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Role of Potassium Nutrition in Nitrogen Use Efficiency in Cereals

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Abstract

Consumption of fertilizer nitrogen (N) is increasing quantitatively, but the corresponding yield increase per unit of N (N use efficiency, NUE) is substantially diminishing over the years. Improving NUE is of paramount importance both from an economic as well as an environmental point of view. Among several strategies to improve NUE, balanced nutrition, particularly balancing N and potassium (K) nutrition and tapping into the synergistic effect of N and K, is recently gaining importance. The efficiency of fertilizer N is only 30-40% in rice and 50-60% in other cereals. There are several reports indicating the positive effects of N and K interaction in terms of crop productivity and economics, but the balance of N and K application is not appropriately practiced in many parts of the world. Positive interaction of N and K has been reported in many rainfed cereals like sorghum, pearl millet, finger millet, maize, and minor millets. In a study based on 241 site-years of experiments in China, India, and North America, balanced fertilization with N, phosphorus (P), and K increased first-year recoveries by an average of 54% compared to recoveries of only 21% where N was applied alone. In several sorghum cultivars grown in Savannah regions, improved N content and N use efficiency with K application has been reported. It has also been demonstrated that with the application of PK, the agronomic efficiency of N (AE_N) improved substantially (6.7 kg grain/kg N) in sorghum and (10.3 kg grain/kg N) in pearl millet. Balanced fertilization improved both AE_N as well as partial factor productivity of fertilizer N at on-farm locations.

Introduction

Inadequate application of potassium (K) combined with over application of nitrogen (N) is a serious problem in modern intensive agricultural production systems. It leads to large N losses, environmental pollution and low nitrogen use efficiency (NUE). Although fertilizer consumption is increasing quantitatively, the corresponding yield increase per unit of nutrient has diminished over the years (Sharma and Sharma, 2011; Benbi and Brar, 2011). The response ratio (kg grain/kg nutrient) in food grain crops in irrigated areas in India (Fig. 1) substantially declined between 1960 and 2008 (Biswas and Sharma, 2008a). The need to improve NUE is therefore of paramount importance both for economical as well as environmental reasons.

K application has been neglected in many developing countries, including India, which has resulted in soil K depletion in agricultural ecosystems and a decline in crop yields (Regmi *et al.*, 2002; Panaullah *et al.*, 2006; Ladha *et al.*, 2003; Wang *et al.*, 2007b; Lal *et al.*, 2007). Higher yields and crop quality can be obtained at optimal N:K nutritional ratios. K is an essential macronutrient required for proper development of plants. In addition to activation of numerous enzymes, K plays an important role in the maintenance of electrical potential gradients across cell membranes and the generation of turgor. It is also essential for photosynthesis, protein synthesis, and regulation of stomatal movement, and is the major cation in the maintenance of cation-anion balances (Marschner, 1995).

N is probably the major agronomic stimulant to crop growth within the farmer's armoury. But to exploit its maximum use efficiently for increasing crop production, the crop must have access to, and take up, an adequate amount of K from the plant-available (exchangeable K) pool of K in the soil. This is because there is a strong interaction between these two nutrients in crop growth. Crop response to applied fertilizer N decreases when the exchangeable K content of a soil is below a critical target level. Because of this interaction, there is little point in applying large amounts of N when soil is low in available K, because N is used inefficiently and causes financial losses to the grower. There is also the risk that any excess unused fertilizer N lost from the soil will have adverse effects on the environment.

Among several strategies to improve NUE, balanced nutrition, particularly balancing N and K nutrition and tapping into the synergistic effect between N and K, is important both in irrigated as well as rainfed production systems

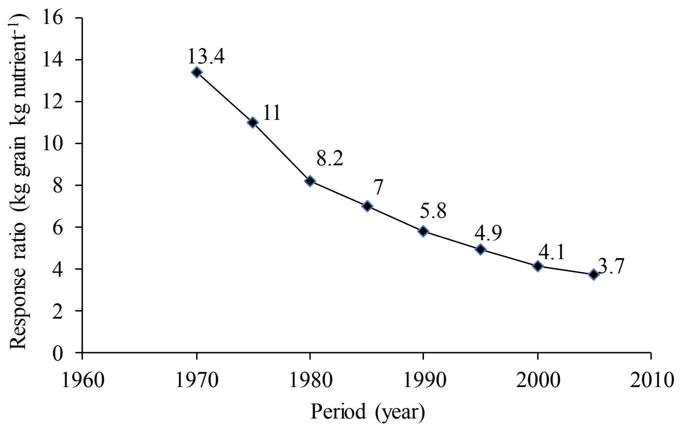

Fig. 1. Fertiliser response of food grain crops in irrigated areas in India.

