Potassium Nutrition of Rice-Wheat Cropping System

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INTRODUCTION

Rice (*Oryza sativa* L.) and wheat (*Triticum aestivum* L.) grown sequentially in an annual rotation constitute a rice-wheat system. It brings together conflicting and complementary practices as repeated transitions from aerobic to anaerobic to aerobic soil conditions result in unique changes in soil structure, physical, chemical and biological environment and nutrient relations. In annual cycle, suitable thermal conditions for both rice and wheat exist in warm-temperate and subtropical areas and at high altitudes in the tropics. The rice-wheat rotation is one of the world's largest agricultural production systems, occupying 26 M ha of cultivated land in the Indo-Gangetic Plains and in China. It accounts for about one-third of the area of both rice and wheat grown in South Asia and its production provides staple grains for more than one billion people, or about 20% of the world's population. In the Indo-Gangetic plain spread over India, Pakistan, Nepal and Bangladesh (**Figure 1**), more than 10 M ha in India is occupied by rice-wheat system (**Table 1**). Only 23% of the total rice area in India produce wheat and approximately 40% of the wheat area produce rice. This paper addresses primarily to rice-wheat system in the Indian part of the Indo-Gangetic plain.

During 1960 to 1990, genetic improvements leading to development of highly fertilizer-responsive rice and wheat varieties and improved management strategies resulted in a dramatic rise in productivity and production from rice-wheat system. Both rice and wheat are exhaustive feeders, and the double cropping system is heavily depleting the soil of its nutrient content. A rice-wheat sequence that yields 7 t ha^{-1} of rice and 4 t ha^{-1} of wheat removes more than 300 kg nitrogen, 30 kg phosphorus, and 300 kg ha^{-1} of potassium from the soil. Even with the recommended rate of fertilization in this system, a negative balance of the primary nutrients still exists, particularly for nitrogen and potassium. The system in fact, is now showing signs of fatigue and is no longer exhibiting increased production with increases in input use.

Importance of potassium nutrition of rice-wheat system stems from two facts: (1) the removal of potassium by above ground plant parts and losses through leaching far exceeds the small additions through fertilizers and manures which should not be sustainable on a long-term basis, and (2) lack of balanced availability of nitrogen, phosphorus, and potassium to rice and wheat that may hinder in achieving the potential yields. Balanced application of nitrogen, phosphorus and potassium also means replenishing the soil potassium reserves which are being continuously mined by following high intensity rice-wheat cropping sequence and should also ensure transferring better soil to future generations of mankind. We have attempted to address these issues in this paper and discussed potassium nutrition of sequentially

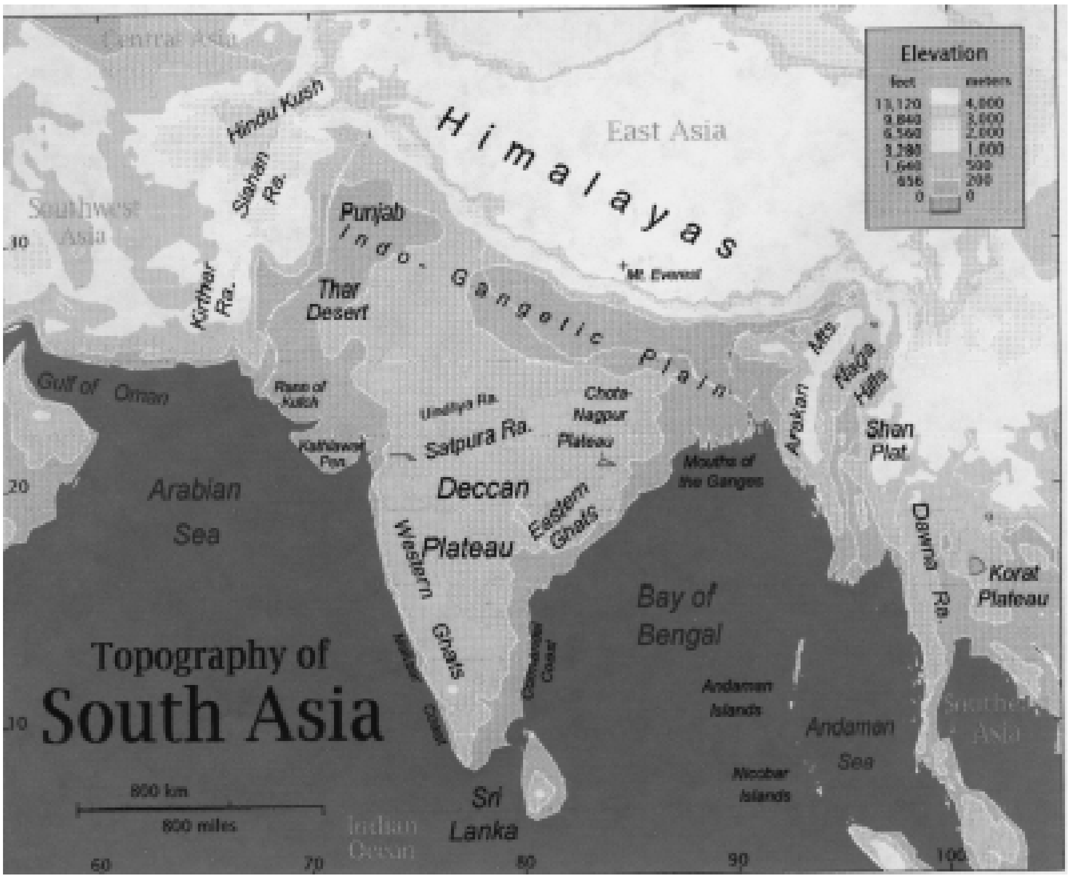

Figure 1. Location of Indo-Gangetic plain, the home of rice-wheat system in the South Asia

grown rice and wheat in the Indo-Gangetic plains of India in terms of producing high yields from this system and maintenance of soil fertility on sustainable long-term basis.

