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Potassium and Zinc Management in Rice (*Oryza sativa* L.) based on 4R concept - A Review

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Abstract

Plant growth is highly influenced by the nutrient supply from soil and the external application of fertilizers. Plants must receive essential nutrients like N, P, K, S and micronutrients for optimum plant growth and development. In current agricultural practices, especially, in cereal-based cropping systems, the soil nutrient balance like potassium and zinc are disturbed to the negative side due to intensive exploitation of native soil nutrients and low external input application. Employing 4R nutrient stewardship (right time, right dose, right source and right method) in soil nutrient management will ensure higher yield, nutrient uptake, nutrient use efficiency, increase in farm income, and minimal damage to the environment through its demand-specific supplement and management. Equilibrium between different pools of nutrients is the major driving factor for nutrient supply and demand in the soil which can be compensated by the external supply of nutrients through the 4R approach. Adoption of 4R stewardship in rice-based systems will ensure the attainment of maximum yield and nutrient use efficiency provided all other growth factors are in optimal supply and will assist in attaining self-sufficiency in rice production.

Keywords: Rice, Potassium, zinc and 4R concept.

Introduction

Rice-based cropping systems are more input-intensive and deplete substantial quantities of nutrients from the soil, which often exceeds their manual addition through external fertiliser sources leading to the deterioration of soil fertility and the emergence of multi-nutrient deficiencies (Ladha *et al.,* 2003, Vijayakumar *et al.,* 2019a, Vijayakumar *et al.,* 2021a). Moreover, current fertiliser consumption of 24.7 Mt of fertilizer (N + P_2O_5 + K_2O) per year, accounts for approximately 14.0% of total global fertilizer consumption. Research in India revealed that nutrient use efficiency/recovery efficiency of major nutrients like N, P and K are merely in the range of 30-35%, 20-25% and 35-40%, respectively (Subramanian *et al.,* 2020). Fertilizer input alone accounts for about 20-25% of the total production cost. Hence, proper management of nutrients is essential for achieving maximum yield and nutrient use efficiency besides environmental safety. An innovative and science based approach of "4R Nutrient Stewardship" (right fertilizer source, at the right rate, at the right time, with the right placement) that enhances timely nutrient supply, less environmental damage, more production and ensures sustainability (Vijayakumar *et al.,* 2021b).

4R -----	**Right source**	**Right Rate**	**Right Time**	**Right Place**

The research work carried out following the principle of 4R to improve the nutrient use efficiency for achieving higher productivity in rice with respect to potassium and zinc are presented here. The research highlighted here are taken under different soil and climatic conditions. Whereas the 4R strategy for N was documented by many researchers (Singh *et al.,* 2002; Surekha *et al.,* 2016; Vijayakumar *et al.,* 2019b; Vijayakumar *et al.,* 2019c) and hence, 4R practices for nutrients like K and Zn are highly important for rice crop and their management are discussed here.

Potassium (K)

Potassium is the third major essential nutrient element which is required by the plant in large quantities almost equal to nitrogen or sometimes even higher (Vijayakumar *et al.,* 2021a). It has a major role in most of the biological processes in the plant without becoming a part of an organic compound (Cakmak, 2005; Armengaud *et al,* 2009; Liu *et al,* 2011). India is the third largest consumer of NPK fertilizers in the world, with current annual consumption of about 18 million tons (Mt) of N+P_2O_5+K_2O, however, K constitutes only one-seventh of the total. As per soil test values, out of the 371 districts 76 (21%) are low in potassium, 190 (51%) are medium in potassium and 105 (28%) are high in potassium **(Table 1).** The southern states of India like Karnataka (3.02 LMT), Tamil Nadu (2.77 LMT), Andrapradesh (2.41 LMT) and Telangana (1.51 LMT) consumed higher K fertilizers (LMT=Lakhs of metric tonnes) (Indiastat, 2020).

Table 1: K status in Indian soil (post-green revolution era)

Number of Soil Samples	Number of districts studied	Per cent of the districts sampled			Reference
		Low	Medium	High	
1.3 million	184	20.0	53.0	27.0	Ramamoorthy and Bajaj (1969)
4.5 million	310	20.0	42.0	38.0	Ghosh and Hasan (1976)

Compared to N and P, Indian soils are rich in K and thus, the magnitude of response of rice to K application is relatively small and directly varies with the initial available K status. Even though most of the soils are known to supply K adequately through K buffering, response of rice crop to K fertilizer is noticed in certain situations such as intensive cultivation, acidic soils and light textured soils has become common calling for steps to generate information regarding its scientific management practices. In general, the response of rice to K depends on the fertility level of the soil, yield, variety, and season. Therefore, acquiring knowledge and better understanding on K management relies on best agronomic practices and soil management, which is highly important for sustainable production and management.

Table 2: K balance sheet in different states of India (Ramamurthy *et al.,* 2017)

State	Nutrients addition (000 t)	Removal (R)	Balance	Mining Index
Alluvial Soils				
Punjab	18.7	763.5	-744.8	40.7
Uttar Pradesh	113.6	1777.2	-1663.6	15.6
Haryana	4.6	490.1	-485.5	105.7
Black Soils				
Maharashtra	196.9	2095.6	-1899.1	10.6
Madhya Pradesh	24.1	848.8	-824.7	35.2
Red Soils				
Karnataka	216.1	603.6	-387.5	2.8
Lateritic Soils				
Kerala	87.3	175.6	-88.3	2.0
Desertic Soils				
Rajasthan	**7.0**	**1068.0**	**-1061**	**152.7**

