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REVIEW ARTICLE

Ongoing soil potassium depletion under intensive cropping in India and probable mitigation strategies. A review

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Abstract

Potassium (K) is essential for plant growth and vital for soil health. However, despite high crop demand, K fertilization continues to be ignored or severely inadequate in Indian agriculture. Over time, this could lead to severe depletion of soil K reserve, irreversibly alter K-bearing minerals, and adversely affect soil fertility and crop productivity. Hence, we should comprehensively assess the alarming situation of soil K mining in India and come up with appropriate solutions. Keeping the above in mind, here we review the soil K pools concerning plant availability, their contents in major soil orders of India, reasons and status of soil K mining under major crops and cropping systems in India, and the impact of long-term K mining on soil K pools and clay minerals. We also address various aspects of sustainable K management in agriculture and suggest future action courses focusing on India. Our main findings are: (i) farmers in India mainly apply nitrogen and phosphorus, but little or no K; consequently, (ii) net K balance continues to be negative for most crops and cropping systems across India (e.g., - 3.29 million tonnes [Mt] in 2000–01, - 7.2 Mt in 2015–16); (iii) long-term K mining primarily depletes the exchangeable and non-exchangeable K pools in soil, and alters clay minerals to various extents; and (iv) the existing K fertilizer recommendations need an upward revision. We further enlist indigenous non-conventional alternatives of K fertilizers to meet the agricultural K demand. This is the first comprehensive review to simultaneously address the ongoing soil K mining in India, its impact, and its potential mitigation strategies. The points raised here would help reduce soil K mining, plan research work, and make policy decisions on K fertilization and residue management with the ultimate goal to prevent soil health deterioration and ensure sustainable crop production.

Keywords Imbalanced fertilization · Potassium mining · Soil potassium pools · Long-term experiment · Potassium management · Non-conventional sources

Contents

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1 Introduction

Potassium (K) is one of the essential nutrients required in massive amounts by plants for numerous metabolic activities viz., synthesis of starch, cellulose, proteins, vitamins; activation of cellular enzymes; enhancing nitrogen (N) and phosphorus (P) use efficiency; imparting resistance to biotic and abiotic stresses; and improving quality of agricultural produce (Epstein and Bloom 2005; Brady and Weil 2012). Since K does not integrate into organic compounds, it is often present in the cationic form in plants. The accumulation of K in cytoplasm controls organic compound synthesis while that in vacuoles modulates cellular osmoregulation processes (Oosterhuis et al. 2014). Potassium is involved in stomatal opening in plants and helps in better adaptation to water scarcity under drought. By aiding ion homeostasis and regulating osmotic potential, K helps alleviate salt stress in plants. Because of similar size, K^+ can also help in reducing the toxic effect of ammonium (NH_4^+) in plants (Oosterhuis et al. 2014). By regulating biosynthesis, conversion, and allocation of essential metabolites, K works towards increasing crop yields. Potassium helps flowering, increasing pollen germination and seed development (Hasanuzzaman et al. 2018). Fertilization with K can vastly improve fruiting in crops. Srivastava et al. (2014) reported ~ 36% increase in fruit yield of Nagpur orange (*Citrus reticulata* B.) with K fertilization as compared to without K fertilization on a smectitic Vertisol. Apart from imparting significant physiological functions in plants that are key for high productivity, K is also crucial for improving the quality and shelf-life of fruits and vegetables (Lester et al. 2010). Under K deficiency, tips and margins of older leaves in most plants show chlorosis (yellowing) followed by necrosis (death of tissues), imparting a burning look on the leaf edges (Subba Rao and Brar 2009). For example, see Figs. 1 and 2 for chlorosis in soybean (*Glycine max*) and necrosis in sorghum-Sudan grass hybrid (*Sorghum bicolor* × *S. sudanense*) leaves, respectively, caused by K deficiency.

Besides plant nutrition, being a structural component of many important soil minerals, K also plays a crucial role in maintaining soil health. Because loss of K from interlayers of K-bearing 2:1 minerals might yield irreversible changes, which would have far-reaching adverse consequences in soil fertility, e.g., nutrient and water holding capacity, release and fixation of various nutrient ions, etc. Under conditions of continuous plant K removal largely exceeding K input, K^+ present between subsequent layers of mica or illite might be replaced by other cations, e.g., H_3O^+, hydrated Ca^{2+}, and NH_4^+ (from N fertilizers), causing transformation of mica or illite into vermiculite or some intergrade minerals (Barré et al. 2008; Moterle et al. 2016; Das et al. 2019c). Such processes have immense significance in soils, as they can alter soil CEC (Hinsinger and Jaillard 1993), retention of important elements (Raheb and Heidari 2012), and also

Fig. 1 Severe K deficiency symptom (yellowing) in soybean (*Glycine max*) grown on a Vertisol in Ngawi, East Java, Indonesia. Courtesy of A. Taufiq, ILETRI, Indonesia. Photograph by the International Potash Institute (IPI) (https://photo.ipipotash.org/, accessed on 14 June 2021, reproduced with permission from IPI).