Source: Biswas and Sharma, 2008a.

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(Ganeshamurthy and Srinivasarao, 2001). NUE depends on several agronomic factors including tillage, time of sowing, appropriate crop variety, proper planting or seeding, sufficient irrigation, weed control, pest/disease management, and balanced and proper nutrient use (Srinivasarao, 2010). These factors largely influence NUE, either individually or collectively. For example, selection of proper planting material, population density, and balanced fertilization could collectively improve NUE by 25 to 50% (Srinivasarao *et al.*, 2006). Multi-site field experiments conducted in North and Northeast China also indicate that the yield responses of maize to medium K supply are greater in high-yield cultivation practices (HP) than in current cultivation practices (CP; Zhang *et al.*, 2011).

Soil degradation is occurring due to inadequate and imbalanced fertilization leading to nutrient mining and development of second generation problems in nutrient management. The estimated supply-demand gap will be about 1.8 million tonnes of N and 1.9 million tonnes of phosphorus (P) by 2011-12. The entire demand for K will continue to be met through imports. It is of concern that the partial factor productivity of fertilizers has been continuously declining. The efficiency of fertilizer N is only 30-40% in rice and 50-60% in other cereals. The efficiency of fertilizer P is 15-20% in most crops and that of K is 60-80%. Low nutrient recovery efficiency not only increases the cost of crop production but also causes environmental pollution.

The positive N-K interaction is also dependent on the form of nitrogen supplied. K depletion of the nutrient solution enhances the absorption of NH_4^+-N but in contrast suppresses the absorption, translocation, and assimilation of NO_3^--N, simultaneously lowering leaf nitrate reductase activity (NR). This behaviour suggests that plants require an adequate supply of K for absorbing NO_3^--N and maintaining high levels of NRA as compared with the assimilation of NH_4^+-N (Ali *et al.*, 1991). K activates plant enzyme functioning in ammonium assimilation and transport of amino acids (Hagin *et al.*, 1990). Therefore, an adequate supply of K enhances ammonium utilization and thus improves yield when both N forms are applied together (Hagin *et al.*, 1990). There have been numerous studies on NH_4^+-K interactions in different crops. K^+ may alleviate NH_4^+ toxicity by inhibiting NH_4^+ uptake and/or by stimulating carbon (C) and N assimilation in the roots (Roosta and Schjoerring, 2008). The chemical similarity and identical ionic status of the NH_4^+ and K^+ ions suggest possible substrate competition via a transport system (Jarvis 1987; Guo *et al.*, 2007). Optimal N and K application is essential for best nutrient management in agriculture. A N-K interaction generally exists in agricultural ecosystems (Gething, 1993; Johnston and Milford, 2009). In this paper we have reviewed the N-K interaction and its effect on NUE in cereals.

NUE is an aggregate efficiency index of contributions to crop yield derived from uptake of indigenous soil N, fertilizer N uptake efficiency and the efficiency with which N acquired by plants is converted to grain yield. Cereals use fertilizer N rather inefficiently. On the basis of a large number of experiments conducted on farmer's fields, Cassman *et al.*, 2002 observed that generally more than 50% of the applied N is not assimilated by plants (Table 1). Under favorable weather conditions the maximum recovery efficiency of nitrogen was nearly 50%. The global cereal N use efficiency was about 33%, and an increase in 1% NUE was calculated to be worth US$234 million (Magen and Nosov, 2008).

Table. 1. NUE in rice and wheat.

Crop	Region	Number of farms	Average N application	Recovery efficiency of N
			kg ha^{-1}	*%*
Rice	Asia - farmers practice	179	117 ± 39	31 ± 18
	Asia - field specific management	179	112 ± 28	40 ± 18
Wheat	India - unfavorable weather	23	145 ± 31	18 ± 11
	India - favorable weather	21	123 ± 20	49 ± 10

Source: Cassman *et al.*, 2002.