Depending on soil type, approximately 90 to 98 per cent of total soil K is found in mineral form. The minerals *viz.,* feldspars and micas contain most of the K. Over long periods of time, these minerals weather, or break down, and K is released. As these minerals weather, some K moves to the slowly available pool. However, this process is too slow to supply the full K needs of field crops. The removal of K from soil in intensive cereal based cropping systems is equal or more than N. The net negative balance for K in the current agricultural scenario is 69% K. This negative balance is due to more removal of K (1.5 times than other element) and the amount of application lower than that of N and P. This huge negative difference of potassium is partly because crops remove an average of 1.5 times more potassium than nitrogen, and the application of potassium through fertilizers is considerably lower than that of N or P (Sanyal *et al.,* 2009) **(Table 2).**

Many reasons are there for the less attention towards the K viz, the benefits from N and P are more readily apparent from initial stages of crop growth; inadequate use of K fertilizers; lack of crop response to applied K, even on low K testing soils. However, significant responses to applied K is noted even in high K soils. To overcome such anomalies, intensive research on total K, exchangeable and non-exchangeable K, and K-fixing capacity of the soils under different soil-crop-climatic conditions and implementation of 4R to be followed widely. Releasing pattern of K from Mineral-K and their cycle of transformation is given below (Figure 1).

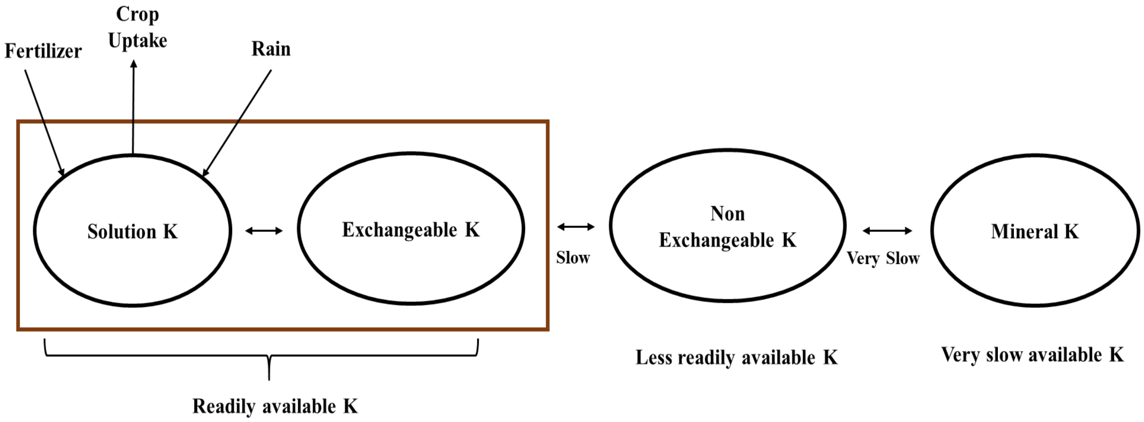

Figure 1: Potassium dynamics in soil

Right Source of K fertiliser

Source of fertiliser comes into the picture as the availability of existing soil K varies with soil factors. Muriate of potash (MOP) is the commonly used K fertiliser in Indian Agriculture. Grain yield was observed with SOP in the areas of S deficiency as it contains 17% sulphur (Surendran, 2005). The highest productivity and profitability were recorded with K_2SO_4 applied as foliar application than potassium nitrate and sulphate of potash. However, soil K application through K_2SO_4 and/or KNO_3 is essential to balance the K removal from soil (Hussain *et al.,* 2020). Moreover, application of graded level of K impacted the extractable K at different locations as 17% increase at Ludhiana, 34, 22, 30 and 14% decrease at Pantnagar, Kanpur, Faizabad and Sabour, respectively (Yadav *et al.,* 2000). Vijayakumar *et al.,* (2019) compared the effect of two potassium source *viz.,* potassium nitrate and muriate of potash on rice growth and yield and found non-significant effect.

Organic source of K

In case of cereal crops, 50-75% of the total biomass is left as a residue after harvesting and India produces around 130 Mt (34% of the total cereal residue) of residues every year (Vijayakumar *et al.,* 2021c). Cereal crops (rice, wheat, maize, millets) produce 352 Mt of residue every year which contributes 70% of the total residues. Recycling of crop residues is particularly important because they usually contain more K than the harvested seed. Crop residues can supply > 200 kg K ha^{-1} annually in rice-wheat system (Yadvinder-Singh *et al*., 2004). Crop residues of rice and wheat are the major source of organic matter (40% C of the total dry matter) and significant amounts of K as 12-17 kg and 9-11 kg ton^{-1}, respectively. However, K content in Indian rice straw is generally more (up to 25 kg ton^{-1}) than other parts of the world. Rice straw is a rich source of K and its incorporation into the soil increased the available K level of soil. There are many ways to use straw as a K source *viz.,* direct residue incorporation, composting and making ash or bio-char (readily available K). It is also cost-effective to apply ash or biochar blended with organic manures in suitable proportion when a huge amount of waste disposal is a problem (Adeoye *et al*., 2001). Retaining of crop residues markedly increases the K availability in soils and many researchers proposed to use crop residue as a potassium source (Chatterjee and Mondal, 1996; Sarkar, 1997; Mishra *et al*., 2001; Singh *et al*., 2010).