Fig. 2 Necrosis due to K deficiency at tips and margins of leaves of sorghum-Sudan grass hybrid (*Sorghum bicolor* × *S. sudanense*) grown on a calcareous soil (from Bihar, India) in a greenhouse of Division of Soil Science and Agricultural Chemistry (SSAC), ICAR-Indian Agricultural Research Institute (IARI), New Delhi. Photographs: (1) Subhadip Paul, PhD Scholar, Division of SSAC, ICAR-IARI, New Delhi. (2) Debarup Das, Scientist, Division of SSAC, ICAR-IARI, New Delhi.

the K mobility, including its release and fixation (Bortoluzzi et al. 2013).

The K requirement of crops, by and large, is as high as that of N, causing its substantial removal from the soil through harvested plant parts, especially under intensive cultivation without adequate K input (Das et al. 2019c, d; 2020). The N: P_2O_5: K_2O consumption ratio in 2019–2020 was 6.96:2.79:1 in India, and it has remained tilted towards N and P (more towards N between N and P) over the last many years despite the average crop uptake pattern hanging around 1.0:0.3:1.3 (FAI 2020; Katyal 2020). Apart from the inadequate application rates, the common practice of removing crop residues from fields further aggravates the problem of K mining in Indian soils, as crop removal is the most significant output in K balance equations (Sanyal et al. 2014). Removing crop residues from fields accelerates nutrient depletion, especially K depletion (Goulding et al. 2021). Straws of small grain crops contain lesser N and P but higher K than grains. For instance, average straw: grain mass ratio for N and P, respectively, are 0.47 and 0.26 for wheat (*Triticum aestivum*) and 0.49 and 0.35 for barley (*Hordeum vulgare*); but, for K are 4.12 (wheat) and 5.04 (barley) (Tarkalson et al. 2009). Hence, removing straws and grains of these crops would extensively speed up soil K depletion than only removing the grains. Rice (*Oryza sativa*) straw contains over 85% of K present in the aboveground parts of the plant, and 14–20 kg K_2O ha^{-1} is removed with the removal of 1 Mg of rice straw (Dobermann and Fairhurst 2002). Potassium removal by rice straw is around six times removed by the same amount of rice grains. In general, K removal by crop residues in India has been estimated to be ~ 5 times supplied through fertilizers (Chander 2011). The outcomes obtained from the farmers' fields under the All India Coordinated Research Projects on Integrated Farming Systems (AICRP-IFS) showed the prevalence of soil K mining under several dominant cropping systems of India, including the most important one, i.e., rice–wheat (AICRP-IFS 2012; Majumdar et al. 2017). For these reasons, K accounted for the major portion of reported negative N-P-K balance in Indian soils over the past few decades (Tandon 2004; Srinivasarao et al. 2011; Dutta et al. 2013; Tewatia et al. 2017; Katyal 2020). The problem of soil K mining is not confined to India only. Data from on-station and on-farm studies worldwide revealed a significant negative balance of K in south Asia and sub-Saharan Africa. In countries like the Philippines, Indonesia, and Thailand, K removal by rice, the most dominant cereal crop there, exceeded K application by 33 to 83 thousand tonnes in 2010–2011 (Majumdar et al. 2021). Annual apparent K balances of -5 to -45 kg ha^{-1} were observed in various countries of sub-Saharan Africa, totalling ~ 3 Mt per year (Mt y^{-1}) of negative balance due to crop cultivation with little or no K inputs (Stoorvogel et al. 1993; Van den Bosch et al. 1998; Majumdar et al. 2021).