Role of K in enhancing NUE

Adequate and balanced application of fertilizer nutrients is one of the most common practices for improving the efficiency of N fertilizer and is equally effective in both developing and developed countries. In a recent review based on 241 site-years of experiments in China, India, and North America, balanced fertilization with N, P, and K increased first-year recoveries with an average of 54% compared to recoveries of only 21% where N was applied alone (Fixen and West, 2002). Much higher nutrient efficiencies could be achieved simply by sacrificing yield, but that would not be economically effective or viable for the farmer, or the environment (Srinivasarao and Subbarao, 1999).

K application and N uptake

Enhancement in uptake of N through K application ultimately helps in increasing the NUE. Yield response to K application depends to a great extent on the level of N nutrition and the interaction is normally positive (Macleod, 1969; Blevins, 1978; Loué, 1978; Guo *et al.*, 2004; Bruns and Ebellhar, 2006; Brennan and Bolland, 2007, 2009). When a moderate N fertilizer level was supplied to wheat (112.5 kg N ha^{-1}), yield increments of wheat after K application were higher than when N or K fertilizer was applied singly. Response to yield and the utilization of nitrogen by maize was

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found to be accentuated when K application was supplemented with farmyard manure (Nakashgir, 1992). However, over-application of N and K does not lead to further yield increments.

The impact of K application on N uptake was studied in three sorghum genotypes in K deficient sandy soils of Guntur district in Andhra Pradesh. In all three sorghum genotypes, K application improved the dry matter yields as well as N uptake (Fig. 2) (Pillai and Nookaraju, 1997). Optimum N:K ratios favor healthy plant growth and development whereas imbalance of N and K supply is detrimental to plant growth (Xie, 2000; Wells and Wood, 2007).

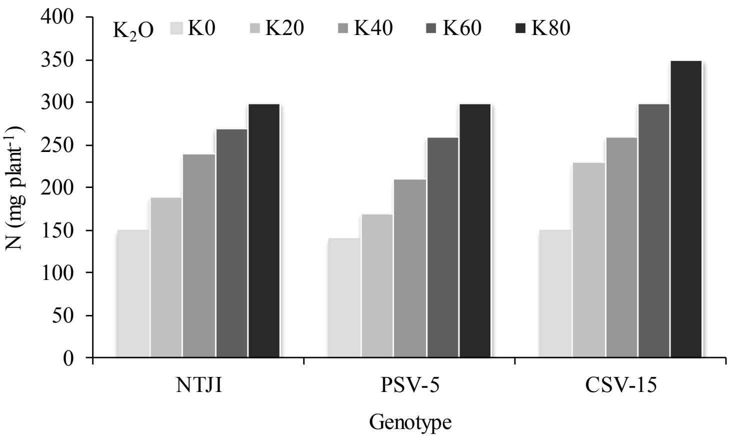

Fig. 2. Effect of K application on nitrogen uptake in three sorghum cultivars in Guntur district in Andhra Pradesh.

Source: Pillai and Nookaraju, 1997.

K application and protein content in plants

Application of K facilitates the uptake and transport of nitrate towards aerial parts of the plant, which in turn enhances the activities of nitrate assimilating enzymes (Anjana *et al.*, 2009). The parallel increase in activities of nitrogen assimilating enzymes with nitrate concentration indicates that these enzymes act in a coordinated manner in order to assimilate N in plants and thus improve the NUE.

In an experiment in which pearl millet was followed by wheat in rotation, the protein content of pearl millet and wheat grain increased due to K application (Table 2). The pearl millet grain protein content increased from 9.85 to 11.29% at 90 kg N ha^{-1}, and from 10.01 to 11.51% at 120 kg N ha^{-1} with the increase in K level from 0 to 60 kg K_2O ha^{-1} (Yadav *et al.*, 2007). Similarly, the wheat grain protein content increased from 10.62 to 11.74% at 120 kg N ha^{-1}, and from 10.86 to 11.87% at 150 kg N ha^{-1} due to the increase in residual K level from 0 to 60 kg K_2O ha^{-1}. Protein yield of grains was significantly increased as a result of K application regardless of the N level. These results show that K improves NUE by favouring protein formation.

