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.

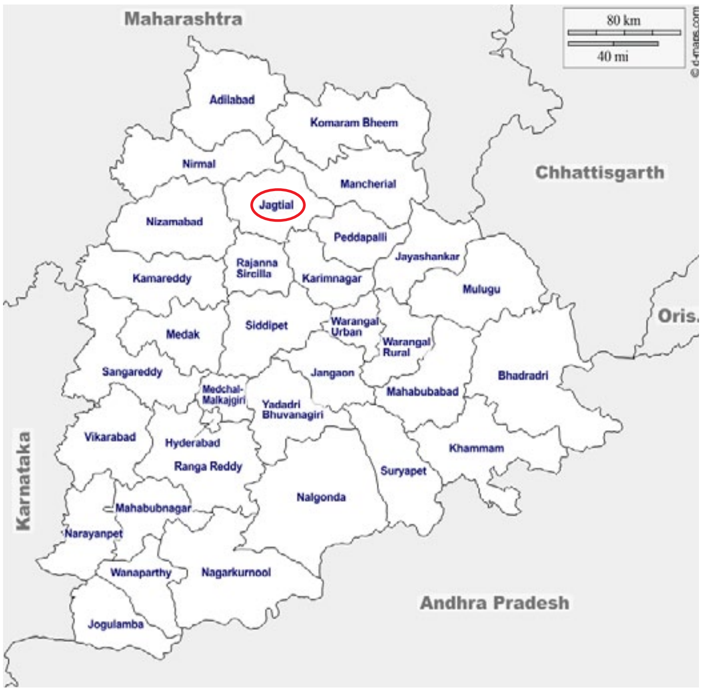


Fig. 2. Map of Telangana state. Jagtial district where experimental plots of rice-rice cropping system were located is indicated with a red ellipse.
Source: https://d-maps.com/continent.php?num_con=13&lang=en.

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.

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.

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.

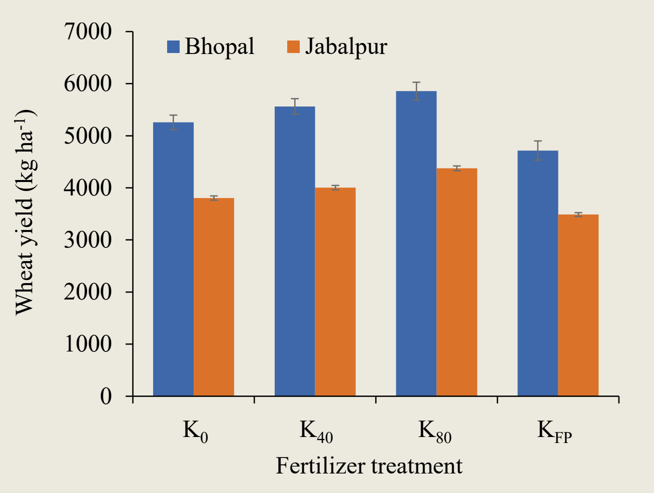


Fig. 4. Mean wheat yield for control and two +K treatment plots harvested in Bhopal and Jabalpur in the 2016-2018 period. Additionally, yield levels of plots where fertilizer regime was applied according to the previous farmers' practice is also shown (K_{FP}). The error bars signify the standard error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

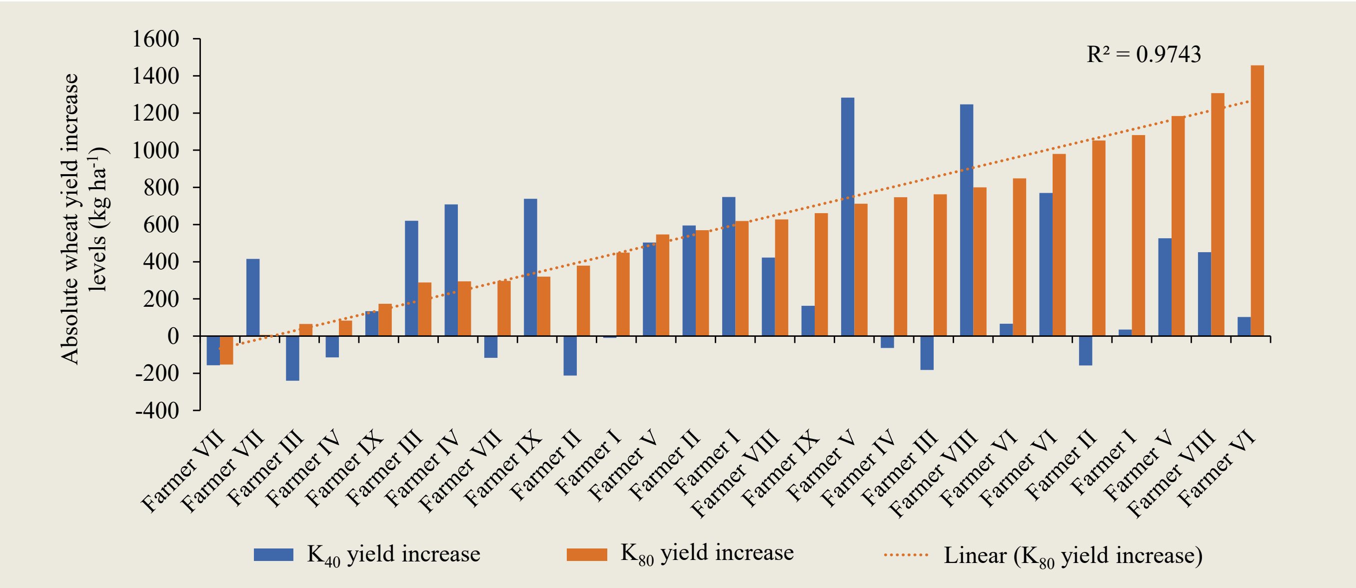


Fig. 5. Absolute wheat yield increase in plots fertilized with MOP in comparison to control plots with no MOP fertilization in 27 plot pairs across Bhopal district and 9 farms harvested in the 2016-2018 period. The data is sorted according to the response in K_{80} treatment. The orange line represents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