A wide range of K concentrations present in manures, compost, and well-matured composted materials act as a source of nutrients (Hue, 1995). Wood ash, plant residues, distillery wastes and blast furnace dust and cement kiln dusts are some of the other alternate sources of K which can be used for K nutrition in agriculture (Sekhon and Ghosh, 1982). A long-term fertilizer experiment conducted at Akola, Maharashtra found that all the fractions of K improved with application of FYM, Zn and sulphur in combination with NPK (Ravankar *et al.,* 2001). Many researchers have documented that increment of non-Exchangeable-K was observed when K application was carried out with plant resource such as rice straw, farmyard manure, green manure and compost. Application of wheat straw + green manure (GM) + rice straw was found to maintain the maximum level of non-exchangeable K followed by FYM + GM + rice straw (Pannu *et al.,* 2001). Use of FYM and green manure also increased the total K availability in soil but a net negative balance in total K was noticed (Sharma *et al.,* 2013). Continuous use of inorganic fertilizers and organic manures positively improved the potassium fractions in soil over control but resulted in negative balance of potassium based on 36 years of soybean-wheat cropping system. Moreover, the correlation studies revealed that total K was positively correlated with the source of K addition and yield of soybean which was followed by lattice K in the black soil (Sawarkar *et al*., 2013; Meena and Biswas, 2014).

Crop residue recycling (retaining crop residues after harvest) is an important strategy to maintain soil fertility. It is important to incorporate crop residues of potassium exhaustive crops (maize, wheat, rice etc.) into soil to add K to soil and prevent its loss. Retention of straw in the rice filed has improved the exchangeable K and non-exchangeable K by 26 and 2% in paddy soil (Yadvinder-Singh *et al*., 2004) and similarly application of 50% recommended K through rice straw (5 t/ha) increased the exchangeable and Non-Exchangeable K (Pavithra *et al.,* 2017). However, the application of rice straw 5 t/ha in soil could change the soil chemical properties meagerly (Tanh *et al.,* 2016) **(Table 3).** Appropriate time and water management are essential to reduce the negative effects of residue incorporation/retention such as release of phenolic compounds that affect nutrient availability (Chivenge *et al.,* 2020).

Table 3: Effect of rice straw incorporation on soil chemical properties

Treatment	pH	SOC	N	P_2O_5	K_2O
Before Experiment	4.10	0.80	0.08	0.034	0.52
Ash from 5 t ha^{-1} rice straw	4.32	1.09	0.09	0.046	0.60
5 t ha^{-1} rice straw	4.40	1.19	0.11	0.041	0.55

Bio-fertilizers-Potassic solubilizing Bacteria (KSB)

Inclusion of plant growth promoting potassium solubilising rhizobacteria (biological K-fertilizers) enhanced K availability in agricultural soils (Meena *et al.,* 2015). The most important KSB used as K biofertilizers are Bacillus mucilaginosus, Bacillus edaphicus, Bacillus circulans and Bacillus cereus. Generally, microorganisms contribute to the release of K+ from K-bearing minerals by acidolysis mechanism (production of the organic and inorganic acids and production of protons). Release of H+ can directly dissolve the mineral K as a result of slow releases of exchangeable K, readily available exchangeable K (Basak *et al.,* 2017). Among the bacteria, A. tumefaciens OPVS 11, R. pusense OPVS 6 significantly induced the acidolysis mechanisms and solubilise K from muscovite and biotite. Application of crop residue @ 4t ha^{-1} along with 30 kg K_2O + potassium solubilizing bacteria (KSB) gives equal yield to that of 4 t ha^{-1} residue + 60 kg K_2O indicating 50% K_2O saving through residue use (Mehta *et al.,* 2020). These biological agents are widely used in China and South Korea and compensate the shortage of commercial K fertilizers (Sheng and He, 2006). Crops like wheat, sorghum, cotton, rapeseed, tomato and eggplant have been inoculated with KSB biofertilizers and found successful in increasing soil K status, crop growth and yield under pot culture as well as field conditions.

Right Rate of K application

Rate of K application depends on the K requirement of the crop, K supply from the native soil and the efficiency of externally applied fertilizer. In addition, the rate of K recommendation is jointly influenced by placement and timing of application. Potassium application rate and crop K uptake immediately influence the soil available K content (Römheld and Kirkby, 2010). Application of 60 kg K_2O/ha was found optimum for direct seeded basmati rice grown in IGP during *kharif* season. Increasing K rate to 90 did not increase the grain yield significantly, while the lower dose of K (<60 kg/ha) reduced grain yield significantly (Vijayakumar *et al.,* 2019b).

In India, the average response to 60 kg K/ha from 785 trials of *kharif* rice was 6.7 kg grain/kg K and that from 378 trials of *rabi* was 8.48 kg grain/kg K (Kanwar, 1974). Mahapatra and Rajendra Prasad (1970) reported that the data obtained from the farmers' fields during 1967-68 indicated a significant response to the application of 30 to 60 kg of K_2O/ha in the following districts *viz.,* Alluvial soils of Barti (U.P), Purnea and Saharha (Bihar), laterite soils of Cuttack (Orissa), the red soils of Chittoor (A.P) and Shimoga (Karnataka) with tall indica as well as with the high yielding varieties. Swarup and Singh (1989) found that after continuous cropping for twelve years, application of K had no effect on rice yield. Lack of response to applied K was attributed to high amount of available K due to the presence of high amount of natural K bearing minerals, the large contribution of non-exchangeable part of K to the K in the plant. Tandon and Sekon (1988) have reported that response to 30-60 kg K_2O/ha ranged from 210-370 kg grain/ha. In a field experiment on black clayey vertisol with rice at Hyderabad, Surekha *et al.,* (2003) reported significant grain yield increase in rice hybrids as well as high yielding varieties (HYVs) to K application at 40 kg K_2O/ha over no K **(Figure 2).** However, the magnitude of response to K was high in hybrid rice (30 kg grain/ kg K_2O) than that of HYVs (17.6 kg grain/ kg K_2O).