Table. 2. Direct and residual effect of K on protein content in grain of pearl millet and wheat in alluvial soils of Haryana, India.

Nutrient application		Pearl millet		Wheat	
Pearl millet	Wheat	Protein content	Protein yield	Protein content	Protein yield
------------*kg ha^{-1}*------------		*%*	*kg ha^{-1}*	*%*	*kg ha^{-1}*
$N_{90}P_{60}K_0$	$N_{120}P_{60}K_0$	09.85	211	10.62	426
$N_{90}P_{60}K_{30}$	$N_{120}P_{60}K_0$	10.75	257	11.13	462
$N_{90}P_{60}K_{60}$	$N_{120}P_{60}K_0$	11.29	282	11.74	506
$N_{120}P_{60}K_0$	$N_{150}P_{60}K_0$	10.01	244	10.86	451
$N_{120}P_{60}K_{30}$	$N_{150}P_{60}K_0$	10.93	297	11.45	452
$N_{120}P_{60}K_{60}$	$N_{150}P_{60}K_0$	11.51	329	11.87	528
CD (5%)		0.79		0.81	

Source: Yadav *et al.*, 2007.

Similarly, application of K in a pearl millet-mustard rotation also increased the grain protein content of pearl millet, which was significantly greater than the control at 40 kg K_2O ha^{-1} (Fig. 3). Protein yield (grain yield X % protein) was significantly increased due to K application, probably via the effect of K promoting photosynthate mobility to increase the utilization of N. Protein yield of pearl millet was increased from 252 to 340 kg ha^{-1}.

Application of K favours an increase in grain protein and amino acid contents (Yang *et al.*, 2004; Venkatesan *et al.*, 2004; Zou *et al.*, 2006b), but responses vary among cultivars (Zou *et al.*, 2006b). Compared with Ningmai 9 (a low-protein wheat cultivar), the role of K in improving the protein content of grain was greater in Yangmai 10 (a medium-protein wheat cultivar). Protein content in wheat grain showed a close positive correlation with N accumulation and translocation (Zou *et al.*, 2006b).

K application and N recovery efficiency (RE_N)

The large number of multi-location on-farm field experiments conducted in India shows the importance of balanced fertilization in increasing crop yield and improving NUE (Table 3). AE_N improved from 6 to 20% in predominant rainfed crops. Based on several balanced nutrition experiments, it was reported that AE_N improved with the application of P and K by 6.7 kg grain/kg N in sorghum, 10.3 in pearl millet,

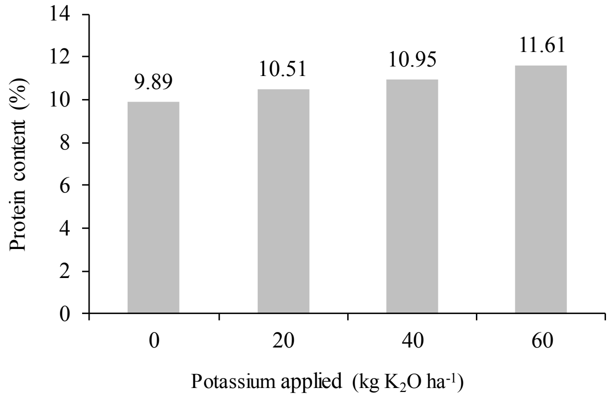

Fig. 3. Impact of K application on protein content of pearl millet in Alluvial soils of Haryana, India. (N and P_2O_5 applied were 120 and 60 kg ha^{-1}, respectively.)

Source: Yadav *et al.*, 2007.

Table. 3. Effect of balance fertilization on yield and AE_N.

Crop	Yield			Agronomic efficiency (AE_N)		
	Control	N alone	+PK	N	+PK	Increase
	---------*mt ha⁻¹*---------			---------*kg grain kg N⁻¹*---------		
Pearl millet	1.05	1.24	1.65	4.7	15.0	10.3
Maize	1.67	2.45	3.24	19.5	39.0	19.5
Sorghum	1.27	1.48	1.75	5.3	12.0	6.7

Source: Prasad, 2009.

Table. 4. RE_K and increase of NUE on maize.