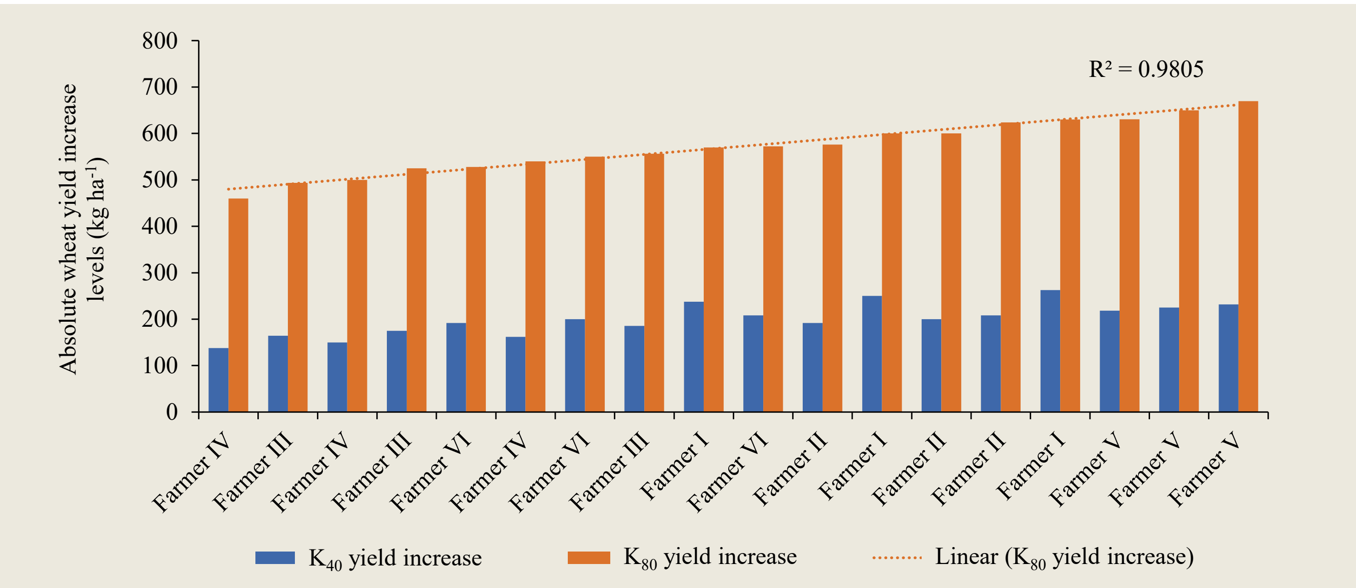


Fig. 6. Absolute wheat yield increases in plots fertilized with MOP in comparison to control plots with no MOP fertilization in 18 plot pairs across Jabalpur district and 6 farms harvested in the 2016-2018 period. The data is sorted according to the response in K_{80} treatment. The orange line represents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

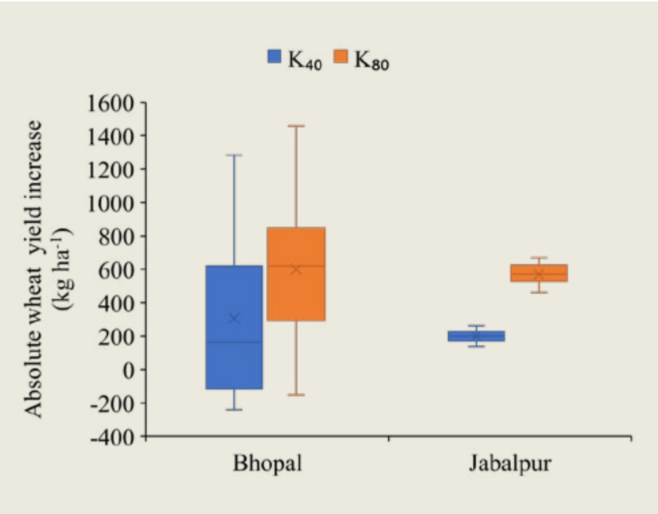


Fig. 7. Box plot diagram illustrates the distribution of the same data as in Fig. 5 and Fig. 6. In the box plot, the middle line represents the median, the upper and lower edge of the box represent the 25th and the 75th percentiles, respectively. The mean is signified by the x-marker. The bars reach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

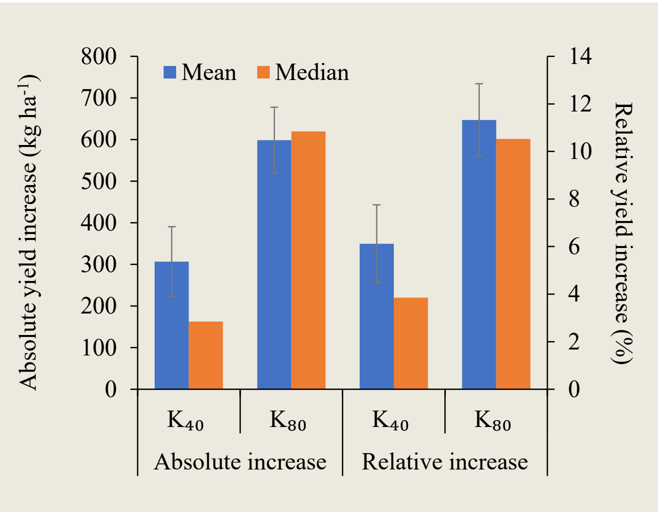


Fig. 8. Absolute and relative yield increases, illustrated both as mean and median, for wheat harvested in Bhopal in the 2016-2018 period. The error bars signify the standard error of the mean.