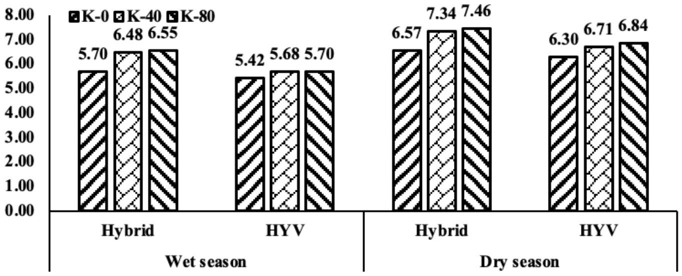

Figure 2: Grain yield (t/ha) of rice as influenced by K application (Surekha *et al*., 2003)

In AICRIP trials of DRR, a significant response to K (50-60 kg K_2O/ha) in rice hybrids was observed at Mandya and Titabar. Further, the split application of K increased grain yield significantly over basal application in the light sandy loam soils of Mandya. From 40 to 50 kg/ha significantly improved grain yield (8%). At Bangalore, Thippeswamy *et al*., (2000) studied the influence of different doses of K fertilizers applied at various growth stages of rice and found that different forms of K *viz.,* water soluble K, hot water-soluble K, available K, 1 N HNO_3 extractable K and 0.1 N HNO_3 extractable K increased with increase in potassium dose up to 80 kg ha^{-1} and decreased with growth stages from tillering to harvest.

Influence of other supplements such as secondary and micronutrients on K use efficiency were evaluated in 60 farmers' fields of Fatehgarh Sahib, Meerut, Baghalpur, Banda and Borabanki with Farmers' fertiliser practice (FFP), FFP with addition of K (+K), FFP with addition of K, S, and Zn (+KM), and FFP with addition of S and Zn (+M) (Singh *et al.,* 2013). Result from the study showed that the application of K along with S and Zn as supplements increase crop yields and productivity in rice-wheat cropping systems. Rice yield in FFP plots ranged from 2.7 t/ha at Banda to 5.9 t/ha at Fatehgarh Sahib. Application of K increased rice grain yields ($p \leq 0.001$) at all locations **(Table 4).** The rice yield increases from applied K in the presence of S and Zn (+M) ranged from 0.4 to 0.7 t/ha across all locations. Highest yield of rice was obtained when K was applied with S + Zn. The increase in yield from added K is However, consistent with reports that application of K has become essential for sustaining high yields in the IGP. K application increased rice yields by 0.6 t/ha in Fatehgarh Sahib and Barabanki, 0.9 t/ha in Meerut, 1 t/ha in Banda, and 1.2 t/ha in Bhagalpur. Application of K, S and Zn with FFP increased rice grain yields by 1.1 t/ha at Fatehgarh Sahib, 1.2 t/ha at Meerut, 1.4 t/ha at Banda, 0.9 t/ha at Barabanki, and 1.4 t/ha at Bhagalpur vis-à-vis FFP alone (Singh *et al.,* 2013).

Table 4: Effect of potassium and sulphur plus Zn (M) additions in rice yield (t/ha) at five locations of northern India

	Fatehgarh Sahib		**Meerut**		**Banda**		**Barabanki**		**Bhagalpur**	
	No M	**+M**	**No M**	**+M**	**No M**	**+M**	**No M**	**+M**	**No M**	**+M**
No K	5.9	6.6	4.9	5.5	2.7	3.3	5.0	5.4	3.5	4.3
K	6.5	7.0	5.7	6.1	3.7	4.1	5.6	5.9	4.6	4.9
Difference*	0.6	0.4	0.8	0.6	1.0	0.8	0.6	0.5	1.1	0.6

Banerjee *et al*., (2018) conducted the experiment in a randomized complete block design with five different K doses (0, 30, 60, 90, and 120 kg K_2O ha^{-1}) and four replications in hybrid rice. The study revealed that the stem and grain dry matter production at 60 days after transplanting (DAT) and harvest were significantly ($p \leq 0.05$) higher at 90 kg K_2O ha^{-1} application. The grain K concentration improved 116% more than the Zero-K ($p \leq 0.05$) with K fertilization of 90 kg K_2O ha^{-1} **(Table 4).** Potassium fertilization had a significant ($p \leq 0.05$) influence on potassium harvest index (KHI) of the tested hybrid, and it was maximum with 120 kg K_2O ha^{-1}, accounting for 130% higher KHI over the control. The application rates of 30, 60, and 90 kg K_2O ha^{-1} resulted in statistically at par KHI values. Potassium mobilization efficiency index (KMEI) in the tested hybrid rice cultivar ranged from 0.71 to 1.54%.

Right Time of K application

Low potassium use efficiency in cereal-based cropping systems is common as the entire recommended dose of K is applied as basal. The sustained supply of K is highly necessary to fulfil the plant demand, especially at the reproductive stage. But the basal application may cause deficiency during the later stage of the crop. Therefore, split application of fertilizer K in rice crop will give higher KUE than its single/basal application by reducing the leaching losses and luxurious consumption of K (Vijayakumar *et al.,* 2022a). A basal dose of K at puddling is normally recommended, but in coarse-textured sandy loam soils, split application of K (half at transplanting and half at the active tillering stage) provides the yield advantage of 250 kg grain/ha (Konar and Garewal, 1989) as compared to a single application at transplanting.