Treatment*	RE_K (%)**		NUE increase (%)***	
	Range	Mean	Range	Mean
N_1K_0	-	-	-	-
N_1K_1	26.7-39.5	33.8	9.4-22.3	14.8
N_1K_2	38.3-42.7	40.5	20.7-25.1	22.2
N_1K_3	39.2-43.6	38.3	20.7-36.7	29.7
N_2K_0	-	-	-	-
N_2K_3	29.0~38.2	29.3	12.2~25.1	18.3

Source: Xie *et al.*, unpublished data; *In:* Zhang *et al.*, 2011.

* These experiments were conducted in Suiping and Xiping County, Henan Province, and Feidong County, Anhui province. The N1 and N2 rates were 195-240 and 255-312 kg N ha^{-1}. The K1, K2 and K3 rates were 105,150 and 195 kg K_2O ha^{-1}.

** Recovery efficiency of K (%) = Plant K uptake [(K fertilized – K unfertilized)/amount of K fertilizer] ×100.

*** Increase of use efficiency of N (%) = Plant N uptake [(K fertilized – K unfertilized)/ amount of N fertilizer] ×100.

and 19.5 kg grain/kg N in maize (Prasad, 2009).

The highest biological yield of wheat was obtained by foliar application of KCl along with N as urea compared with other treatments, namely, the control (no spray), KNO_3, KCl, and N as urea only (Khan *et al.*, 2006). A positive N-K interaction has been reported in many long-term experiments (Belay *et al.*, 2002; Cai and Qin, 2006; Wang *et al.*, 2007a). Response to K applications in both rice and wheat increases with N application, indicating that higher K rates are required at higher N rates (Mondal, 1982). The recovery efficiencies of K (RE_K) and N fertilizer in maize increased at 105-150 kg K_2O ha^{-1} and 195-240 kg N ha^{-1} (Table 4). Optimal N-K ratios favored crop growth and enhanced K and NUE. N-K interaction is not only positive for yields of rice and groundnut (Table 5) but it also improved the AE_N.

The interactions between N and K on crop growth and final yield seen at the agronomic level can be explained by their effects and interactions on the growth processes within the plant at the tissue and individual cell levels. Knowing how growth is controlled by these interactions within the plant makes it easier to understand why it is important to have sufficient exchangeable K in the soil. K has the property of high phloem mobility and, as a result, a high degree of re-utilization by re-translocation via the phloem (Marschner, 1995; Marschner *et al.*, 1997). K cycling and recycling play an important part in NO_3^- translocation from root to shoot as counter ion and assimilate loading in the phloem (Maathuis, 2007). The partitioning and the amount of phloem re-translocation of K^+ from the shoot and cycling through the root are quite different depending on plant type and can be changed by stress (Jiang *et al.*, 2001; Lu *et al.*, 2005). Cycling and recycling of K^+ increased with increasing shoot growth rate, which is in accordance with the suggested role of K^+ for charge balance of NO_3^- in the xylem and organic acids in the phloem (Engels and Kirkby, 2001). The changes in K^+ concentration in the cortex were related to the role of K^+ in the transport of NO_3^- in the xylem and effects on recycling to the roots in the phloem (Jarvis *et al.*, 1990). The effect of K in increasing agronomic efficiency may vary under different situations. With the application of 50 kg K_2O ha^{-1} the AE_N was much higher in sorghum fodder (f) as compared to wheat (Table 6).

Table 5. N-K interaction effect on yield and AE$_N$ in rice and groundnut.

K rates	N rates (kg ha^{-1})				N rates (kg ha^{-1})			
	60	80	60	80	60	80	60	80
	Rice yield		AE$_N$		Groundnut pod yield		AE$_N$	
kg ha^{-1}	-------*mt ha^{-1}*-------		-------*kg kg^{-1}*-------		-------*mt ha^{-1}*-------		-------*kg kg^{-1}*-------	
0	3.10	3.02			1.68	1.70		
30	3.40	3.30	5.16	3.50	1.84	1.93	2.66	2.87
60	3.64	3.61	9.00	7.37	2.07	2.15	6.50	5.62
90	3.75	3.83	10.83	10.12	2.06	2.23	6.30	6.62
Mean	3.48	3.44			1.91	2.00		
LSD (0.05): N=NS, K=0.10, N×K=0.12					N=0.05, K=0.08, N×K=NS			

Source: Mitra *et al.*, 2001.