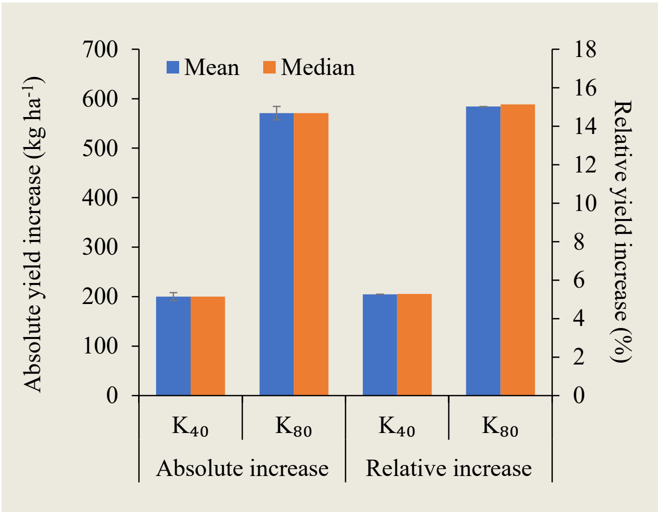


Fig. 9. Absolute and relative yield increases, illustrated both as mean and median, for wheat harvested in Jabalpur in the 2016-2018 period. The error bars signify the standard error of the mean.

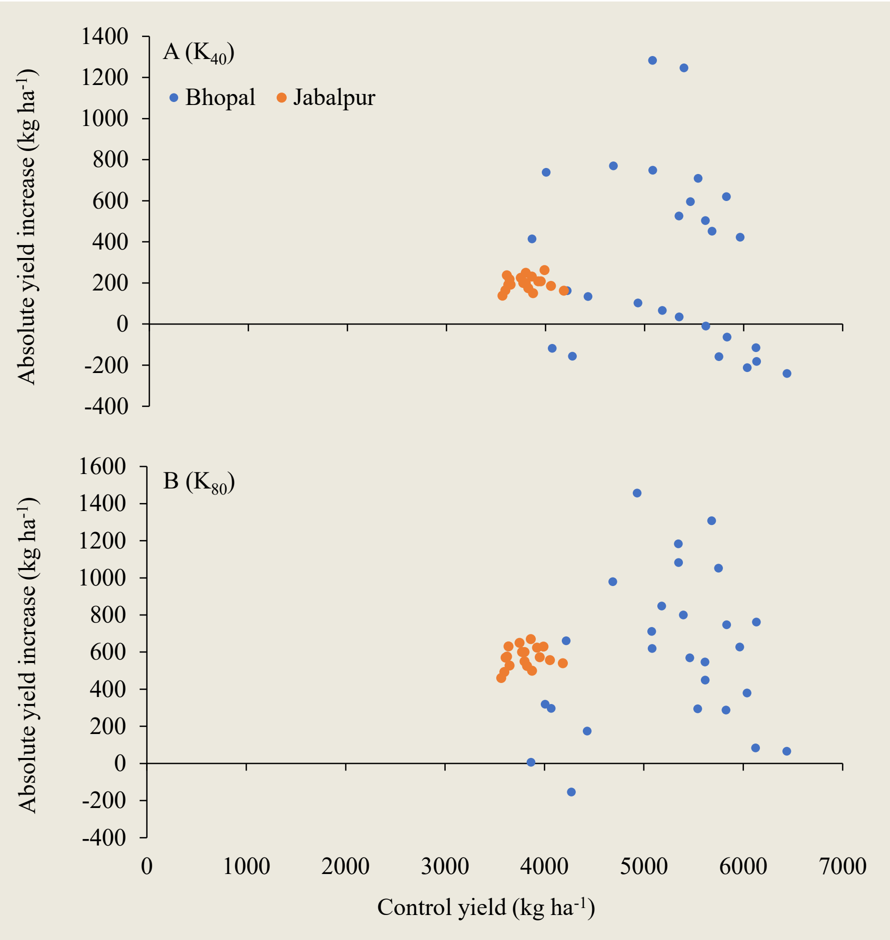


Fig. 10. Absolute yield increase in (A) K_{40} and (B) K_{80} treatments as a function of the control yield of wheat crop. Linear regression analysis identified no significant linear regression equation. Blue and orange points represent experimental plots at Bhopal and Jabalpur, respectively.

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).

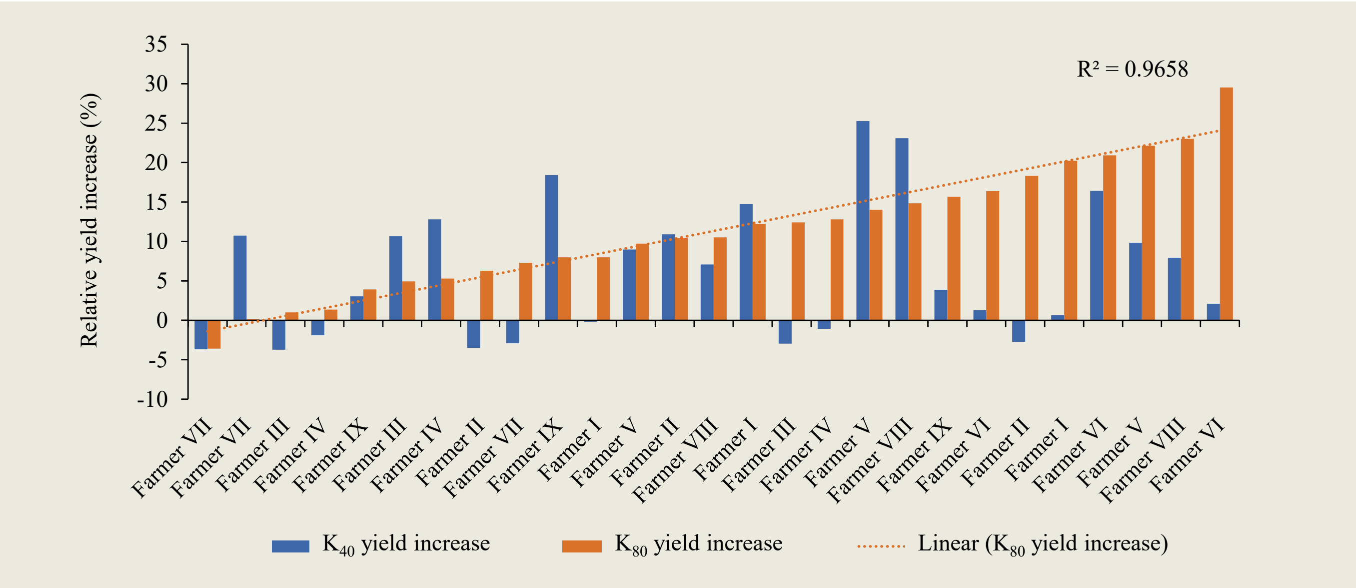


Fig. 11. Relative wheat yield increases in plots fertilized with MOP in comparison to control plots with no MOP fertilization in 27 plot pairs across Bhopal district and 9 farms harvested in the 2016-2018 period. The data is sorted according to the response in the K_{80} treatment. The orange line represents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