Mining of K caused by imbalanced fertilization, including inadequate or no K input through fertilizer for prolonged periods implies overdependence of the prevailing cropping systems for K nutrition on soil's native K reserves. The K demand of crops over the "depletion in the exchangeable pool" and "external K input" is met by the non-exchangeable K pool (Bilias and Barbayiannis 2017; 2019a). Consequently, continuous K mining alters the dynamic equilibrium: soil solution K $\rightleftharpoons$ exchangeable K $\rightleftharpoons$ non-exchangeable K and shoots up the net flux of K^+ in the backward direction. As a result, large portions of non-exchangeable K are released to compensate for the losses in solution and exchangeable pools. Due to the sluggish rate of weathering of primary minerals, e.g., micas, feldspars, and associated slow K release, the structural pool of K has very little involvement in supporting plant K nutrition (Sanyal 2014a). Hence, soil K mining is most likely to manifest as depletion in exchangeable and non-exchangeable K pools. The problem might be more severe in soils inherently poor in available and non-exchangeable K, e.g., kaolinitic Alfisols of India (Srinivasarao and Vittal 2007; Das et al. 2019c). Inceptisols of Indo-Gangetic Plains (IGP) contain large amounts of mica/illite in clay and silt fractions; consequently, they have large reserves of non-exchangeable and structural K (Sanyal 2014a; Majumdar et al. 2017; Pal 2017). Whereas smectitic Vertisols of central and southern parts of India, mostly, are high in exchangeable K and medium to high in non-exchangeable K contents (Srinivasarao et al. 2007). Irrespective of soil orders, total K content is generally high (Table 1). The K-rich soils may not show any noticeable effect of K mining on K pools and crop production for a brief time frame, though their K fertility status may gradually decline. Over a long time, plant-available K reserve (i.e., exchangeable and non-exchangeable pool) could get exhausted due to K mining to the extent that even the inherently K-rich soils become unable to support desired levels of crop yields without adequate K input from outside (Sanyal 2001; Singh and Wanjari 2014; Das et al. 2018, 2021). Mining of soil K for prolonged periods have been found to adversely affect the K supplying capacity of a kaolinitic Alfisol (Ranchi), illitic Inceptisols (Cuttack and New Delhi) and a smectitic Vertisol (Jabalpur) of India (Das et al. 2018; 2019c; 2021). Occasionally, mineral distortion was also observed due to long-term soil K mining in India (Das 2018b; Das et al. 2019c) and elsewhere (Moterle et al. 2016; Firmano et al. 2020). Besides causing soil K mining, inadequate or no application of K has also been suspected as one of the primary reasons behind the persistent low N use efficiency (floating around 30–40%, rarely 50%) despite the adoption of better agronomic practices and use of improved crop varieties over time (Katyal 2019, 2020). Negative K balance in agricultural fields is a threat to food security in India and most of the developing and several developed nations (Cakmak 2010; Lu et al. 2017). Soil K depletion has been marked as one of the main reasons behind crop yield stagnation and poor nutrient use efficiency in

Table 1 Soil K pools in some Inceptisols, Alfisols and Vertisols of India. [a]Textural class: SCL sandy clay loam, CL clay loam, C clay, L loam, SC silty clay, [b]WSK, water soluble K; EK exchangeable K, NEK non-exchangeable K (based on boiling nitric acid extraction), [c]Coarse clay: 2–0.2 µm; fine clay: < 0.2 µm, [d]Data are averages of four locations (Kreeri, Kunzer, Dialgam, Ganasthan) in mid altitude zone (Kerewa), [e]Structural K.

Location	Depth (cm)	Illite or mica content in clay (%)	WSK[b]	EK	NEK	Total K [e]	Reference
			mg kg^{-1}				
Inceptisols							
New Delhi, Delhi	0–15 (SCL[a])	54	17.8	122	1,407	18,135	Das (2018b); Das et al. (2021)
Gosaba, West Bengal	0–15 (CL)	40	85.0	375	3,939	27,495	Sarkar et al. (2013)
Cuttack, Orissa	0–15 (SCL)	36	20.9	72.5	635	20,635	Das et al. (2018)
Varanasi, Uttar Pradesh	0–15 (C)	–	8.0	66.0	1,947	–	Srinivasrao et al. (2007)
Golaghat, Assam	0–15 (L)	42	20.0	68.8	1641	19,900	Das (2018a)
Lesser Himalaya[d], Jammu and Kashmir	0–15 (CL)	62	5.0[d]	56.0[d]	612[d]	14,221[d]	Wani and Kumar (2008)
Alfisols							
Ranibundh, West Bengal	0–15 (SCL)	38	19.9	79.9	2,636.4	12,909	Sarkar et al. (2013)
Ranchi, Jharkhand	0–15 (SCL)	24	8.84	72.1	460.1	24,648	Das et al. (2019c)
Md. Bazar, West Bengal	0–15 (SCL)	24	3.9	48.0	211	10,296	Sarkar et al. (2013)
Phulbani, Orissa	0–15 (SCL)	–	4.0	81.0	725	–	Srinivasrao et al. (2007)
Haveri, Karnataka	0–20 (SCL/CL)	–	2.9	52.3	582	–	Harsha and Jagadeesh (2017b)
Vertisols							
Rahuri, Maharashtra	0–13 (C)	16 (coarse clay[c]), 13 (fine clay)	–	365	1,430	9,900[e]	Pandian and Datta (2009)
Coimbatore, Tamil Nadu	0–16 (C)	10 (coarse clay), 9 (fine clay)	–	382	1,750	13,200[e]	Pandian and Datta (2009)
Jabalpur, Madhya Pradesh	0–15 (C)	37	17.0	137	845	–	Das et al. (2019d; 2021)
Rewa, Madhya Pradesh	0–15 (C)	–	9.0	171	1051	–	Srinivasrao et al. (2007)
Indore, Madhya Pradesh	0–15 (SC to C)	–	14.8	256	305	12,855	Anupama et al. (2018

present-day intensive cultivation (Regmi et al. 2002; Ladha et al. 2003). If allowed to go unchecked, soil K mining will eventually deteriorate soil health in general, soil K fertility in particular, and ultimately jeopardize agricultural sustainability as a whole.