Table 1. Area under rice-wheat system in the Indo-Gangetic plain & contribution of rice plus wheat to total cereal production & total calorific intake in different countries

Country	*Area (Mha)*	*Area (%)*		*Contribution (%)*	
		Rice	*Wheat*	*Total cereal production*	*Total national calorific intake*
India	10.3	23	40	85	60
Pakistan	2.3	72	19	92	62
Bangladesh	0.5	5	85	100	94
Nepal	0.6	35	84	71	63

Adapted from Singh and Paroda (1994), Aslam (1998) and Yadav et al. (1998)

Potassium Fertilizer Use in the Indo-Gangetic Plain

General recommendation for application of potassium for rice is to apply 25 kg K ha^{-1} in Punjab and up to 50 kg K ha^{-1} in states like Uttar Pradesh and West Bengal. For wheat the range in the Indo–Gangetic plains is 21 to 58 kg K ha^{-1} (Tiwari, 2000). Diagnostic surveys (Yadav *et al.*, 2000b) have indicated that rice-wheat farmers in the Indo-Gangetic plain seldom adopt recommended fertilizers doses and potassium fertilizers are rarely used. Fertilizer use pattern for rice-wheat system in the Indo-Gangetic plains varies greatly from one part to another. For example, out of 36 districts in Punjab and Haryana states in the northwestern India, 34 districts consumed more than 100 kg (N + P_2O_5 + K_2O) ha^{-1} (**Table 2**). On the other hand, 95 out of 155 districts of the eastern part comprising Uttar Pradesh, Bihar and West Bengal consumed 100 kg (N + P_2O_5 + K_2O) ha^{-1} or less. While nitrogen remained heavily subsidized, reduction in subsidies of phosphate and potash in India adversely affected their consumption. This resulted in continued imbalanced fertilizer use. The N/K_2O was wider in northwestern states of Punjab and Haryana consuming highest amount of fertilizer per unit area as compared to in eastern states of the Indo-Gangetic plain (**Table 2**). Thus highest amount of potassium fertilizers are being applied in West Bengal followed by Bihar, Uttar Pradesh, Punjab and Haryana. Percentage of the total potassium fertilizer applied in the kharif season when rice is grown was, however, in the reverse order – highest in Punjab and lowest in West Bengal.

Table 2. Fertilizer consumption pattern in 1997-98 in different states in the Indo-Gangetic plains of India with particular reference to potassium

State	*No. of districts*	*Classification of districts on the basis of $N+P_2O_5+K_2O$ consumption (kg ha^{-1})*					*$N+P_2O_5+K_2O$ consumption (kg ha^{-1})*	*$N: P_2O_5 : K_2O$*	*Consumption of K fertilizer*	
		>200	*200-150*	*150-100*	*100-50*	*<50*			*kg K ha^{-1}*	*Share in kharif (%)*
Punjab	17	4	7	6	–	–	169.6	1:0.29:0.022	2.9	67
Haryana	19	3	5	9	1	1	139.9	1:0.28:0.006	0.6	69
Uttar Pradesh	83	3	13	21	15	31	117.5	1:0.24:0.038	3.5	42
Bihar	55	1	1	12	31	10	85.9	1:0.25:0.087	5.6	32
West Bengal	17	1	1	7	8	–	108.8	1:0.47:0.313	18.9	33

Source: Fertiliser Association of India (1999)

Potassium Fertility of Soils in the Indo-Gangetic Plain

Soils in the Indo-Gangetic plain generally contain sufficient exchangeable potassium and potassium bearing minerals able to release exchangeable potassium to meet crop requirements. Total potassium in alluvial soils of the Indo-Gangetic plain ranges from 1.28 to 2.77% and exchangeable potassium contents of 78-273 mg K kg^{-1} soil (Tandon and Sekhon, 1988). Potassium fertility of soils can be defined better by understanding the mineralogy of soil potassium and forms of potassium and their content in soils under rice-wheat system in the Indo-Gangetic plain.

Mineralogy of Soil Potassium

Potassium feldspars and micas are the potassium minerals present in the soils of Indo-Gangetic alluvial plains in northwest India (Sidhu, 1984). Potassium feldspar species present in these soils are microcline and orthoclase. Mica minerals present are muscovite and biotite in the coarser fractions and illite in the finer fractions. The dioctahedral mica-illite is partially weathered muscovite mica with layer charges less than that for muscovite; part of its charge originates in the octahedral layer, unlike the muscovite.

Soils in western and central Uttar Pradesh have illite and chlorite as the dominant clay minerals (Ghosh and Bhattacharya, 1984). Tarai soils contain largely illite and chlorite but also some mixed layer minerals, kaolinite and quartz. In the western Uttar Pradesh, smectite was found to be the dominant clay mineral along with illite, chlorite, kaolinite, quartz, feldspar and allophane. The salt affected alluvial soils in the Indo-Gangetic plain were found to contain smectite-mica and chlorite-vermiculite interstratified minerals. In the lower Gangetic basin, illite or smectite are the dominant minerals in the soils.