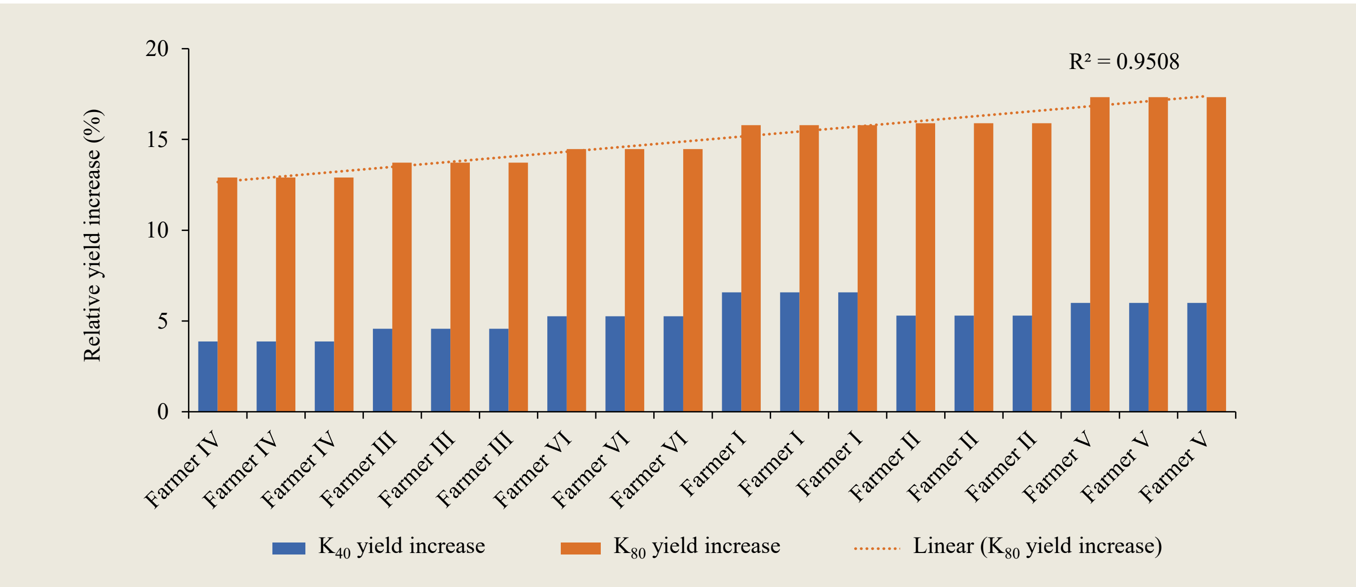


Fig. 12. Relative wheat yield increases in plots fertilized with MOP in comparison to control plots with no MOP fertilization in 18 plot pairs across Jabalpur district and 6 farms harvested in the 2016-2018 period. The data is sorted according to the response in K_{80} treatment. The orange line represents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

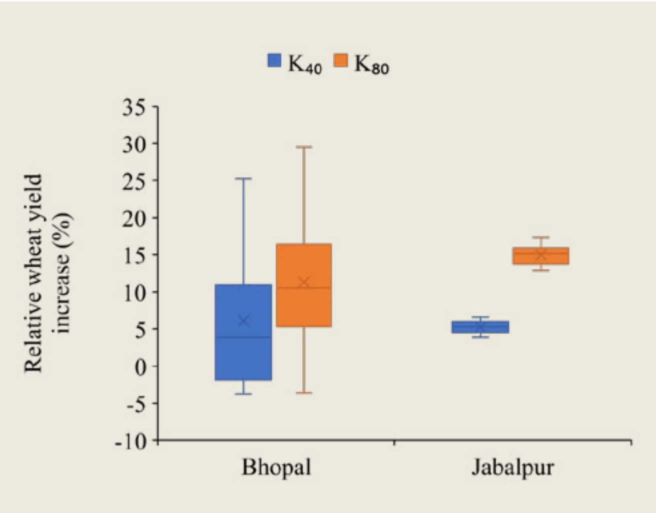


Fig. 13. Box plot diagram illustrates the distribution of the same data as Fig. 11 and Fig. 12. In the box plot, the middle line represents the median, the upper and lower edge of the box represent the 25th and the 75th percentiles, respectively. The mean is signified by the x-marker. The bars reach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