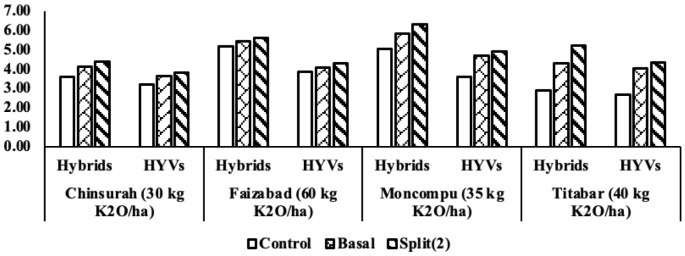

Figure 3: Response of rice to Potassium application (Grain yield t/ha)

Whereas, Thakur *et al*., (1998) failed to obtain any differences in yield between basal and two and three splits at 30 and 45 kg K_2O/ha. In AICRIP trials of DRR (DRR, 1990-96), in addition to significant response to recommended K rate by rice hybrids and HYVs at all the locations **(Figure 3),** split application of K increased grain yield over basal application in the acidic light soils with medium to low available K of Moncompu and Titabar but, had no advantage in heavy and loamy soils with high to me

In a clay loam soil with high available K_2O (454 kg/ha), split application of K failed to bring significant difference in grain yield as compared to application of full dose of potassium at the time of transplanting (Chennabasappa *et al.,* 1998). Ravichandran *et al*., (2011) reported that on clay soils (Vertisol) of Cauvery delta region with high K+ and NH4+ fixation potential, rice yields and N recovery efficiency can be increased by applying K fertilizers one week before N top-dressing. Application of K before N presumably suppressed fixation of NH4+ from applied fertilizer because selective exchange sites in the 2:1-layer clay minerals were occupied by K+. Application of K @ 75 kg ha^{-1} in two splits (basal and panicle emergence) in rice under rice-maize system of IGP had significantly higher grain yield, AEK and REK compared to basal application alone. Residue retention on surface may have further added advantage over no-residue situation (Singh *et al.,* 2020) **(Table 5).** Two split application of 60 kg K_2O/ha (half at basal + half at panicle initiation) increased the growth, yield attributes and yield of direct seeded basmati rice in *kharif* season during both the years of study (Vijayakumar *et al.,* 2019a).

Table 5: Effect of split K application and residue retention on yield and KUE under the rice-maize system (Singh *et al.,* 2020)

Treatment	Yield		AEK (kg grain kg^{-1} K)		REK (%)	
	Rice	Maize	Rice	Maize	Rice	Maize
No K	7.91	7.80	-	-	-	-
75 kg K as basal	8.38	8.40	7.58	9.68	52.4	50.2
75 kg K 2 splits (basal + PI)	8.69	8.90	12.58	17.74	60.8	58.4
75 kg K basal and residue retention	8.86	9.37	15.32	25.32	45.0	41.1
75 kg K 2 splits and residue retention	9.10	9.54	19.19	28.06	53.3	52.8

Right Method of K application

The source-sink dynamics of plant nutrients in the soil eventually determine the nutrient status of soils at any given point of time. The lateral root architecture in rice crop plays pivotal role in nutrient acquisition especially major nutrients *i.e.,* nitrogen (N), phosphorus (P) and potassium (K). The increment in root surface area can increase the uptake of K from the K-enriched zone. In rice, K is known to influence the number of productive tillers, filled grains per panicle, grain weight, tolerance to both high and low temperature, wind stress, physiological disorders and pests and diseases. Usually, all the potassium will be applied to the soil before transplanting as a basal dose. In case of split application, along with nitrogen, it is applied to the soil after draining the water so that the fertiliser will be placed in the mud and field will be irrigated after 24 hours. Samui and Bandopadhyay (1992) reported that application of K @ 90 kg K_2O/ha in split doses either to soil or foliage was found to increase the grain yield of pre-*kharif* direct seeded upland rice over no application of K in clay loam soils of West Bengal with best treatment being soil application of 45 kg K_2O/ha + foliar application of 22.5 kg K_2O/ha at tillering and another 22.5 kg K_2O/ha at panicle initiation. Sarma *et al*., (1995) found that seed hardening with 4% KCl and application of 60 kg K_2O/ha significantly increased plant moisture content and nitrate reductase (NR) - activity and decreased the proline content of the leaf in the direct seeded summer rice crop in sandy loam soils of Assam. Foliar application of 10 kg KCl m^{-3} to rice at panicle initiation, boot leaf and 50% flowering stages significantly increased seed yield and improved quality (seed germination and 100-seed weight) both in the monsoon and winter seasons (Jayaraj and Chandrasekharan, 1997). Splitting a total of 95 kg ha^{-1} of KCl to rice (1/3 at sowing in soil, 1/3 as a foliar spray at flag leaf stage and a 1/3 as foliar spray at grain development) gave significantly higher yields than a soil application all at time (Narang *et al.,* 1997). Similarly, Badar *et al*., (2006) reported that application of KSB with K- and P-bearing minerals on sorghum enhanced dry matter yield by 48%, 65%, and 58% and K uptake by 41%, 93% and 79% in clay, sandy and calcareous soils, respectively. Two foliar sprays of 2% KNO_3 (1st spray active tillering + 2nd spray @ panicle initiation) are recommended as substitute to top dressing of 30 kg K_2O/ha. However, the soil K balance is more negative in case of foliar spray compared to soil application (Vijayakumar *et al.,* 2019c).

Fertigation - Application of fertilisers through irrigation water is getting popular with respect to the water soluble fertilisers like potassic fertilisers. Selecting right source of K (soluble in water, compatible with other fertilisers and devoid of precipitation) is necessary for the efficient application of K (Mohammad 2004). The most common K sources are KCl, KNO_3, and K_2SO_4 and their solubility at 20°C is 34% for KCl, 31% for KNO_3 and 11% for K_2SO_4. The compatibility of potassic fertilisers to the other basic fertilisers is given below **(Table 6)**.