Sekhon *et al.* (1992) carried out a systematic study of mineralogical composition of silt and clay fractions in soil samples collected from 29 established soil series from all over India. Of these, 8 soil series are from rice-

Table 3. Mineralogical composition of clay and silt fractions in soil samples collected from rice-wheat growing regions of the Indo-Gangetic plains

Soil series and location	*Clay fraction*		*Silt fraction*	
	Dominant mineral	*Associated mineral*	*Dominant mineral*	*Associated mineral*
Nabha, Ludhiana, Punjab	Illite	Vermiculite, chlorite, quartz, feldspar, kaolinite	Quartz, mica	Vermiculite, feldspar
Khatki, Meerut, Uttar Pradesh	Illite	Chlorite, vermiculite, quartz, feldspar, kaolinite	Quartz	Mica, vermiculite
Akbarpur, Etah, Uttar Pradesh	Illite	Smectite, vermiculite, chlorite, kaolinite, quartz, feldspar	Quartz, mica	Vermiculite, feldsapr
Rarha, Kanpur, Uttar Pradesh	Illite	Vermiculite, chlorite, quartz, feldspar, kaolinite	Mica, quartz	Vermiculite, feldspar
Jagdishpur Bagha, Muzaffarpur, Bihar	Illite	Chlorite, smectite, quartz, feldspar	Quartz, mica	Feldspar, chlorite, vermiculite, 2:1-2:2 intergrades
Raghopur, Muzaffarpur, Bihar	Illite	Chlorite, smectite, quartz, feldspar	Quartz	Mica, feldspar, chlorite, vermiculite, 2:1-2:2 intergrades
Hanrgram, Bardhaman, West Bengal	Smectite, Illite	Vemiculite, kaolinite, quartz, feldspar, chlorite	Quartz	Mica, vermiculite, feldspar
Kharbona, Birbhum, West Bengal	Kaolinite	Illite, smectite, quartz, feldspar	Quartz	Mica, vermiculite, feldspar, kaolinite

Adapted from Sekhon et al. (1992)

wheat regions in the Indo-Gangetic plain. The results of this study as described in **Table 3** reveal that except in two series from lower Gangetic plains in West Bengal, illite is the dominant clay mineral in the 7 soil series spread over states of Punjab, Uttar Pradesh, and Bihar. Dominant minerals in the silt fraction in the entire Indo-Gangetic plain are quartz-feldspar, quartz-mica or quartz alone (**Table 3**).

Depending upon climate, vegetation and drainage, minerals continue to weather and proton exchange constitutes an important means for potassium release from micas. The degraded micas thus formed acquire inter-layer space from which more potassium can be released in time. However, if application of potassium fertilizer increases the concentration of potassium in soil solution, K^+ may get into expanded interlayer space and become fixed by reversing the weathering process. Since hydrated form of Ca^{2+}, the dominant cation in the solution of most soils under rice-wheat system in the Indo-Gangetic plain, is bigger in size than K^+, it enlarges the interlayer space releasing more K^+ in the process. When potassium is removed by plant roots from the soil solution, more potassium continues to be released from the clay minerals by cation (including proton) exchange. The gradual release of potassium from positions in the mica lattice results in the formation of hydrous mica or illite.

Forms of Soil Potassium

Soil potassium is often considered to exist in solution, exchangeable and non-exchangeable (fixed and structural potassium) forms. The amount of solution and exchange potassium is usually a small fraction of total potassium (1-2% and 1-10%); the bulk of soil potassium exists in potassium-bearing micas and feldspars (Sekhon, 1995). The amount of potassium present in the soil solution is often smaller than the crop requirement for potassium. Thus continuous renewal of potassium in the soil solution for adequate nutrition of high yielding varieties of rice and wheat is obvious. Similarly, exchangeable potassium component has to be continuously replenished through the release of fixed potassium and weathering of potassium minerals. Hence, potassium availability to crops is a function of the amounts of different forms of potassium in soil, their rates of replenishment and the degree of leaching. The release of potassium from illitic materials through weathering may account for the apparent lack of response to potassium in alluvial soils of the Indo-Gangetic plain. Dynamic equilibrium reactions occurring between different forms of potassium have a profound effect on the chemistry of soil potassium. The direction and rate of these reactions determine the fate of applied potassium and release of non-exchangeable potassium. Under certain conditions, added potassium is fixed by the soil colloids and is not readily available to plants. Clays of 2:1 type can readily fix potassium and in large amounts.

The extent of variation in the amount of water-soluble potassium as a proportion of exchangeable potassium suggests that for a given amount of exchangeable potassium , one soil may supply more potassium to plants than another. In general, illite dominant soils have a larger proportion of water soluble to exchangeable potassium than smectite dominant soils. This ratio however, differs among soils. For example, Brar and Sekhon (1986) studied four loam soils from Indo-Gangetic alluvium and found that desorption of potassium by electroultrafiltration differed considerably although the soils tested similar exchangeable potassium. Sekhon *et al.* (1992) determined different forms of potassium in samples collected from 8 well defined benchmark soil series in the Indo-Gangetic plain of India. The data are shown in **Table 4**. The water soluble potassium content in the soil varied from 0.37 to 0.80 me kg^{-1}. Exchangeable potassium content was influenced by the clay mineralogy of the series. The soils from Punjab, Uttar Pradesh and Bihar with illite as the dominant clay mineral contained 1.00 to 1.80 me kg^{-1}. But the two soils from West Bengal with smectite (Hanrgram) and kaolinite (Kharbona) as the dominant clay minerals contained 2.23 and 0.70 me kg^{-1} exchangeable potassium, respectively. Effect of clay mineralogy was also very striking in

Table 4. Forms of soil potassium in samples collected from nine soil series in rice-wheat growing regions of the Indo-Gangetic plain (average of three samples)