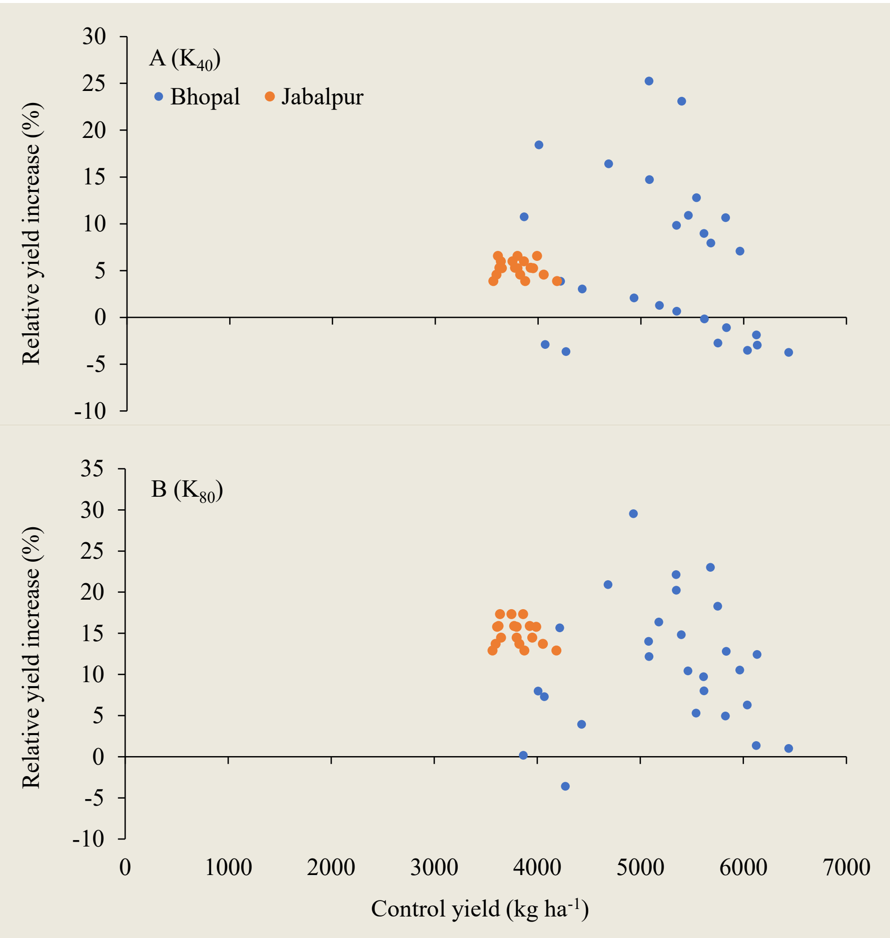


Fig. 14. Relationship of control yield and relative yield increase level. Linear regression analysis identified no significant linear regression equation. Blue and orange points represent experimental plots at Bhopal and Jabalpur, respectively.

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.

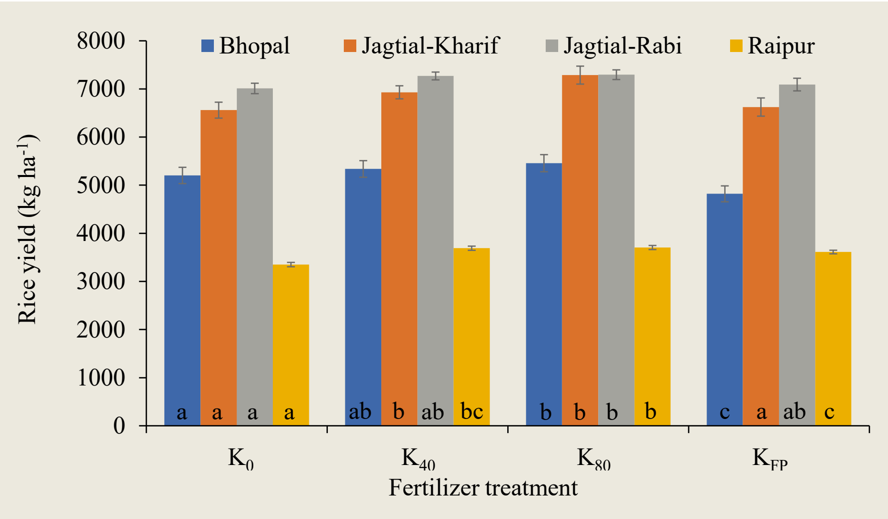


Fig. 15. Mean rice yield for control, two +K treatment plots, and plots with fertilizer regime according to the previous farmers' practice (K_{FP}), harvested in Bhopal, two seasons in Jagtial, and Raipur. The error bars signify the standard error of the mean. The differences between the treatments at 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.

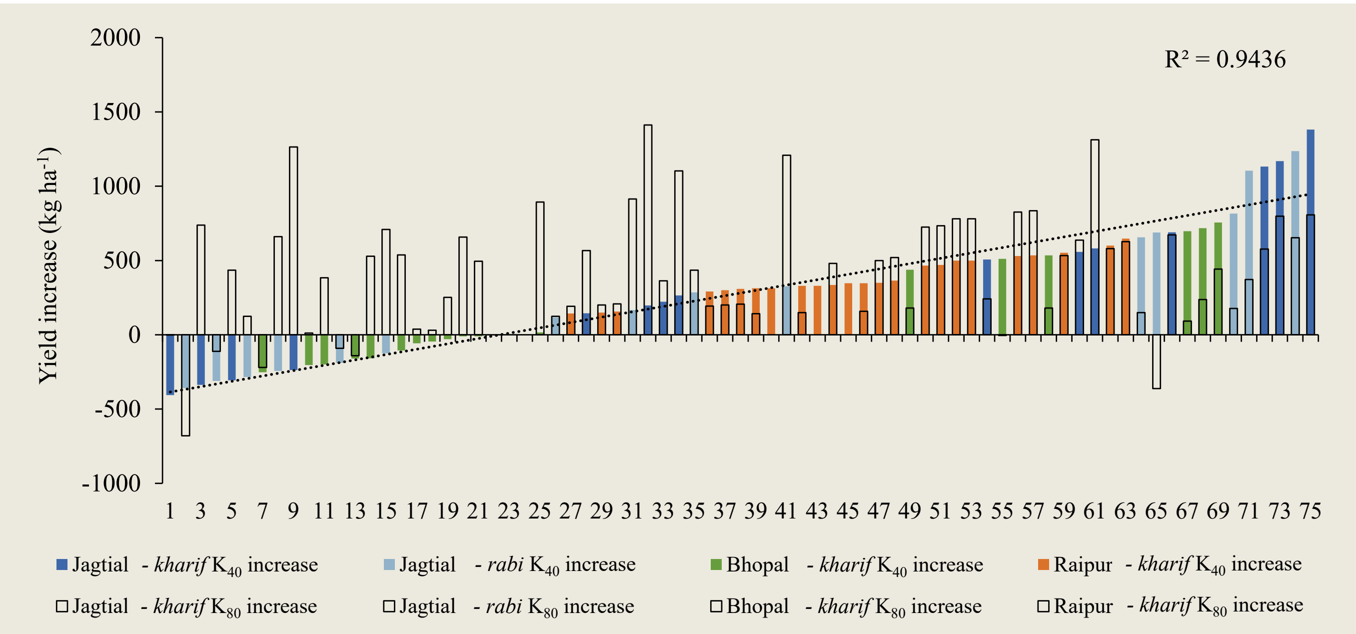


Fig. 16. Absolute rice yield increases in plots fertilized with MOP in comparison to control plots with no MOP fertilization in 75 plot pairs across three districts. The data is sorted according to the response in K_{40} treatment. Transparent outlined bars represent the absolute yield increase in K_{80}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