ZINC-(Zn)

Next to major nutrients, zinc (Zn) is the most important micro nutrient element required for rice crop growth and metabolism. After N, Zn was found most wide spread nutrient deficit in India and rest of the world also (Choudhary *et al.,* 2022). Availability of Zn is less under flooded conditions due to formation of sparingly soluble compounds with sulphide and carbonates (Vijayakumar *et al.,* 2022b). In addition, growing of modern high yielding varieties remove large quantities of native soil Zn at the end of every

Table 6: Compatibility of potassic fertilisers with other fertilisers for Fertigation

Nutrient source	NH_4-NO_3	CO $(NH_2)_2$	$(NH_4)_2$ HPO_4	$(NH_4)_2$ HPO_4	$CaNO_3$
KCl	C	C	C	C	I
K_2SO_4	C	C	C	C	I
KNO_3	C	C	C	C	I
KH_2PO_4	C	C	C	C	I
$K_2S_2O_3$	C	C	C	C	I

C= Compatible I= Incompatible

harvest, lowering the native soil Zn concentration and contributing to lower grain Zn concentration (De Steur *et al.,* 2014). Further, the availability of Zn for crop uptake from the soil is affected by the concentrations of macro and micro nutrients, the nature and physico-chemical, biological properties of the soil (Fageria *et al.,* 2012; Hafeez *et al.,* 2013). Increasing cropping intensity in a piece of land and changes in the fertilizer input management practices had lowered the Zn availability status in rice grown soils of India which is being practiced on a large-scale (Prasad, 2005).

The Zn content in different agricultural soils is mainly depends on the nature of inherited parent material, ore depositions and agricultural activities such as nutrient supplements through fertilizers, FYM and waste products (Alloway, 2004). Generally, Zn is present in the soil in several chemical forms namely water soluble, exchangeable, organic pool and structural component. Intensity of different forms of Zn, governs by the soil chemical properties *i.e.,* pH, redox potential and organic matter **(Figure 2)**, which plays a critical role in Zn solubility in soils (Alloway, 2009).

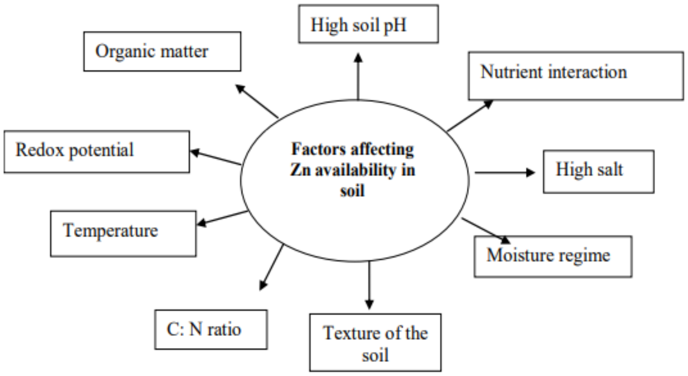

Figure 2: Factors influencing Zn dynamics in soil

Moreover, spread of Zn deficiency is common in alkaline soils due to their high pH and calcareous soil too by formation of $ZnCO_3$. The Zn sufficient soil maintain the water-soluble Zn level in the soil solution to the tune of 4×10-10 to 4×10-6 M. Soil pH is having major control on Zn solubility in soil as depicted in the equation log (Zn2+) =5.8-2 pH by using thermodynamic parameters of reaction. This equation clearly shows that divalent cation (Zn2+) activity is decreased 100-fold for every one unit change in pH. A lot of strategies are made to regulate the water-soluble Zn level in the soil solution to ensure uninterrupted supply of Zn to support the plant growth and development (Senguttuvel *et al.,* 2023).

Strategies to address the Zn deficiency

Right Source of Zinc

As per FAI (2010), several Zn fertilisers are approved by the FCO and available in the market for agricultural use to manage Zn deficiency in soil. Currently, Zn deficiency is cured by the application of $ZnSO_4$ as source of Zn to all crops and the application rate varies from 10 to 25 kg/ha/season based on the crop and soil levels. Zinc Sulphate ($ZnSO_4.7H_2O$) containing about 21% zinc is the most used source of Zn in our country. Availability of good quality zinc sulphate is the main constraint in the current scenario. Therefore, a lot of chemical compounds with enriched Zn content are being developed and available in the market. Next to $ZnSO_4$, chelated Zn (12%) secured second place in the list of widely used Zn fertilisers **(Table 7)**. Apart from these, new fertilisers like zinc coated urea, phosphate and nano sized Zn are used in the rice cropping systems for alleviating Zn deficiency. In most of the experiments, $ZnSO_4$ was found most efficient in correcting Zn deficiency in different crops. The water insoluble ZnO and Zn frits were distinctly inferior to water soluble $ZnSO_4$ on coarse textured sodic soils whereas they tended to approach the efficiency of soluble $ZnSO_4$ on fine textured soils. This was due to high fixation of Zn from soluble sources and low solubility of fixed fraction in the soil. The recommendation for Zn, which is generally marketed as Zn sulfate heptahydrate ($ZnSO_4.7H_2O$), varies from 10 to 25 kg/ha/season, depending upon the crop, environmental, and soil conditions. Moreover, availability and quality of zinc sulphate in the market are not meeting the requirement. Even use of novel nutrient carriers like nanoparticles, composites and Zn infused material will play a major role alleviating the Zn deficiency in soil in near future (Gobinath *et al.,* 2021).

Table 7: Frequently used Zn fertilizers in Indian Fertilizer sector

Chemical	Formula	Percentage
Zinc sulphate monohydrate	$ZnSO_4.\ H_2O$	36
Zinc Sulphate Heptahydrate	$ZnSO_4.7H_2O$	22
Zinc Oxysulfate	$ZnSO_4.XZnO$	25
Zinc Oxide	ZnO	80
Zinc nitrate	$Zn\ (NO_3)_2.\ 3H_2O$	23
Sodium Zn EDTA	NaZn EDTA	13