In the present article, an attempt has been made to briefly discuss the status of soil K mining in India under major crops and cropping systems, the impact of K mining on major soil orders of India, and the strategies to be undertaken by today's researchers and farmers to mitigate the crisis of rapid K depletion and associated soil health deterioration.

2 Soil K pools

2.1 Availability to plants

Traditionally, K has been shown to reside in 4 pools in a soil, viz. soil solution (often estimated as water-soluble) K (0.1–0.2%), exchangeable K (1–2%), non-exchangeable or fixed or interlayer K (1–10%), and lattice or structural K of primary minerals (90–98%) (Barber 1995; Brady and Weil 2012). However, the existing knowledge that the non-exchangeable K content of soils varies from 1 to 10% of total K needs to be rechecked based on recent findings (Li et al. 2015b; Wang et al. 2016). For example, while working with nine contrasting soils collected from different regions of China, Wang et al. (2016) observed that non-exchangeable K was as high as 21–56% of the total soil K. They employed the sodium tetraphenyl boron ($NaBPh_4$) method (Cox et al. 1999) and provided sufficient time for extraction of the maximum amount of K.

Plants can directly take up soil solution K as K^+ (Sparks 1987). Exchangeable K replenishes soil solution K following plant uptake. Such replenishment is fast (completes within tiny fractions of a second) as it involves reversible exchange reactions between other cations (e.g., H_3O^+, NH_4^+, Ca^{2+}, and Mg^{2+}) from solution and K^+ held on non-specific sites, e.g., planar surfaces of layer silicate minerals, negatively charged sites on organic matter or iron/aluminum oxides (Sparks and Huang 1985; Bourg and Sposito 2011; Bell et al. 2021). Consequently, soil solution and exchangeable or surface adsorbed K forms are traditionally considered readily or immediately available to plants (Barber 1995). However, the operationally defined exchangeable K might not be entirely plant-available. Exchangeable K in soils is estimated by extracting with a molar solution of NH_4OAc (pH 7). A section of this, known as the minimum exchangeable K, though exchanges with NH_4^+, does not exchange with Ca^{2+} even when K activity in soil solution approaches zero (Schneider 1997; Islam et al. 2017). The same extrapolates to ($Ca^{2+} + Mg^{2+}$) because they behave similarly when exchanging with K^+ held by soil solids (Le Roux and Sumner 1968). Given the fact that Ca^{2+} and Mg^{2+} usually are the dominant cations in arable soils (Le Roux and Sumner 1968), the minimum exchangeable K portion of the exchangeable pool (extracted by NH_4OAc) might be almost unavailable to plants (Islam et al. 2017).

Non-exchangeable K is dynamically linked to exchangeable as well as soil solution pools (Bilias and Barbayiannis 2019a), and can replenish both of them; but at much slower rates than those observed between exchangeable and solution K. Non-exchangeable K assumes a significant role in maintaining K supply to plants in soils with low exchangeable K (Ghorban 2007; Dhar and Sanyal 2000), or soils where exchangeable K is nearing minimum exchangeable K (Das et al. 2019c; 2021), or soils having significant amounts of K-fixing minerals, like interstratified illite or vermiculite (Khan et al. 2014; Li et al. 2017b), or soils undergoing intensive cultivation without adequate external K input (Islam et al. 2017; Das et al. 2019c; 2021). In extreme situations, the non-exchangeable pool might contribute to as high as 80–100% of total K availability to plants (Hinsinger 2002).

Potassium held between subsequent layers of mica, or even illite (i.e., clay-sized mica), is exceptionally stable due to the intense attraction between K^+ and highly negative layer charge, which is about 1 mol per 10-oxygen formula unit (Thompson and Ukrainczyk 2002; Bell et al. 2021). Indeed, their availability to plants would be much lower than those held between the subsequent layers of secondary phyllosilicates like vermiculite or smectite, owing to lower layer charge (than mica or illite) in these minerals (Pal 2017; Bell et al. 2021). Within micas, the release of K from interlayers of biotite is easier than that from muscovite due to shortened and strengthened K–O bond in the ditrigonal cavity of muscovite (Sanyal 2014a). In the presence of biotite, weathering of muscovite is improbable (Pal 2017), rendering muscovite unimportant as a source of K in soils so long as biotite is present (Sanyal et al. 2009).

Release rates of structural K associated with feldspars are slower than those from micas (Rich 1968). Even then, feldspars, especially the sand-sized fractions, can contribute to plant's K nutrition, as earlier researchers suggested (Rehm and Sorensen 1985; Niebes et al. 1993). However, the weathering and subsequent release of K from micas (even for the easily weathered ones) and feldspars are prolonged processes and at least orders of magnitude slower than the rate of K uptake by plants (Sanyal 2014a).

Based on the rates at which K becomes available for plant uptake, the four pools of soil K can be differentiated as (i) readily or immediately available (soil solution and exchangeable K); (ii) slowly available (non-exchangeable K); and (iii) extremely slowly available (structural K).