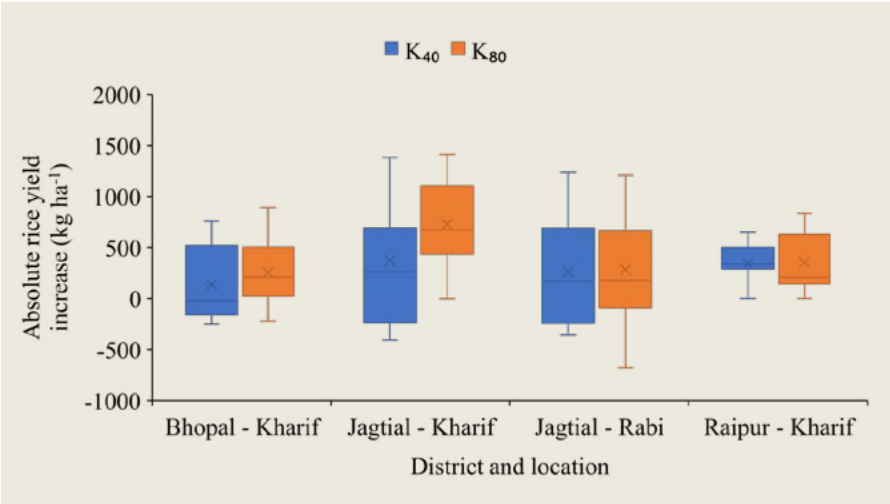
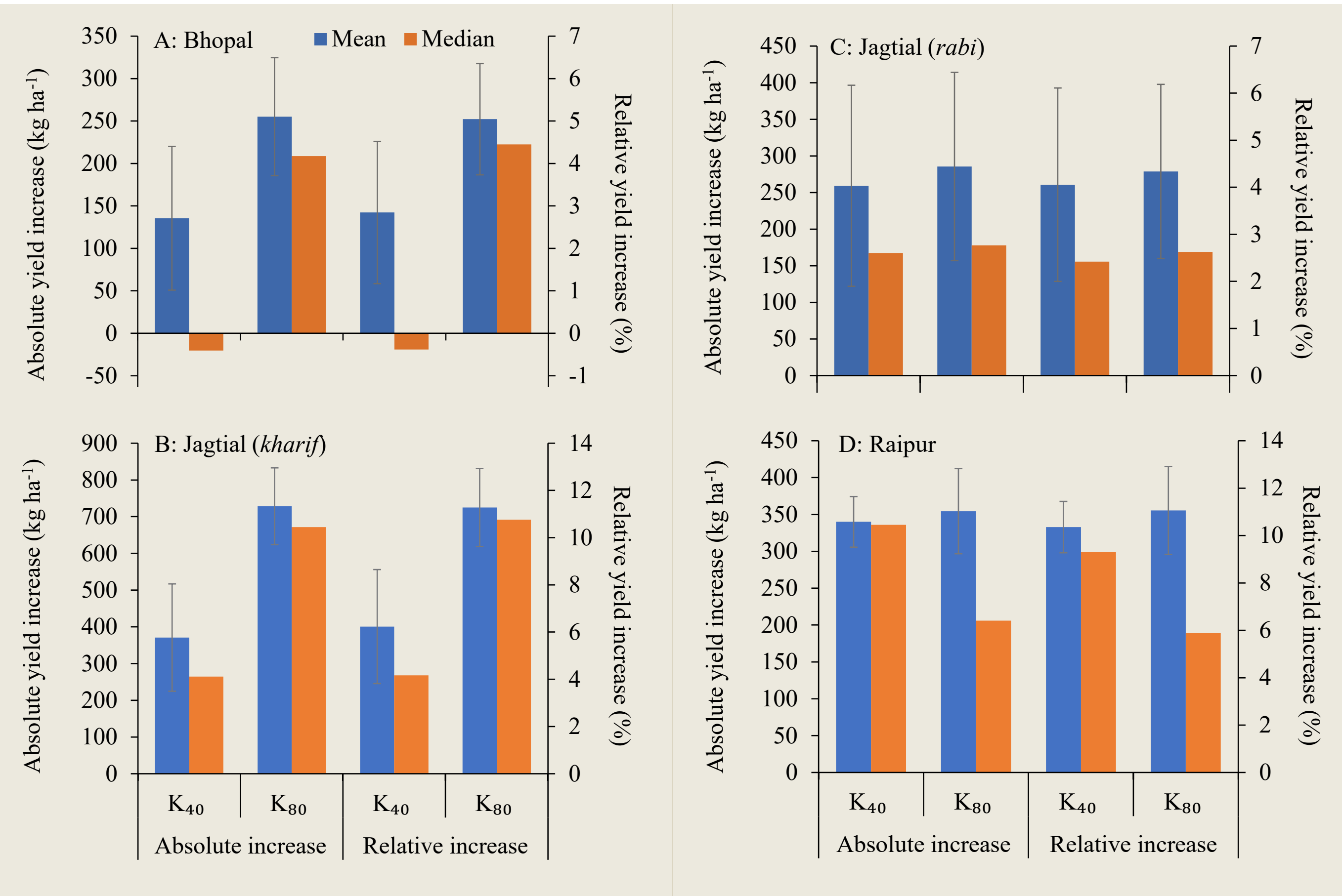


Fig. 17. Box plot diagram illustrates the distribution of the same data as Fig. 16. In the box plot, the middle line represents the median, the upper and lower edge of the box represent the 25th and the 75th percentiles respectively. The mean is signified by the x-marker. The bars reach the maximum and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