Soil series and location	***Water soluble K (me kg^{-1})***	***Exchange-able K (me kg^{-1})***	***Non-exchangeable K (me kg^{-1})***	***Total K (me kg^{-1})***
Nabha, Ludhiana, Punjab	0.70	1.46	34.2	676.9
Khatki, Meerut, Uttar Pradesh	0.37	1.80	39.7	692.3
Akbarpur, Etah, Uttar Pradesh	0.37	1.40	34.1	510.3
Rarha, Kanpur, Uttar Pradesh	0.38	1.73	47.6	705.1
Jagdishpur Bagha, Muzaffarpur, Bihar	0.67	1.00	49.3	464.1
Raghopur, Muzaffarpur, Bihar	0.80	1.37	56.4	666.7
Hanrgram, Bardhaman, West Bengal	0.47	2.23	15.4	315.4
Kharbona, Birbhum, West Bengal	0.46	0.70	2.5	89.7

Adapted from Sekhon et al. (1992)

influencing the non-exchangeable potassium content of the soils in the Indo-Gangetic plain. The two soils from West Bengal contained only 15.4 and 2.5 me kg^{-1} non exchangeable potassium, whereas all the remaining six soil series with illite as the dominant clay mineral showed very high content of non exchangeable potassium varying from 34.1 to 56.4 me kg^{-1}. Trends in total potassium content were also similar to that for non-exchangeable potassium; minimum potassium contents were observed in soils from West Bengal. The typical illitic soils with highest intensity of rice-wheat cropping system in the Indo-Gangetic plain contained from 464 to more than 700 me kg^{-1} total potassium.

Assessment of Potassium Supplying Capacity of the Soils

Soil testing is widely used in the Indo-Gangetic plain to estimate amount of potassium that may become available to plants during rice and wheat cropping seasons. Use of 1*M* ammonium acetate at pH 7.0 to extract plant available potassium (exchangeable + water soluble potassium) is the most used soil potassium availability index. But its suitability as a measure of plant available potassium remains controversial, particularly when soils with different textures and clay mineralogy are considered together. For example, in Gurdaspur (Punjab), 40% of soil samples were found to be deficient in potassium while only 7% of the plant samples exhibited deficiency of potassium (Tandon and Sekhon, 1988). Critical levels for 1*M* ammonium acetate-extractable potassium for rice soils has been reported to vary from 0.17-0.21 cmol K kg^{-1} (Prasad and Prasad, 1992). Soils have been grouped into 3 categories of low, medium and high on the basis of 1*M* ammonium acetate extractable potassium values; soils analyzing < 55 mg K kg^{-1} soil are rated as low with respect to available potassium and soils analyzing >110 mg kg^{-1} soils are rated as high in available potassium. Tandon and Sekhon (1988) suggested that soils with low available potassium are expected to readily respond to potassium application. Soils with low available potassium and high in reserve potassium status will need lower rates of potassium application and soils with high available and low reserve potassium status can support crops for some years without potassium fertilizer application.

Most of the soils in the Indo-Gangetic plain contain illite as dominant clay mineral. The high root density, relatively high maximum influx and low minimum solution concentrations for potassium uptake indicate that rice and wheat depend on non-exchangeable fraction for much of their potassium supply in these soils (Meelu *et al.*, 1995). Hence, it appears desirable to include a measure of non-exchangeable potassium in our estimate of plant available potassium. A measure of non-exchangeable potassium in soil is determined by boiling 1*M* HNO_3, but this availability index is not always correlated to grain yields and total potassium uptake by rice and wheat. Information is now available to show that sub-soil potassium fertility makes a significant contribution to plant nutrient, and that differences in the mineralogy and reserve potassium and relationship between exchangeable potassium and water soluble potassium among soil series and soil types suggest the need for different rates of critical limits for different soils (Sekhon, 1995). In addition, ammonium acetate-extractable potassium for soil testing should include soil properties such as clay content, cation exchange capacity and organic matter content. On alkaline soils, reduced potassium activity in soil solution from preferential potassium adsorption may contribute to low potassium uptake by rice, when ample potassium is available (Dobermann *et al.*, 1996). Other methods such as Q/I relationship and electro-ultra filtration are laborious and/or expensive and not used in routine analysis of soils.

All chemical soil tests used for potassium for rice and wheat production have theoretical limitations, including that (1) nutrient availability in irrigated rice-wheat ecosystem is extremely dynamic and tests on air-dried soil may not fully reflect nutrient status after submergence, (2) differences in clay mineralogy and physical properties have a strong impact on desorption characteristics and plant availability (3) unextracted nutrient pools may also contribute to plant uptake, (4) diffusion is a key process of potassium transport to the root surface, and (5) kinetics of nutrient release are not measured. Dynamic soil tests overcome many of the theoretical limitations associated with rapid chemical extractions (Dobermann *et al.*, 1998). The resin capsule, for example, integrates intensity, quantity and delivery rate measures of P and K supply to the rice and wheat roots and it provides parameters that help to assess both short and long-term nutrient supplying power in a dynamic manner. In spite of conclusive evidence of the role of non-exchangeable potassium in plant nutrition and the role of soil texture on potassium release, most soil testing laboratories yet do not seem to be taking these into account while making potassium recommendations. The question of critical limits of potassium in soil continues to first problem of interpretation. More work is required for developing field applicable critical limits for diagnosing the potassium deficiencies in soils and crops.