2.2 Relative distribution in major soil orders of India

Sizes of K pools in some Inceptisols, Alfisols, and Vertisols of India are listed in Table 1. Dey et al. (2017) studied the relative abundance of different forms of K in some selected series representing alluvial, black and red soils of India. They found that non-exchangeable K is generally more prevalent in illite dominant alluvial soils than smectitic black soils and kaolinitic red soils. Kaolinite dominant red and lateritic soils (broadly fall under the order Alfisols) have low contents of exchangeable and non-exchangeable K pools (Srinivasarao and Srinivas 2017; Das et al. 2019c). Light textured alluvial soils with extensive mica contents (frequently categorized as Inceptisols if not as Entisols) show a medium level of exchangeable K and a high non-exchangeable K content (Srinivasarao and Takkar 1997; Srinivasarao et al. 1997). Smectitic black soils (mainly in the order Vertisols or vertic groups of any other order) with higher clay content and cation exchange capacity (CEC) showed high levels of exchangeable K and medium to high non-exchangeable K content (Srinivasarao et al. 2003).

Based on soil samples from 500 districts of India, Muralidharudu et al. (2011) reported that 49% of soils were high (>280 kg ha^{-1}), 42% medium (121–280 kg ha^{-1}), and 9% (<120 kg ha^{-1}) were low in available K (NH_4OAc-K). Srinivasarao et al. (2007) reported low exchangeable K (<50 mg kg^{-1}) in Alfisols of Bangalore, Anantapur, and Ranchi, and Inceptisols of Rakh Dinasar, Ballowal Saunkhri, and Agra. Exchangeable K was in the medium range (50–120 mg kg^{-1}) in Alfisol of Phulbani, Inceptisol of Faizabad, Vertisols of Ajira, and Akola. They observed that Inceptisol of Jhansi, and Vertisols of Bijapur, Bellary, Solapur, Rajkot, Rewa, Indore, and Kovilapatti were high in exchangeable K (>120 mg kg^{-1}). Srinivasarao et al. (2007) also categorized soils across India based on non-exchangeable K extracted by HNO_3. They observed low contents of non-exchangeable K (<300 mg kg^{-1}) in Alfisols of Bangalore, Anantapur, and Vertisols of Akola, and Bijapur; medium non-exchangeable K (300–600 mg kg^{-1}) in Inceptisols of Rakh Dinasar, and Ballowal Saunkhri, Alfisol of Phulbani, and Vertisols of Bellary, Solapur, Rajkot, Indore, and Kovilapatti; and high non-exchangeable K (>600 mg kg^{-1}) in some Inceptisols of Agra, Faizabad, and Jhansi; and Vertisols of Ajira, and Rewa.

Total K content in soils may show variations over depth. For example, surface soils had lower K than sub-surface soils (Sharma et al. 2010). Similarly, relatively higher amounts of available K were found on the surface than in sub-surface soils (Harsha and Jagadeesh 2017a; Sahoo et al. 2020). However, no regular trend was observed in depth-wise variation of exchangeable K up to 60 cm from surface in some soils of Assam, India under varying land-use systems (Das et al. 2019a, b).

3 Mining of soil K under intensive cultivation in India

3.1 Reasons behind soil K mining in India

Mining of soil K in agricultural lands occurs when K balance is negative, i.e., removal by the harvested portion of crops exceeds the external K input, including the K recycled back to the ground with crop residues (Sanyal et al. 2014; Majumdar et al. 2017). In India, the removal of K is more or less equivalent to uptake for field crops as their residues are mostly removed from the fields after harvesting (Sanyal et al. 2014). Crop residues and animal excreta (e.g., cow-dung) generally find use as a source of energy for cooking and heating in rural areas, rather than recycling them back to the fields (Hasan 2002). Crop residues have plenty of other uses in rural households in India, prompting their removal from the crop fields (Sanyal et al. 2014). On top of that, K fertilization is nil or severely inadequate in many parts of the country, including the intensively cultivated areas (Sanyal 2014a). Though local recommendations advocate proper balance among N, P, and K fertilizers, most farmers opt for N only or N and P with little or no K fertilizer (Sanyal 2014b). Surveys conducted in upper- and trans-Gangetic Plains of India revealed that most of the farmers apply N at more than recommended rates, along with P at nearly recommended rates, but apply far more minor than recommended rates of K if applied at all (Singh et al. 2015).

