased quantities of fertilizers applied, incidents of K deficiency are commonly observed. The objective of this study was to record the effects of K deficiency during cotton's (*Gossypium hirsutum* L.) early reproductive stage on carbohydrate content and metabolism, total antioxidant capacity and oxidative damage of cotton flower buds as well as the physiology of the leaf, subtending to the flower buds. Growth chamber experiments were conducted using cotton cultivar DP0912 and treatments consisted of normal K and deficient K fertilization for the duration of the experiment. Potassium deficiency resulted in significant oxidative damage in the cotton flower buds, despite the substantial increase in their total antioxidant capacity. Sucrose metabolism of the flower buds was markedly affected resulting in significant reductions in all non-structural carbohydrate concentrations. Furthermore, K deficiency disturbed leaf physiology leading to increased membrane damage, decreases in chlorophyll and carotenoid content and ultimately leaf photosynthetic rates. Concomitant increases in specific leaf weight under K deficient conditions indicated reductions in photoassimilate translocation, which in conjunction with the disruptions observed in flower bud sucrose metabolism, due to the insufficient antioxidant response, resulted in significant decreases in flower bud retention.

Organic Acids Exuded From Roots Increase the Available Potassium Content in the Rhizosphere Soil: A Rhizobag Experiment in Nicotiana Tabacum

Yongfeng Yang, Zhixiao Yang, Shizhou Yu, and Hongli Chen. 2019. HortScience 54(1):23-27. DOI: https://doi.org/10.21273/HORTSCI13569-18.

Abstract: Organic acid secretion from higher plant roots into the rhizosphere soil plays an important role in nutrient acquisition and metal detoxification; however, their precise functions and the related mechanisms in abiotic stress tolerance remain poorly understood. Tobacco is an important crop plant, so thoroughly elucidating these factors in tobacco is of high priority. In the present study, the activation effect on soil potassium (K), contents of exuded organic acids, and physiological changes in the roots of various tobacco varieties under both normal K supply and K-deficiency stress were investigated. Our results showed that one high-K variety (ND202) exhibited a significantly higher total content of organic acids in the root exudates and the highest available K content in the rhizosphere soil, compared with two common ones (K326 and NC89). Moreover, the high-K tobacco variety was less affected in terms of root vigor under K-deficiency stress, and displayed greater increases in the activities of the stress-resistant enzymes consisting of superoxide dismutase (SOD), peroxidase (POD), and catalase (CAT). Taken together, these results provide evidence that tobacco roots exude large amounts of organic acids to increase the available K content in the rhizosphere soil and improve the utilization rate of soil K.

Response of Potted Anthurium (*Anthurium andreanum* Lind.) to the K^+: Ca^{+2}: Mg^{+2} Balance in the Nutrient Solution

Sosa-Flores, P.V., L.A. Valdez-Aguilar, D. Cartmill, A.D. Cartmill, and A. Benavides-Mendoza. 2019. J. Plant Nutr. 42(4):351-361. DOI: https://doi.org/10.1080/01904167.2018.1555848.

Abstract: The climatic conditions of the humid tropical areas of México allow the year-round production of cut flowers and potted plants of anthurium. However, the scarce basic and applied research on tropical ornamental species limits the development of technology to increase productivity and quality. In this article, we are reporting the information as to the effect of the proportions of potassium (K^+), calcium (Ca^{+2}), magnesium (Mg^{+2}) in the nutrient solution on anthurium growth using mixture analysis and response surface methodology. The sum of all the three cations was 20 meq L^{-1} and each one is expressed as a fraction of this total concentration. Response surface analysis detected that spathe and leaf areas decreased in plants fed with solutions of high proportions of Mg^{+2}. Total shoot and root fresh weight, as well as total dry weight and root volume, also demonstrated the deleterious effects of high Mg^{+2}. In general, the best growth occurred in two areas of the explored space; a) an area of high Ca^{+2}, with optimum proportions ranging from 0.24-0.44 for K^+, 0.54-0.68 for Ca^{+2}, and 0.01-0.08 for Mg^{+2}, and b) another area of high K^+, on which the optimum proportions ranged 0.54-0.65 for K^+, 0.25-0.29 for Ca^{+2}, and 0.10-0.21 for Mg^{+2}. Shoot and root K^+, Ca^{+2}, and Mg^{+2} concentration was significantly affected by the cation balances in the external solution, however, there was not a clear tendency as to the effect of each cation in the mixture; nonetheless, the internal K^+: Ca^{+2}: Mg^{+2} balances were affected by the balances in the nutrient solution, as in the shoot they were located in a very specific area of the explored space, indicating that anthurium plants accumulated more Mg^{+2} compared to what it is in the external solution, whereas Ca^{+2} was lower than that of the external solution. Plants accumulated K^+ at high rates regardless of the external balance. In conclusion, the optimum nutrient solutions for anthurium may contain very wide ratios of K^+ as long Ca^{+2} and Mg^{+2} are maintained at low proportion in the nutrient solution.