Potassium Removal by Rice-Wheat System

The amount of potassium removed by rice-wheat cropping system can be as high as 325 kg ha^{-1} (**Table 5**). Field crops generally absorb potassium faster than they absorb nitrogen or phosphorus or build up dry matter. The removal of potassium depends on the production level, soil type and whether crop residues are removed or recycled in the soil. When crop residues are retained in the field, large amounts of potassium are recycled. Average potassium uptake per ton of grain is about 27.3 kg ha^{-1} for wheat and 25.0 kg ha^{-1} for rice (Tandon and Sekhon, 1988). Removal of potassium by rice-wheat system far exceeds its additions through fertilizers and recycling. Optimum application of nitrogen increased potassium uptake by 57% over control plots and nitrogen and phosphorus application increased potassium uptake by 145% (Tandon and Sekhon, 1988).

Table 5. Nutrient (nitrogen, phosphorus and potassium) removal by rice-wheat cropping systems

Cropping system	*Total productivity (t ha^{-1})*	*Nutrient uptake (kg ha^{-1})*			*Reference*
		N	*P*	*K*	
Rice-wheat	13.2	278	53	287	1
Rice-wheat-cowpea	9.6 + 3.9 (dry)	272	67	324	2
Rice-wheat-jute	6.9 + 2.3 (fibre)	170	33	212	2
Rice-wheat	107	185	38	271	3
Rice-wheat	8.8	235	40	280	4
Rice-wheat-mungbean	11.2	328	30	279	5

1. Kanwar and Mudahar (1986); 2. Nambiar and Ghosh (1984); 3. Saggar et al. (1985); 4. Sharma and Prasad (1980); 5. Meelu et al. (1979)

Response of Rice-Wheat System to Applied Potassium

Yield response to applied potassium is a function of crop, variety, soil characteristics and application of other nutrients. Rice tends to respond more to potassium than wheat. Possibly, due to retarded respiration rates of roots under anaerobic soil conditions, adequate absorption of potassium by rice roots can only be ensured by high potassium levels in the soil. Earlier studies conducted on large number of farmers fields showed that application of 50 kg K ha^{-1} gave response of 290 and 240 kg grain ha^{-1} in wheat and rice, respectively (Randhawa and Tandon, 1982). Average agronomic response of

6 kg grain kg^{-1} K to the application of 37.5 kg K ha^{-1} was observed in rice and wheat. In later studies carried out in Punjab, Haryana and Uttar Pradesh, response of rice to 25-50 kg K ha^{-1} ranged from 210-370 kg grains ha^{-1} (Meelu *et al.*, 1992). Dobermann *et al.* (1995) observed significant yield increase of 12% to potassium in rice at Pantnagar. In a 5-year field study on a sandy loam soil (ammonium acetate extractable potassium-123 kg ha^{-1}), application of 25 kg ha^{-1} resulted in a mean increase in yield of rice and wheat by 280 and 160 kg grain ha^{-1}, respectively, (Meelu *et al.*, 1995). In a number of long-term experiments on rice-wheat system located all over the Indo-Gangetic plain (**Table 6**), average response to application of 33 kg K ha^{-1} over 120 kg N and 35 kg P ha^{-1} to each crop ranged from 0 to 0.5 t ha^{-1} in rice and 0 to 1.3 t ha^{-1} in wheat. The low responses to fertilizer potassium observed in rice and wheat on alluvial soils of the Indo-Gangetic plain suggest that release of native potassium from illitic minerals in these soils could meet the potassium needs of these crops (Hundal and Pasricha, 1993).

Table 6. Response of sequentially grown rice and wheat (t ha^{-1}) to application of potassium in long-term experiments conducted in the Indo-Gangetic plains of India

Location	*Years*	*Crop*	*No NPK*	*N*	*NP*	*NPK*
Barrackpore†	1972-97	Rice	1.6	3.5	3.9	4.0
		Wheat	0.8	2.1	2.3	2.4
Pantnagar†	1972-96	Rice	3.4	5.0	5.0	5.4
		Wheat	1.6	3.8	3.8	3.9
R.S. Pura	1981-90	Rice	2.1	4.2	4.8	4.8
		Wheat	1.1	1.9	3.1	3.5
Palampur	1978-89	Rice	2.3	4.1	4.0	4.5
		Wheat	1.2	1.3	2.4	3.7
Faizabad	1977-90	Rice	1.0	3.9	4.7	4.8
		Wheat	0.8	3.6	4.5	5.5
Kanpur	1977-87	Rice	1.7	3.5	4.2	4.4
		Wheat	1.2	3.5	4.1	4.2
Pantnagar	1977-90	Rice	2.3	4.0	4.2	4.4
		Wheat	1.4	3.5	3.5	3.5
Varanasi	1977-88	Rice	2.1	4.1	3.7	3.8
		Wheat	1.3	3.1	3.5	3.6
Rewa	1978-90	Rice	2.0	3.9	4.1	4.2
		Wheat	1.0	1.5	2.7	2.9

Adapted from Swarup (1998)† and Hegde and Sarkar (1992)

Using time series analyses, Bhargava *et al.* (1985) showed that response to potassium has been increasing with time. The response of wheat to potassium in different agroecological regions was in the range of 6.7-12.7 kg grain kg^{-1} K during 1977-1982 as against 2.0-5.0 kg grain kg^{-1} K during 1969-1971. The corresponding values for rice were 6.5-10.7 kg and 1.8-8.0 kg grain kg^{-1} K (**Table 7**). The increasing trend in response to potassium over the years suggests the need for its application in intensive rice-wheat cropping system.