One of the primary reasons behind the neglect of K fertilization in India is the general belief that Indian soils are inherently abundant in K reserves owing to K-containing minerals and can support crops without K fertilization. Secondly, as India is almost 100% dependent on imports for K fertilizers, there has always been an attempt to curtail K fertilization to reduce the burden on the national exchequer (Sanyal 2014a). Next comes the rise in K fertilizer prices after decontrol in August 1992 (from INR 2.83 before decontrol to INR 7.50 kg^{-1} K_2O after decontrol) and the introduction of nutrient-based subsidy in April 2010 (from INR 8.43 in 2010–2011 to INR 28.33 kg^{-1} K_2O in 2012–2013), which further worsened the situation (Chander 2017; FAI 2017; Sanyal 2014a). Moreover, farmers are unaware that yield increment due to K fertilization can translate into economic gains, as discussed later (see 5.4 Economics of K fertilizer use). Also, farmers are most likely oblivious of the ongoing soil K mining caused by imbalanced fertilization and its harmful effects on soil fertility and crop productivity. The first two reasons are mainly at the level of policymakers; the rest are at the farmers' level. For these reasons, fertilizer K consumption remained only ~ 10% of total fertilizer-NPK consumption in India for the last five decades (Majumdar et al. 2017).

In reality, not all soils in India are rich in K-containing minerals, e.g., red and lateritic soils (often classified as kaolinitic Alfisols). Compilation of soil-test data of 500 districts across the country revealed that in ~ 51% of the cases, soils were low (< 120 kg ha^{-1}) to medium (120–280 kg ha^{-1}) in available K (NH_4OAc-K) (Muralidharudu et al. 2011). Also, an abundance of K-containing minerals does not ensure adequate K supply to plants at required rates and at times of highest crop demand (Sanyal et al. 2014; Sanyal 2014a; Majumdar et al. 2016), especially when the micaceous minerals are mostly dioctahedral (Pal 2017).

3.2 Major crops and cropping systems of India and K uptake

As per the estimates for 2015–16, net sown area (NSA) and gross cropped area (GCA) in India were 139.51 and 195.05 million ha (Mha), respectively, with a cropping intensity of ~ 141% (Anonymous 2019). Cereals have the largest share (~ 62%) in GCA, followed by oilseeds (~ 14.4%), pulses (~ 11.6%), fiber crops (6.56%), vegetables (3.46%), and fruits (2.36%). Individually, rice has the highest share (~ 22%) in GCA, followed by wheat (~ 16%) (Anonymous 2019). Potassium uptake per unit mass of economic yield, expressed as kg K Mg^{-1}, varies from one crop to another, e.g., ~ 16 for rice (Buresh et al. 2010); ~ 19 for wheat (Chuan et al. 2013); ~ 7 for groundnut (*Arachis hypogaea*), ~ 1.2 for sugarcane (*Saccharum officinarum*), and ~ 12 for cotton (*Gossypium* spp.) (Dutta et al. 2013). However, due to the largest area coverage, annual N, P, K uptakes (for 2015–16) at the country scale were highest for cereal crops (Table 2). Table 2 shows annual N, P, K uptake for 2015–16 (at country scale) by different crop groups of India, calculated based on crop production data (2015–16) and nutrient content per unit mass of primary produce. Potassium uptake and balance are strongly influenced by cropping systems. Unless climate and other factors become limiting, two or more crops are usually grown in sequence within a year in much of India (Majumdar et al. 2021).

Over 60% of Indian soils fall under three soil orders, viz. Inceptisols, Alfisols, and Vertisols (Singh and Chandran 2015). Inceptisols have the highest area coverage (39.4%) (Singh and Chandran 2015). These soils are considered to be agriculturally productive and offer outstanding natural grazing grounds. It is cultivated chiefly for grain crops, e.g., rice, wheat, maize (*Zea mays*), and barley; oilseeds, e.g., mustard (*Brassica juncea*); improved pasture and various vegetables and fruits. The range of crops grown varies with agro-climatic zones. A large part of the Inceptisol area belongs to IGP, which in turn occupies nearly 13% of the total geographical area (TGA) of the country (Patil et al. 2014).

Table 2 Annual N, P, K uptake (2015–16) by major crop groups of India (adapted from Tewatia et al. 2017). [a]Calculated based on crop production data (2015–16) and nutrient content per unit mass of main produce; Mt million tonnes, P and K uptakes were obtained from P_2O_5 and K_2O uptakes using division factors of 2.29 and 1.2, respectively.

Crop group	Nutrient uptake[a] (Mt)		
	N	P	K
Cereals	6.56	1.344	7.71
Pulses	1.21	0.121	0.61
Oilseeds	1.38	0.244	0.93
Fiber	1.02	0.183	0.70
Fruits	0.51	0.059	0.88
Vegetables	0.56	0.089	0.73
Plantation	0.49	0.045	0.41
Forage	1.00	0.103	1.03
Spices	0.18	0.038	0.21
Sugarcane	0.82	0.205	1.11
Tuber	0.04	0.007	0.04
Others	0.02	0.004	0.03
Total	13.78	2.44	14.37

Alfisols cover 42.2 Mha area, which is around 13% of the TGA of the country (Bhattacharyya et al. 2013). These soils are generally low in available K content, making it difficult to grow crops without external K input (Srinivasarao et al. 2007). However, these soils are well suited for forestry, grazing, and once cleared, a range of grain crops, fruits, and vegetables can be grown. Alfisols are mainly seen in southern and eastern India, supporting upland rice, wheat, groundnut, and finger-millet (*Eleusine coracana*) based systems (Srinivasarao et al. 2007). Among the major crops grown in Alfisols of southern India, finger-millet is one of the high K demanding crops which can remove K as high as 50 kg ha^{-1} (in low rainfall areas) to 150 kg ha^{-1} (under optimum rainfall condition) during its life cycle (Srinivasarao et al. 2014).