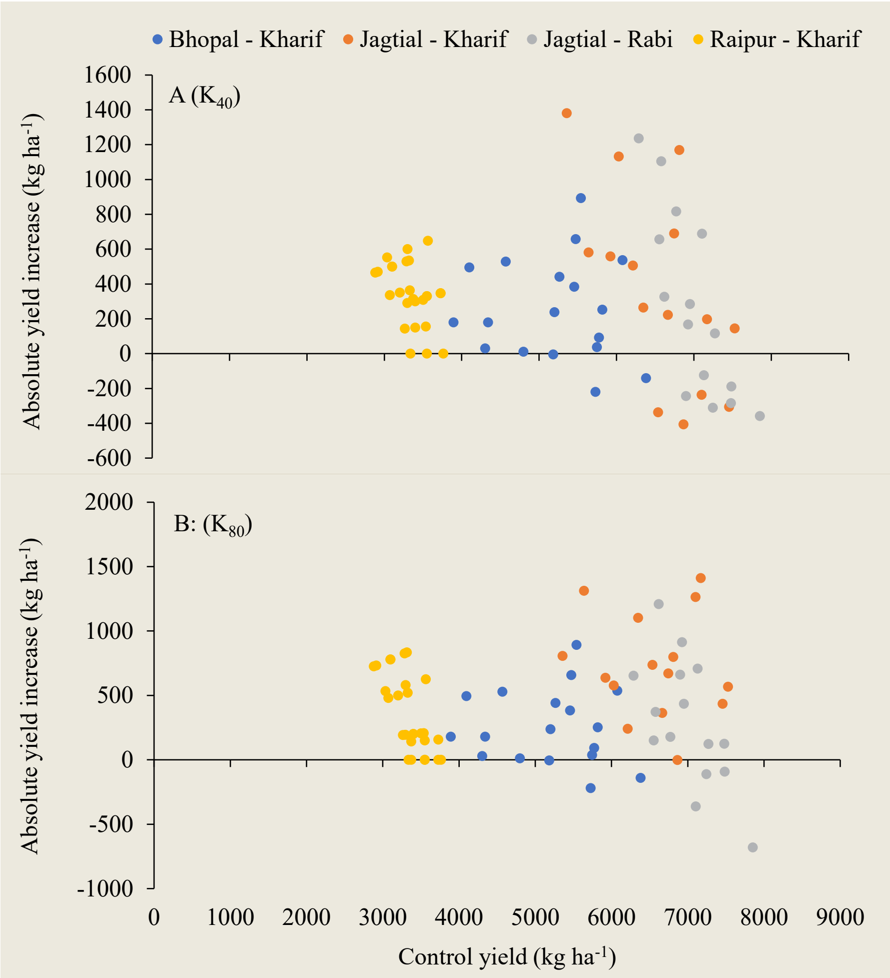


Fig. 19. Absolute yield increase in (A) K_{40} and (B) K_{80} treatments as a function of the control yield of rice crop. Linear regression analysis identified no significant linear regression equation. Different locations are represented by different colors according to the legend.

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.

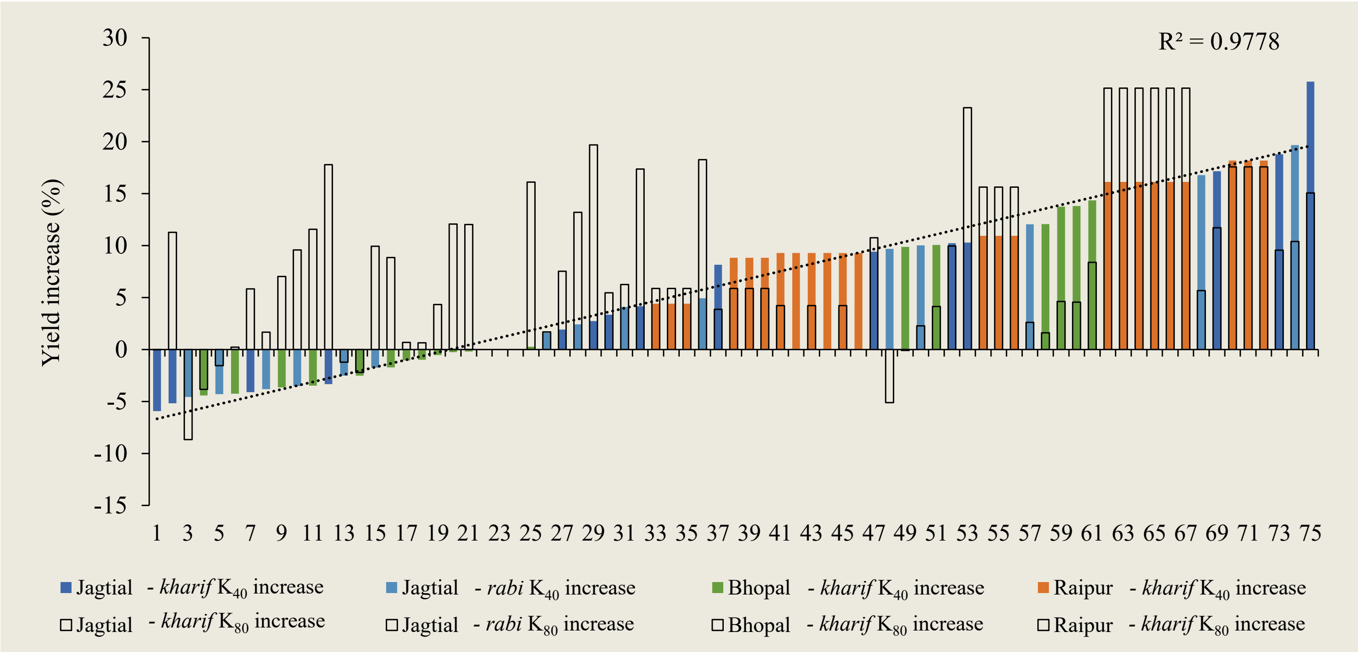


Fig. 20. Relative rice yield increases in plots fertilized with MOP in comparison to control plots with no MOP fertilization in 75 plot pairs across three districts. The data is sorted according to the response in K_{40} treatment. Transparent outlined bars represent the relative yield increase in K_{80}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