Table 7. Response of rice and wheat to applied potassium (along with nitrogen and phosphorus) in different agroecological regions over different periods

Region	*Response of 50 kg K ha^{-1} (kg grain kg^{-1}K)*			
	Rice		*Wheat*	
	1969-71	*1977-1982*	*1969-71*	*1977-82*
Humid, Western Himalayan	8.0	10.7	5.0	12.7
Subhumid, Satluj-Ganga Alluvial Plain	4.8	7.0	3.4	7.8
Subhumid to humid Eastern Uplands	4.4	9.8	2.0	7.1
Arid western Plains	1.8	6.5	2.6	6.7

Adapted from Bhargava et el. (1985)

A large proportion of area (about 2.8 M ha) in the Indo-Gangetic plain is highly alkaline (pH >8.5) and contains excessive concentration of soluble salts, high exchangeable sodium percentage (> 15%) and $CaCO_3$. Swarup and Singh (1989) found that application of fertilizer potassium did not significantly increase crop yields in rice-wheat rotation on reclaimed sodic soils in Haryana even after continuous cropping for 12 years. However, in salt affected soils of Kanpur, application of 25 kg K ha^{-1} to both crops produced additional grain yield of 0.50 and 0.61 t ha^{-1} of rice and wheat, respectively (Tiwari *et al.*, 1998).

Time and Method of Potassium Application

Common recommendation is to apply full dose of potassium as basal at puddling for rice and at sowing of wheat. When cation exchange capacity of soil is low and drainage in soil is excessive, basal application of potassium to rice should be avoided. Because rice and wheat require large quantities of potassium, a sustained supply is necessary up to heading stage when the reproduction stage is complete. On coarse textured soils, split application of fertilizer potassium in both rice and wheat may give higher nutrient use efficiency than its single application due to reduction in leaching losses and luxury consumption of potassium (Tandon and Sekhon, 1988). Tiwari *et al.* (1992) have cited several references showing distinct benefit of applying potassium in split doses. In Punjab, Kolar and Grewal (1989) reported a yield advantage of 250 kg grains ha^{-1} by split application of potassium (half at transplanting + half at active tillering stage) as compared with single application at transplanting. Similarly, in a sandy loam soil of Uttar Pradesh, Singh and Singh (1987) reported a yield advantage of 440-490 kg grain ha^{-1} in wheat by split application of potassium as compared to a single application. At sowing of wheat and transplanting of rice, potassium fertilizers are normally applied by drilling, placement or broadcast followed by incorporation. Muriate of potash (KCl) is a major fertilizer potassium source for rice and wheat because of its low cost and high potassium analysis. However, its use in salinity affected areas is discouraged. Potassium sulphate may be used in areas with S deficiency.

Interactions of Potassium With Other Nutrients

The interaction among plant nutrients is a common feature of crop production. Potassium plays an important role in ensuring efficient utilization of nitrogen. Large quantities of nitrogen used in intensive rice-wheat cropping system encourage crop uptake of nitrogen and potassium and in turn heavy depletion of soil potassium. Application of nitrogen and phosphorus resulted in 145% increase in potassium uptake as compared to control (Tandon and Sekhon, 1988). If insufficient nitrogen and phosphorus or other essential plant nutrients restrict the crop development, amount of potassium present even at low soil test values may be sufficient to meet crop needs. Tiwari *et al.* (1992) reported that response to potassium application in rice increased with increasing rate of nitrogen application. In order to obtain high yields, need for applying increasing rate of potassium with increasing levels of nitrogen was suggested.

Effect of Potassium Fertility Status of Soils on Response to Potassium

Responses of rice and wheat to potassium application are expected to be high on soils testing low in 1*M* ammonium acetate-extractable potassium than on high potassium soils. Significant responses of wheat to applied potassium were observed up to 25 kg K ha^{-1} on soils testing low in available potassium in Punjab, but no significant increase in wheat yield was observed on soils testing medium and high in available potassium (Sharma *et al.*, 1978; Stillwell *et al.*, 1975; Yadvinder-Singh and Khera, 1998). Rana *et al.* (1985) observed that rice responded to 50 kg K ha^{-1} on soils testing low and medium in available potassium, but no significant response to applied potassium was observed on soils testing high in available potassium. Experiments carried out by Kapur *et al.* (1984) revealed that wheat responded up to a dose of 75 kg K ha^{-1} on low potassium soils and up to 50 kg K ha^{-1} on medium and high potassium soils. On the same lines, Azad *et al.* (1993) observed that whereas wheat yield increased significantly up to 75 kg K ha^{-1} on soils testing low in available potassium, significant increase in wheat yield was observed only at 25 kg K ha^{-1} on soils testing medium as well as high in available K. Based on results of more than 2200 trials with wheat, similar relationship was observed by Tandon (1980). Tandon and Sekhon (1988) concluded that response of high yielding varieties of rice and wheat to K application in soils rated medium in available K were only marginally lower than responses in low K soils. Such results emphasize the need for fresh look at soil fertility limits used for categorizing soils into low, medium and high with respect to available K, particularly for highly productive rice-wheat cropping system.

Field experiments conducted at different locations in the Punjab showed that rice responded more to applied potassium in north-eastern districts (Gurdaspur, Amritsar, Kapurthala and Hoshiarpur) than in central and south-western districts (Ludhiana, Bathinda, Sangrur, Ferozepur) (Singh and Bhandari, 1995). The values of available potassium in soil ranged from 150-180 kg K ha^{-1} in southwestern districts and 112-165 kg K ha^{-1} in central and northeastern districts. The lower rates of potassium release from clay minerals could be possible reason for the greater responses to applied potassium in northeastern districts as compared to control and southwestern districts (Hundal and Pasricha, 1993). A recent study (1997-2000) conducted at two locations in Punjab showed that both rice and wheat responded significantly to potassium application up to 50 kg K ha^{-1} on loam soil at Gurdaspur, whereas no significant increase in crop yields was observed on sandy loam soil at Ludhiana. Soils at both the locations tested low in available potassium. These studies suggest that same test values represent different potassium supplying capacity of different soils.