Table 6. Effect of N-K interaction on yield and AE$_N$ in wheat and sorghum.

K rates	N rates (kg ha^{-1})		AE$_N$	N rates (kg ha^{-1})		AE$_N$
	0	120		0	80	
	Wheat yield			Sorghum (f) yield		
kg ha^{-1}	------*kg ha^{-1}*------		*kg kg^{-1}*	------*kg ha^{-1}*------		*kg kg^{-1}*
0	1.42	1.52	0.83	5.27	5.24	-
50	1.89	2.12	1.85	5.48	6.72	15.5
Mean	1.63	1.82		5.37	5.98	
LSD(0.05): N=0.16, K=NS, N×K=NS				N=0.42, K=NS, N×K=0.53		

Source: Golakiya *et al.*, 2001.

Table 7. Effect of K application on PFP$_N$ in pearl millet at two levels of applied N.

K rates (kg K ha^{-1})	90 kg N ha^{-1}		120 kg N ha^{-1}	
	PFP$_N$	Increase	PFP$_N$	Increase
	kg kg^{-1}	*%*	*kg kg^{-1}*	*%*
20	23.8	-	20.3	-
40	26.6	11.7	22.6	11.3
60	27.8	16.8	23.8	17.3

N level 120 kg N ha^{-1}

Source: Yadav *et al.*, 2007.

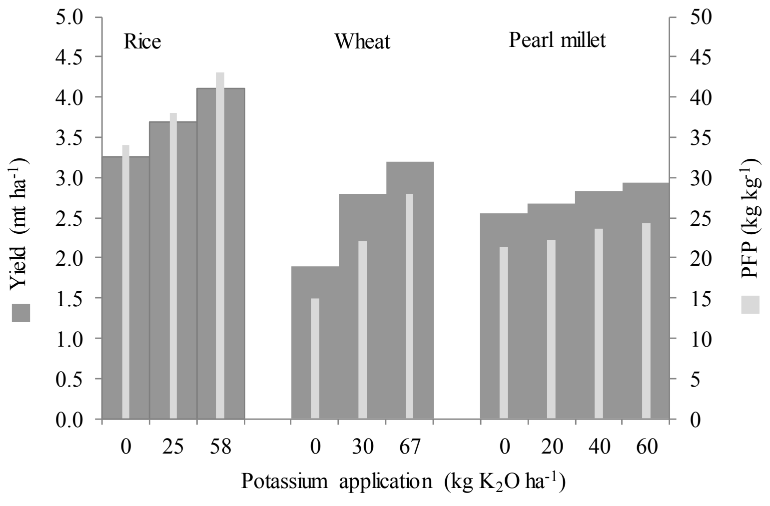

Fig. 4. Effect of applied K on PFP$_N$ and yield of rice, wheat and pearl millet.

Adapted from: Magen and Nosov, 2008; Yadav *et al.*, 2007.

K application and partial factor productivity of N (PFP$_N$; kg yield per kg N applied)

In India, the PFP$_N$ is decreasing over time. An initial decline in PFP$_N$ is an expected consequence of the adoption of N fertilizers by farmers and is not necessarily a problem within the system contexts (Bijay-Singh and Yadvinder-Singh, 2008). However the low PFP$_N$ during the last decade is due to low fertilizer NUE and is of particular concern. The application of K not only improved the yield of rice, wheat and pearl millet but also improved the partial factor productivity of applied N (Fig. 4). The study carried out by Yadav *et al.* (2007) further revealed that application of K increased the partial factor productivity of N irrespective of the level of applied N (Table 7). The PFP$_N$ in pearl millet was increased at the application of 90 kg as well as 120 kg N ha^{-1} but the increase at the higher level of N was more the result of the combination with the high level of K.