Early Maturing Bt Cotton Requires More Potassium Fertilizer under Water Deficiency to Augment Seed-Cotton Yield But Not Lint Quality

Ahmad Naeem Shahzad, Muhammad Rizwan, Malik Ghulam Asghar, Muhammad Kamran Qureshi, Syed Asad Hussain Bukhari, Aysha Kiran, and Abdul Wakeel. 2019. Nature: Scientific Reports 9, Article number 7378.

Abstract: Exhaustive crops such as cotton require potassium (K) in copious amounts as compared to other crops. High yielding cultivars in cotton-wheat cropping system, have further increased its demand in cotton growing areas of Pakistan. As cotton is grown in arid and semiarid areas, therefore often prone to water deficiency. The reproductive growth particularly flowering and boll setting are highly sensitive to low soil water potentials, where enough K supply can play a vital role. In this two-year field studies, three cultivars (early, mid and late maturing) were cultivated at two K fertilizer levels 100, 200 kg K ha^{-1} along with control with no K fertilizer application at two irrigation levels. In first irrigation level, water was applied as per full irrigation schedule, while in water deficit irrigation water was applied at deficit irrigation schedule started after flowering till harvesting. It has been revealed that K application has impact on boll setting as well as seed cotton yield, however early and mid-maturing cultivars are more responsive to K fertilization. Furthermore, irrigation level had significant impact against K fertilization and relatively better response was observed in deficit irrigation as compared to full irrigation. Nevertheless, fiber quality parameters were unaffected by K fertilization. Considering the best benefit cost ratio under water deficiency, it is concluded that 100 kg K_2O ha^{-1} should be applied at the time of seed bed preparation for economical seed-cotton yield of early maturing Bt cotton.

Does Fertilization Impact Production Risk and Yield Stability Across an Entire Crop Rotation? Insights from a Long-Term Experiment

Macholdt, J., H.-P. Piepho, and B. Honermeier. 2019. Field Crops Research 238:82-92. DOI: https://doi.org/10.1016/j.fcr.2019.04.014.

Abstract: The objective of our analysis was to demonstrate a novel application of production risk (probability of a yield falling below a certain level) and yield stability analysis based on the totalized yield across a `sugar beet-winter wheat-spring barley´ crop rotation. We evaluated a long-term experiment spanning more than 60 years regarding the effect of mineral NPK fertilization and the additional supply of manure on the production risk, the risk development over time (trend), and the stability of biomass yields. We found that positive impacts such as reduced production risk and enhanced yield stability were the highest for the mineral N supply, were intermediate for the K supply, and were the lowest for the P supply. The full amount of the mineral nutrient fertilization, particularly in combination with an additional manure supply, resulted in lower production risk and more stabilized crop rotational yields compared to one-half the amount of nutrient supply. The mineral fertilization of NPK (at one-half and a full amount) led to a decreasing risk trend, particularly with the additional manure supply. The risk trend of the variants with P and K (but without N) or even no mineral nutrient fertilization only decreased over time with the manure supply. The lowest production risk and the best combination of high and stable yields of the crop rotation were found at full mineral NPK fertilization in addition to manure. In contrast, the highest production risk and the worst combination of the lowest and most unstable yields were obtained under a fertilization regime without N or even under non-fertilized management. The production risk and yield stability of this fertilization regime could be reduced via regular manure application carried out once per three-year rotation during the experimental period.

Read On

Updates to Corn and Soybean Potassium Fertilizer Guidelines in Minnesota

Kaiser, D. University of Minnesota Extension. 21 April 2019. Farm Forum.

Changes were recently made to the University of Minnesota's potassium (K) fertilizer guidelines for corn and soybean. These changes were made to reflect research evaluating critical soil test levels and primarily centers on medium and fine textured soils.

5 Factors to Consider for Potassium Fertilizer: Focus K Strategies on a Proven Yield, Not a Yield Goal

University of Minnesota. 11 April 2019. Successful Farming.

Decisions on optimal fertilizer management can be challenging in years with low commodity prices, says Daniel Kaiser, University of Minnesota (U of M) Extension soil fertility specialist. In the article below, he gives five factors that farmers should consider as they make decisions for applying K for corn and soybean.

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