Changes in Soil Potassium Under Rice-Wheat System

Deficiency of potassium in the Indo-Gangetic plain is not as wide spread as nitrogen and phosphorus but soils testing high with respect to available potassium some years ago are becoming potassium-deficient due to heavy removal by rice and wheat and inadequate potassium application. Since depletion of soil potassium reserves is a matter of deep concern from the point of view of sustainability of rice-wheat system, it is important to analyze the data from long-term experiments so as to plan efficient management of both potassium fertilizers and soil potassium reserves. In six out of 8 benchmark soil series in the Indo-Gangetic plain studied by Sekhon *et al.* (1992) for detailed characterization of potassium, measurements were made again after 10 years to assess changes in potassium fertility of soils. The data pertaining to changes in ammonium acetate and HNO_3 extractable potassium are listed in **Table 8**. Both the indices show considerable decrease in availability of potassium in a span of 10 years thereby suggesting that crops may start responding to potassium fertilizer in course of time. Tiwari (1985) observed a decline in available and non-exchangeable potassium by 17% and 2.8% after two cropping cycles measured on 14 fields at Kanpur (Uttar Pradesh). In long-term experiments progressing at different locations in the Indo-Gangetic plain, a decrease in available potassium has been observed at all sites in treatments where no potassium has been applied during 13 to 14 year period (**Table 9**). Except at Ludhiana, a decrease in available potassium content of soil was noticed even in treatments receiving potassium for both wheat and rice. These data suggest that fertilizer doses considered as optimum can still result in potassium depletion from the soil at high productivity levels and in the process become sub-optimal doses.

Table 8. Changes observed in potassium fertility in some soil series in rice-wheat growing regions of the Indo-Gangetic plain

Soil series and location	*Ammonium acetate – K ($mg\ kg^{-1}$)*		*HNO_3 – K ($mg\ kg^{-1}$)*	
	First sampling	*After 10 years*	*First sampling*	*After 10 years*
Nabha, Ludhiana, Punjab	104±54	63±41	965±255	875±230
Akbarpur, Etah, Uttar Pradesh	125±41	71±23	1448±203	1231±188
Rarha, Kanpur, Uttar Pradesh	95±33	79±20	1531±353	1497±180
Hanrgram, Bardhaman, West Bengal	132±53	93±16	425±160	400±191
Kharbona, Birbhum, West Bengal	42±17	29±16	119±34	109±26

Adapted from Sekhon (1999)

In rice-wheat system, potassium is readily displaced from the exchange complex due to increased concentrations of Fe(II), Mn(II) and ammonium during flooding phase (rice) (Ponnamperuma, 1972). Though the displacement of potassium from the exchange complex ceases during aerobic phase (wheat), Kadrekar and Kibe (1973) and Singh and Ram (1976) have shown that alternating wetting and drying increases the availability of exchangeable potassium in the soil. Nevertheless, as discussed by Dobermann *et al.* (1996) for a Pantnagar soil, perhaps due to unfavourable ratios of potassium to other cations (Ca^{2+}, Mg^{2+}, Fe^{2+}) in the soil, potassium nutrition of rice-wheat system in the Indo-Gangetic plains is not assured. The rapid decline in plant available potassium after flooding of dry soil (Cassman *et al.*, 1995; Olk *et al.*, 1995) some what similar in mineralogy to those found in the Indo-Gangetic plain contrast with the general view that flooding a soil increases the solution potassium.

Table 9. Changes in available potassium in soils in different treatments (no NPK, 50% NPK, 100% NPK†, 50% NPK + FYM, 50% NPK + crop residues, 50% NPK + green mnaure) in long-term fertility experiments on rice-wheat system at various locations in the Indo-Gangetic plain

Location	*Duration of the experiment*	*1M ammonium acetate extractable K (mg kg^{-1})*	
		At beginning	*After 12 to 15 years*
Ludhiana	1983-84 to 1997-98	46	4-17% increase (except in no NPK treatment)
Pantnagar	1983-84 to 1997-98	65	17-34% decrease
Kanpur	1985-86 to 1997-98	82	10-22% decrease
Faizabad	1984-85 to 1997-98	161	10-30% decrease
Sabour	1984-85 to 1997-98	58	7-14% decrease except in 50% NPK + FYM treatment

Adapted from Yadav et al. (2000a)
†100% NPK = 120 kg N + 26 kg P + 33 kg K ha^{-1}

Potassium Balance in Soils Under Rice-Wheat System

Introduction of modern production technologies for rice and wheat with high nitrogen responsive high yielding varieties has resulted in increased annual removal of potassium by above ground portions of the crops. Long-term studies have indicated that continuous rice-wheat cropping will lead to depletion of potassium in soil even when optimum levels of fertilizer potassium have been applied. From the nutrient removal data (**Table 5**) it is evident that in rice-wheat system annual removal of potassium equals or exceeds that of nitrogen, while the replacement of potassium by fertilizer represents only a fraction of nitrogen (**Table 2**). Furthermore, most of the potassium uptake in rice and wheat crops is stored in straws, which is mostly removed from the field as animal feed and is not directly returned to the soil. Long-term studies have shown that potassium balance in rice wheat system is highly negative and application of recommended doses of potassium has only slightly improved the potassium balance (**Figure 2**) (Nambiar and Ghosh, 1984). In a long-term experiment at Ludhiana, net negative potassium balance of more than 200 kg K ha^{-1} year^{-1} was observed when no potassium was applied to rice or wheat (**Table 10**). Application of fertilizer potassium to rice, wheat or both resulted in less negative potassium balance. Removal of all the straw from the fields leads to potassium mining at alarming rates because 80-85% of the potassium absorbed by rice and wheat crops is in the straw. Also one must keep in mind that potassium rates applied by most farmers are lower than those used in the long-term experiments.