The Vertisols are found primarily in Peninsular India, covering 26.6 Mha constituting around 8.1% of the TGA (Singh and Chandran 2015). Groundnut, soybean, cotton, maize, and pigeon pea (*Cajanus cajan*) are the most common crops grown during the rainy season, while crops like safflower (*Carthamus tinctorius*), chickpea (*Cicer arietinum*), sunflower (*Helianthus annuus*), and sorghum (*Sorghum bicolor*) are preferred during the post-monsoon period (Bhattacharyya et al. 2013). Vertisols are generally high in available K and medium to low in non-exchangeable K, which may get depleted under long-term cropping, especially without adequate K input (Srinivasarao et al. 2007). In addition, neglecting K fertilization in Vertisols (black soils) sometimes caused acute K deficiency in plants grown therein (Gurav et al. 2019).

3.3 Soil K mining under major crops and cropping systems

Averaged over all crop groups of India, Tewatia et al. (2017) calculated a net balance (unit area basis) of − 42.2 kg K_2O ha^{-1} for 2015–2016. Negative K balance was highest for sugarcane (− 121.2 kg K_2O ha^{-1}), followed by fruits (− 70.9 kg K_2O ha^{-1}), and lowest for pulses (− 14.7 kg K_2O ha^{-1}) (Fig. 3). The negative balance for cereals (− 45.9 kg K_2O ha^{-1}) was near the average of all crop groups since cereals account for the most significant portion of GCA in India (Tewatia et al. 2017; Anonymous 2019). Consequently, cereal crops have the most significant impact on the K balance in Indian agriculture. On-farm studies (trials conducted at farmers' fields) on major cropping systems conducted under the aegis of AICRP-IFS across India indicated that K among the primary nutrients is the most neglected in the fertilization schemes followed by farmers (Table 3). Those studies recorded large negative K balances under farmers' fertilizer practices (FFP) irrespective of cropping systems. Interestingly, existing state recommendations (SR) were also not able to prevent soil K mining. However, for most of the cropping systems studied, K mining under FFP was slight to extensively higher compared with SR. Application of deficient secondary and micronutrients along with state recommended NPK (SR+M) caused greater mining of K due to an increase in yield and associated K uptake (Table 3).

The IGP is crucial for agricultural production and the economy in India since it contributes as high as 50% of its food grain production, which helps to feed around 40% of the country's population (Chandran et al. 2014). However, due to continuous ignorance towards K fertilization, the soils in these areas face accelerated degradation (Majumdar et al. 2017). Rice–wheat (R-W) system, a dominant system in IGP, could remove K from soil to the tune of 325 kg K ha^{-1} (Singh et al. 2003). Moreover, deleterious effects of alternate flooding and drying adopted in the R-W system in these areas have further aggravated K loss from exchange complexes (Ponnamperuma 1972). Singh et al. (2013) observed a decrease in both exchangeable and non-exchangeable K in IGP under the R-W system, where farmers did not add K. Shukla et al. (2005) assessed the NPK balances for the different sub-regions of IGP, viz. trans, upper, middle, and lower IGP. They found that the net balance was negative for each of the three nutrients in all sub-regions, except for N in the middle IGP. For K, the situation was much worse than N and P, as evidenced by its large share in the deficit (82%) compared with 12.5% and 5.5% in the case of P and N, respectively.

3.4 Soil K mining at national scale

State-wise, K balances for the year 2000–01 were calculated by Pathak et al. (2010) based on K inputs from fertilizers, animal manures, composts, crop residues, burned rice straw, rain, and irrigation water, and outputs towards crop K uptake and leaching losses. They estimated a negative K balance of ~ 3.29 Mt for the entire country. The K budget was negative for every state other than Himachal Pradesh, Orissa, Karnataka, and Kerala (Fig. 4). Later, Satyanarayana and Tewatia (2009) attempted to find out the K balances for 2007–08 in India's major agricultural