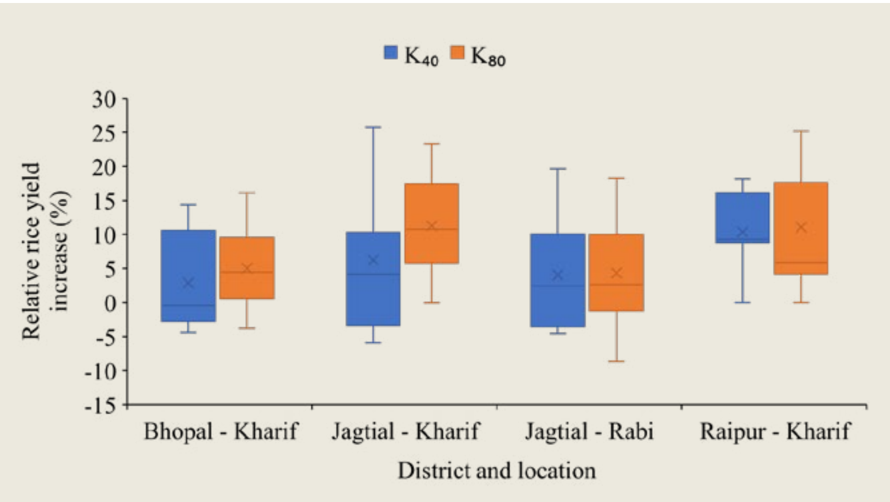


Fig. 21. Box plot diagram illustrates the distribution of the same data as in Fig. 20. In the box plot, the middle line represents the median, the upper and lower edge of the box represent the 25th and the 75th percentiles, respectively. The mean is signified by the x-marker. The bars reach the maximum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

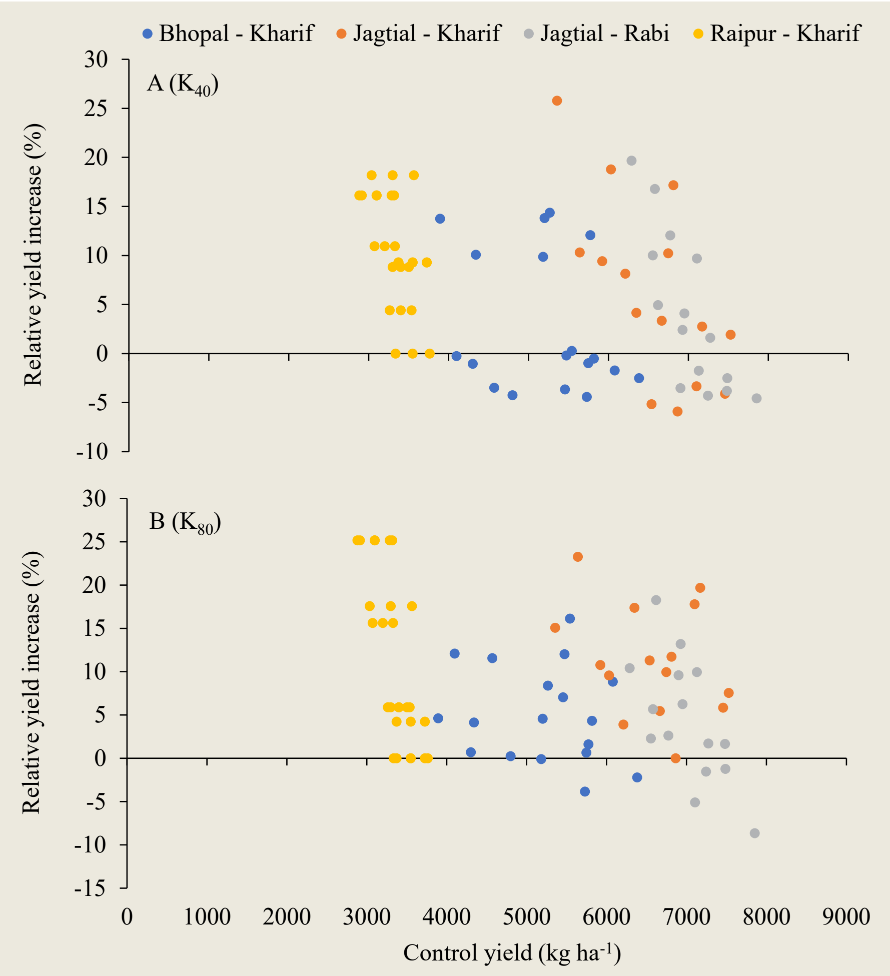


Fig. 22. Relative yield increase in (A) K_{40} treatment and (B) K_{80} as a function of the control yield of rice crop. Linear regression analysis identified no significant linear regression equation. Different locations are represented by different colors according to the legend.

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

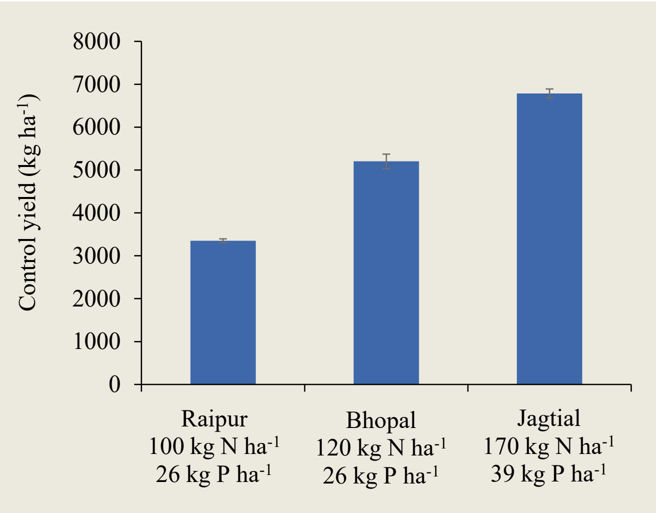


Fig. 23. Control rice yields across three locations. Error bars represent standard error of the mean. Amounts of applied background N and P are shown for each location.

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.

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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.