The negative potassium balances mean that it will be impossible to maintain the present production levels of the rice-wheat system. Results from long-term fertility experiments in India show that crop response to potassium application start appearing over a period of time in soils which were initially well supplied with potassium (Nambiar and Ghosh, 1984). Such responses to

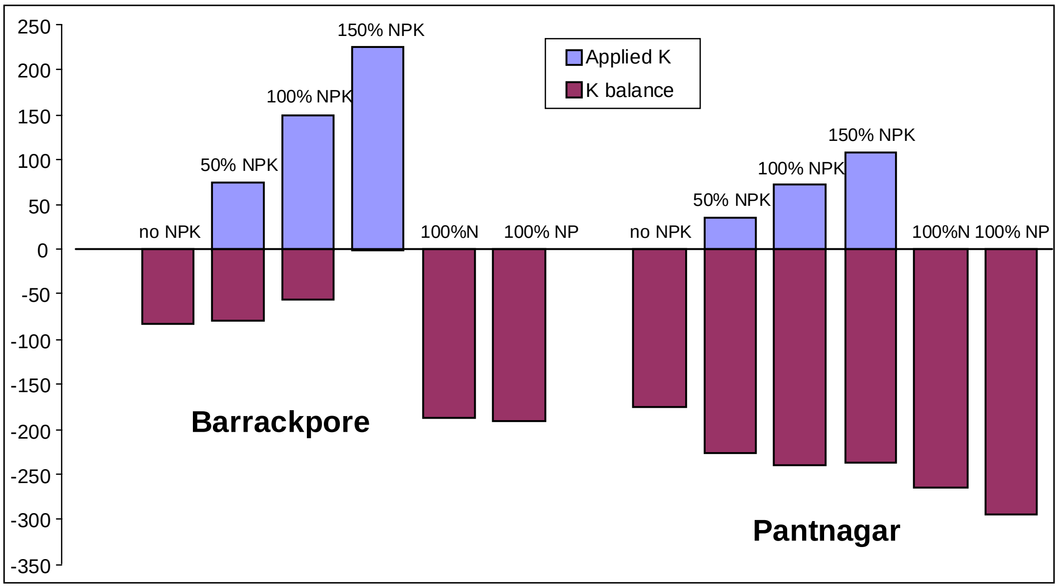

Figure 2. Potassium balance (applied minus removed by rice and wheat) in diffeent treatments in long-term experiments at Barrackpore and Pantnagar

Table 10. Annual potassium balance (applied as fertilizer minus removed by plants) as influenced by direct, residual and cumulative application of potassium in a rice-wheat system at Ludhiana in northwestern India

K applied (kg K ha^{-1})		*Mean grain yield of rice (1990-2000) (t ha^{-1})*	*Mean grain yield of wheat (1990-2000) (t ha^{-1})*	*Mean annual K balance (kg K ha^{-1})*
Rice	*Wheat*			
0	0	5.30	4.70	–215
0	25	5.36	4.90	–198
0	50	5.38	5.02	–182
0	75	5.45	4.98	–162
25	0	5.32	4.87	–211
50	0	5.42	4.75	–188
75	0	5.53	4.84	–173
25	25	5.39	4.96	–202
50	50	5.59	5.07	–161
75	75	5.53	4.97	–103

potassium started appearing after 3 years in rice and 11 years in wheat at Pantnagar (Uttar Pradesh) and after 3 and 7 years respectively at Barrackpore (West Bengal). Long-term studies suggest that application of FYM and recycling of crop residues can help improve the potassium balance in the rice-wheat cropping system. There is however, a need to work out long-term potassium balances in the rice-wheat system based on precise data on potassium removal from a field or region through straw, potassium inputs from irrigation or rainwater besides the well defined inputs and outputs such as fertilizers, manures and grains. Straw management can strongly influence potassium budgets and can help in efficient management of potassium for a sustainable rice-wheat system in the Indo-Gangetic plain.

Conclusions

A better understanding of potassium in soil in relation to productivity is immensely important to develop sustainable rice-wheat cropping system in the Indo-Gangetic plain. Due to nitrogen remaining heavily subsidized, there exists a continued imbalance in the use of nitrogen, phosphorus and potassium fertilizers. Amount of fertilizer potassium applied in different states varied from 3 kg K ha^{-1} in Punjab to 19 kg K ha^{-1} in West Bengal. Removal of potassium by rice-wheat system far exceeds its additions through fertilizers and recycling. Most of the soils in the Indo-Gangetic plain contain illite as dominant clay mineral and are medium to high in ammonium acetate (1*M*, pH 7.0) extractable potassium. Therefore, response of rice and wheat to applied potassium are generally small. Farmers apply very small quantities of potassium fertilizers to rice and wheat whereas total annual potassium removal by rice-wheat system exceeds 200 kg K ha^{-1} causing depletion of soil potassium supply. The suitability of ammonium acetate extractable potassium as an index of plant available potassium for different soils varying in texture and clay mineralogy remains controversial. Highly negative potassium balances (applied through fertilizers minus removal by crops) mean that it will be impossible to maintain the present production levels of the rice-wheat system. Potassium balances worked out after taking into consideration management of straw and potassium inputs from irrigation water may, however, suggest means and ways to achieve sustainability of rice-wheat cropping system.

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