In recent times, many initiatives were taken by Government of India such as Fertilizer Control Order (FCO) to manufacture Zn-enriched urea (coating of 2.0% Zn onto urea). A study with different sources of Zn-enriched urea was conducted in sandy clay soil of Delhi to understand the mechanism and efficacy on rice crop (Singh *et al.,* 2009). The yield enhancement was found with Zn-enriched urea ranging from 7.7% (0.5% ZEU-ZnO) to 35.9% (2.0% ZEU-ZS) in aromatic rice crop. Rice grain yield significantly increased by 12 to 180% compared to unfertilized plots through balancing Zn application and Zn source (Slaton *et al.,* 2005). Among Zn sources, zinc chelate (Zn-EDTA) + two foliar sprays (0.5% Zn-EDTA) seem to be the most efficient Zn fertilization strategy for increasing Zn concentration in rice kernel parts, uptake, ZnUEs and productivity (Ghasal *et al.,* 2017). Foliar application of zinc oxide (ZnO) solutions can be one of the potential alternatives for zinc fertilization, but it is restricted due to particle size. Size dependent ZnO chemical can be used in field crops as fertilisers. With respect to nano ZnO, RDF + two foliar sprays of nano ZnO @ 1000 ppm and RDF + two foliar sprays of nano ZnO @ 1500 ppm being on par with each other recorded significantly higher grain yield and total zinc uptake compared to other zinc fertilization methods (Jangid, 2019). Similarly, soil amended nano ZnO improved the DTPA-Zn content in calcareous soil of IGP region (Gobinath *et al.,* 2018).

Prior research on zinc in soil and rice production mostly concentrated on the use of $ZnSO_4$ or other ionic zinc compounds as a source of zinc and the effectiveness of their usage in rice-growing soils (Mandal *et al.,* 2000). But in recent years, farmers have tended to use alternate chemicals. Because zinc chelate (Zn-EDTA) is inexpensive, it is employed as a source of zinc in rice (Das and Saha, 1999).

Right Rate of Zn application

Rate of Zn application differs with soil type and prevalence of its deficiency in soil. For normal soils about 25-50 kg $ZnSO_4$/ha for three crop seasons is recommended (Nayyar *et al.,* 1993). Twice this amount is advocated for sodic soils with pH of more than 10. In the co-ordinated experiments conducted by ICAR-IIRR, alkaline soils of Faizabad recorded linear increase in grain yield up to 100 kg/ha but the rate of response was found to decrease with increments in Zn dose. In contrast, Zn response was curvilinear at Raipur (neutral pH). As per the available literature, maximum achievable grain yields (9.2 t/ha) with Zn nutrition were recorded at medium level (50 kg Zn SO_4/ha) and beyond this level it may cause toxicity to the rice. Potential yield from alkali soils (pH- 9.4-9.7) which are considered unproductive could be realised with higher rate of application of $ZnSO_4$ than the normal application rate due to their fixation behaviour (AICRIP report, 2017). In addition, the beneficial effect of zinc application to rice grown on the alkali soils was far more than that of gypsum.

Correcting Zn deficiency through Zn foliar spray also has an impact on the Zn mobilization in the crops. The application of Zn through foliar at the rate of 0.1% to 0.5% through $ZnSO_4$ increased the Zn concentration in unpolished and polished rice. Thus, a rise in the grain Zn concentration in both unpolished and polished rice may be used as a technique to boost the Zn concentration in diets (Cakmak, 2008). In addition, it is necessary to pay attention to the seasonal climatic conditions in each growing zone to improve grain Zn concentration through Zn foliar spray. Nayyar *et al*., (1993) reported that rate of Zn application varies with the crop and the extent of Zn deficiency and sodic soils whose characteristics are highly conductive for Zn fixation, require relatively much higher doses of Zn than normal soils to ensure an adequate supply of zinc to the rice crop. Similar dose of foliar application namely 0.5% by various chemicals like $ZnSO_4$ and Zn-EDTA may behave differently and achieve a different level of impact on the plant growth and its concentration inside the plant. Combined application of $ZnSO_4$ and ZnEDTA at 0.5% at different intervals significantly improved the Zn content in straw as well in grain (Anusuya *et al.,* 2019). But the efficacy was found higher with $ZnSO_4$ spray rather than EDTA formulation. However, the maximum zinc use efficiency (42.2%) was observed with foliar spray of $ZnSO_4$ @ 0.5% over Zn EDTA spray in the rice genotype IR14M117. In case of soil application, Zn alone and in combination with other nutrients would support the Zn transportation in the plants. Combined application of Zn (6 kg/ha) and sulphur (30 kg/ha) achieved the maximum yield (7.63 t/ha) over control plot (7.09 t/ha) and 7% of yield advantage was observed with combined application of Zn with S. The amount of Zn content in grain and straw was recorded highest with the application of 1.0 kg Zn ha^{-1} as Zn-EDTA than that of 10 and 20 kg Zn ha^{-1} as inorganic $ZnSO_4$ application (Naik and Das, 2008). The split application of $ZnSO_4.7H_2O$ performed better in terms of growth, yield and nutrient content than that of single basal application and split application of Zn-EDTA.

Right Time of Zn application

The split application of Zn sources in soils and its impact on rice's nutrient content is poorly understood. Basal application of Zn is normally recommended practice. Any further delayed application is associated with yield loss (Sadana and Takkar, 1983). But foliar application is resorted to as a mid-season corrective measure. Normally, 0.5% $ZnSO_4$ solution is sprayed thrice starting from third week after planting twice or thrice at weekly intervals. However, a delay in the application of Zn in the soil even by a week causes a yield loss in rice. To ensure efficient utilization of Zn applied to soil and to avoid yield losses, it is desirable to add the recommended dose of zinc within one week of transplanting. Supply of Zn through foliar mode at boot leaf and grain filling stage could be the best and effective practice to enhance and enrich the plant with Zn (Anusuya *et al.,* 2019). Applying Zn at these stages, significantly increase growth, physiology, zinc use efficiency, grain zinc content and yield attributes in rice. Moreover, combination of soil plus foliar application is also under investigation to achieve the maximum Zn enrichment in grains. Combined application of 1.25 kg Zn ha^{-1} through Zn-EDTA and 0.5% foliar spray at maximum tillering (MT) and panicle initiation (PI) stages of rice crop registered the maximum Zn content in different parts of rice (Ghasal *et al.,* 2017). Similarly, higher level of Zn (2.5 kg of $ZnSO_4$) is equivalent to lower dose of Zn-EDTA at 1.25 kg Zn (Zn-EDTA) due to their efficiency in rice crop.