Application of K greatly influenced PFP$_N$ (kg grain/kg applied N) in maize. At different locations/years and with the application of K the PFP$_N$ varied from 21.1 to 53.3 kg grain/kg applied N (Table 8). Averaged over years and sites the PFP$_N$ was 32.7, 35.3, 38.0, and 39.0 kg grain/kg applied N at 0, 30, 60, and 90 kg of applied K$_2$O ha^{-1}. The graded levels of applied K increased PFP$_N$ by 7.9, 16.2 and 19.3%, over K$_0$ application. Nitrogen recovery (kg N uptake/kg applied N) varied from 19 to 50% at different locations/years and on average increased from 32 to 41% in K$_0$ and K$_{90}$ treated plots, indicating the favorable effect of applied K on N utilization. The practical implication of this will be the improved utilization and a lower loss of applied N under balanced fertilization.

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Table 8. Effect of K on PFP_N (kg grain kg^{-1} N) and apparent N recovery (%) in maize.

K level	2003	2004	2005	2006	2007	Average	Increase over K_0
kg K_2O ha^{-1}			PFP_N *(kg kg N^{-1})*				*%*
0	21.1	32.0	26.8	38.2	45.4	32.7	-
30	24.2	37.9	27.3	39.5	47.6	35.3	7.9
60	27.0	41.8	27.4	41.3	53.3	38.0	16.2
90	26.4	40.9	30.9	48.2	48.8	39.0	19.3
			Apparent N recovery (%)				
0	19	32	30	41	40	32	-
30	22	39	31	41	44	35	9.3
60	24	44	30	41	42	36	12.5
90	23	46	37	50	47	41	28.1

Source: Brar *et al.*, unpublished data.

Table 9. Increase in grain yield and NUE achieved at IPI on-farm experiments in Asia and Europe.

Crop	Country	N rates	K rates	Yield increase	Increase in NUE
			kg ha^{-1}		*%*
Maize	India	125	30-90	200-1300	18 (6-29)
	China	150	75-180	200-1800	18 (5-29)
	Ukraine	30	30	720	15.5
Rice	Bangladesh	100	33-66	690-900	26.3 (23-30)
Wheat	China	90	60-120	230-610	10-23

Range in brackets.

Source: Magen and Nosov, 2008.

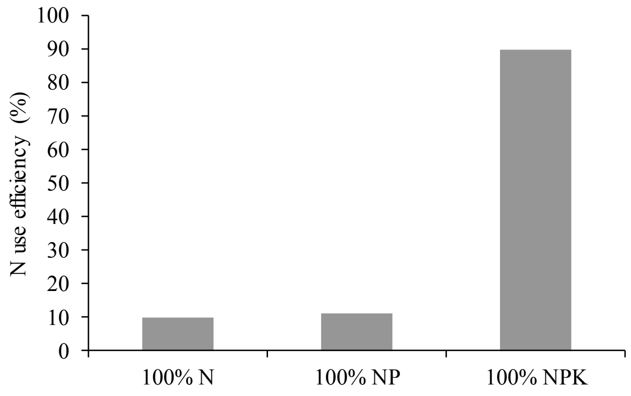

Fig. 5. NUE in finger millet with K application on K deficient Alfisols in Bangalore, India.

Source: Vasuki *et al.*, 2009.

K application and NUE

Fertilizer NUE is controlled by many factors such as crop demand for N, supply of N from the soil, fertilizer and manure application and losses of N from the soil-plant system. Imbalanced and inappropriate use of N and other nutrients such as K in agro-ecosystems can modify NUE. On-farm experiments carried out by IPI in Asia and Europe suggest that besides yield, the NUE, on average, can be increased from 15.5% in the Ukraine for maize to 26.3% for rice in Bangladesh with the application of appropriate amounts of K (Table 9).

The NUE normally depends on the extent of deficiency of K. On K deficient alfisols in Bangalore, India, there was a spectacular increase in NUE with the application of K. In the absence of applied K the application of both N and P failed to improve the NUE. NUE increased from 10% to 90% with the application of K on red laterite K deficient soils (Vasuki *et al.*, 2009, Srinivasarao 2010) (Fig. 5).

Conclusion

Balancing the fertilizer N application of different crops with fertilizer K is an urgent need to achieve higher NUE.

A gain of 20% in NUE can easily be achieved via balanced fertilization with K. A positive relationship between N and K exists for the uptake and utilization of N by plants to form protein and amino acids which ultimately affect the quality and yield of crops. Balanced use of N and K fertilizers in cereals and other crops will not only prove more profitable for farmers but also lead to reduced environmental degradation and climate change effects caused by dissipation of N originating from agricultural soils.

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