Right Method of Zn application

Application of Zn in the soils has proven to be superior to foliar application due to its assured supply to the crop at an early growth stage to maturity resulting in healthy plants. Another advantage of applying $ZnSO_4$ to soil is that the amount of this material unused by the rice crop to which it is applied becomes available to the subsequent crop. In view of the relatively low efficiency of soil applied Zn in sodic soil, efforts were made to enhance the same by dipping rice seedling roots in ZnO suspension (0.5-2%) and transplanting in Zn enriched nursery. Sadana and Takkar (1983) reported that Zn application irrespective of methods, caused significant increase in grain yield and Zn content of grain. Soil application of $ZnSO_4$ before transplanting produced maximum grain yield (140%) over control. Top dressing $ZnSO_4$, 7 or 15 days after transplanting produced similar grain yield. Foliar spray of 1% or 2% $ZnSO_4$ solution increased yield significantly over control, but was inferior to all other methods of Zn application. Dipping rice seeding roots in a 4% ZnO suspension and supplemented with 1% foliar sprays of $ZnSO_4$ solution gave yields similar to $ZnSO_4$ application. Application of Zn fertilizers or Zn-enriched [nitrogen (N)- phosphorus (P)- potassium (K)] fertilizers (ferti-fortification) offer a rapid solution for increasing Zn concentration in grain and straw. Pooniya *et al*., (2013), observed that co-application of zinc enriched urea, ZEU (2%) along with green manure increased the physiological efficiency and partial factor productivity of basmati rice; while application of 2.0% ZEU as $ZnSO_4.H_2O$ recorded the highest total Zn uptake 3081.6 g ha^{-1}. Ferti-fortification with green manuring to rice through various zinc enriched urea with green manure and foliar spray of 0.2% ($ZnSO_4.H_2O$) could act as an alternate method to enhance the Zn concentration in grain and straw.

Integrated use

Application of organic manures like FYM, GM and amendments like gypsum is known to improve Zn use efficiency. On moderately sodic soils (pH 9.7) the increase in rice yield from Zn application was far greater than Zn applied with gypsum (Takkar and Singh, 1978; Takkar and Nayyar, 1982), probably because of low sodium or adequate calcium supply. But on highly deteriorated sodic soils (pH 10.4) deficient in both calcium and zinc, the best rice yields could be achieved with the application of both gypsum and Zn. Sahahane *et al.,* (2019) reported that combined application of Zn with 75% RDF + microbial inoculation (Anabaena-Providencia consortia (or) Anabaena-Pseudomonas bio-filmed bio-fertilizer) performed statistically better over Zn application with RDF and can be used in nutrient management of rice. Regular incorporation of Sesbania green manure over the years before transplanting of rice helps in improving diethylene triamine penta acetate (DTPA)-extractable micronutrient cations of the soil (Nayyar and Chhibba, 2000).

Growing of Zn rich rice seeds plays a major role in enrichment of Zn in the rice grains than the poor Zn seeds. The range of zinc concentrations in polished and brown rice is 6.3-24.4 g g^{-1} and 13.6-28.4 g g^{-1}, respectively. As per the report submitted by ICAR-IIRR, several rice varieties and landraces had recorded zinc content and top 5 entries having high zinc are Poornima (31.3), Ranbir Basmati (30.9), ADT 43 (30.9), Chittimutyalu (30.5) and Type 3 (30.3) and top 5 entries with less loss after polishing are white Ponni, Bas 386, Kanishk, Giri and Karjat 4 which can be used in breeding programme for development of high Zn varieties for Zn enrichment. SRI coupled with RDF + Zn in hybrid rice assumes greater significance in enhancing the rice productivity with better Zn-biofortified grains besides higher nutrient use efficiencies to combat widespread malnutrition and acute Zn deficiencies in humans and livestock in the northwestern Himalayas **(Table 8)**.

Table 8: Response of rice to different methods of Zn application

Crop	Mode of application and level	Benefits	Reference
Rice	Soil application @ 5 mg/kg	10% and 86% improvement over no Zn	Muthukumararaja and Sriramachandran (2012)
Rice	Soil Application Zn @ 6 kg	5% improvement in yield over control	Singh *et al*., (2012)
Rice	Soil, Soil + Foliar	-	Phupong *et al*., (2010) Girijaveni *et al.,* (2020)

Conclusion

Synchronizing K and Zn demand in the plant by supplying adequate quantity of nutrients during high nutrient demand stage is need of the hour to fetch optimum crop yield and productivity and also ensure the effective utilization of added K and Zn nutrients. Addition of high analysis fertilisers alone will not improve the nutrient use efficiency, while inclusion of multiple nutrient mixtures and bio-inoculants reduces the negative balance of K and Zn via timely and correct addition of nutrients though right source that may lead to higher nutrient use efficiency and good returns on yield and productivity. Current discussions on 4R approach for K and Zn have established the importance of these unnoticed elements and their significance for nutrient use efficiency in rice based cropping system. Further, in depth studies are required to support this management aspect with their nutrient budget, balance sheet, mining ability, fixation behaviour in different soils to improve the productivity and yield in rice based cropping system. Additional research is required to determine the ideal foliar Zn rates for the commercial rice cultivars under a wide variety of growing environments.

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