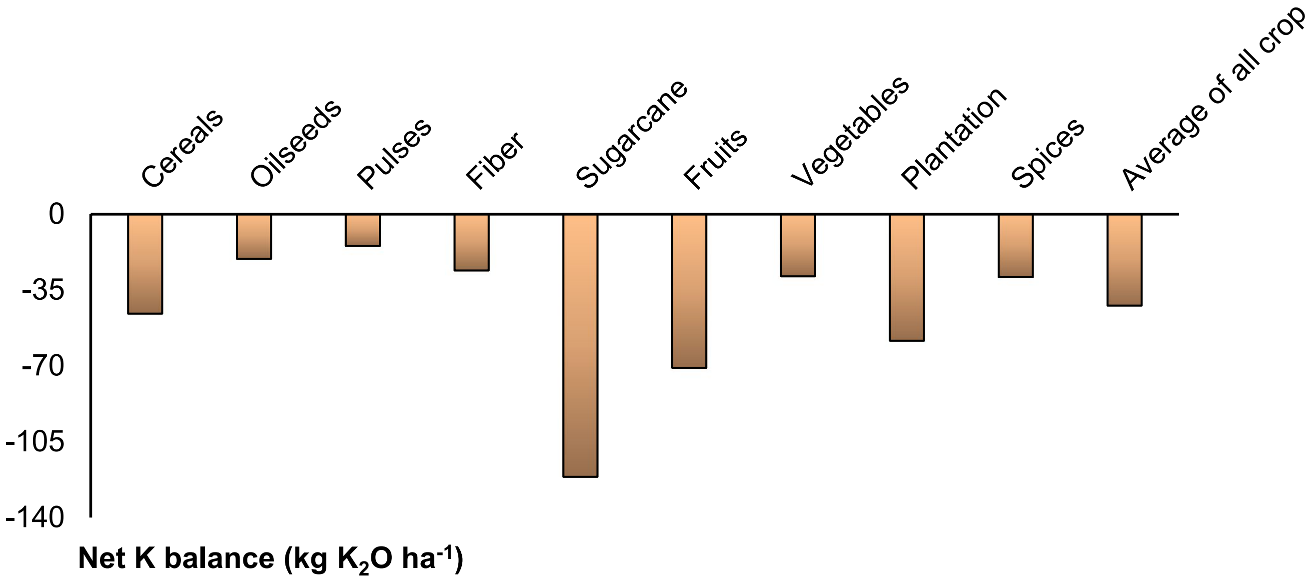


Fig. 3 Annual net K balance per unit area (expressed as kg K_2O ha^{-1}) for 2015–16 under various crop/crop groups in India (adapted from Tewatia et al. 2017).

Table 3 Apparent K balance in cultivators' fields under different cropping systems of India (adapted from AICRP-IFS 2012, Majumdar et al. 2017). [a]Values in parentheses indicate the number of trials conducted in that location, [b]FFP, farmers' fertilizer practice; SR state recommendation for N, P and K, SR + M state recommendation for N, P, and K along with secondary and micronutrients needed for that site, [c]Based on K input through fertilizer and K removal by crops, [d]Pearl millet: *Pennisetum glaucum*; green gram: *Vigna radiata*.

Cropping system	Location	Nutrient management scheme	Nutrient addition (kg ha^{-1}) N–P–K	Apparent K balance[c] (kg ha^{-1})
Rice–wheat	Kaushambi, Uttar Pradesh (24)[a]	FFP[b]	206–28–0	− 150
		SR	220–48–75	− 85
		SR + M	220–48–75	− 99
Pearl millet[d]-mustard	Deesa, Gujarat (18)	FFP	114–37–0	− 104
		SR	130–39–54	− 62
		SR + M	130–39–54	− 68
Pearl millet-wheat	Thersa, Gujarat (18)	FFP	130–35–0	− 65
		SR	200–44–83	− 12
		SR + M	200–44–83	− 18
Cotton-pearl millet	Deesa, Gujarat (18)	FFP	202–38–0	− 85
		SR	320–44–83	− 8
		SR + M	320–44–83	− 19
Rice-green gram	Kakdwip, West Bengal (18)	FFP	53–27–34	− 95
		SR	100–35–66	− 95
		SR + M	100–35–66	− 110
Maize-wheat	Kangra, Himachal Pradesh (18)	FFP	50–14–22	− 31
		SR	170–38–58	− 31
		SR + M	170–38–58	− 39
Maize-Bengal gram (chickpea)	Gadak, Karnataka (24)	FFP	80–38–0	− 133
		SR	110–33–21	− 148
		SR + M	110–33–21	− 160
Rice-rice	Warangal, Andhra Pradesh (24)	FFP	298–60–71	− 101
		SR	240–52–66	− 123
		SR + M	240–52–66	− 136

states based on Fertilizer Association of India (FAI)-statistics on K fertilizer consumption and crop K uptake. For some states, they considered K input from irrigation water and/or organic manures, etc., besides fertilizer as K inputs. However, due to the unavailability of data, only fertilizer was considered K input for most (12) of the states. On the output side, authors not only took into account the field crops, but also the K removals by vegetables and fruits for all 16 states, and crops like rubber tree (*Hevea brasiliensis*), coffee (*Coffea* spp.), tea (*Camelia sinensis*), and jute (*Corchorus* spp.) in states wherever applicable. They observed the highest K mining in the central and western region (~ 3.19 Mt as K) followed by northern (~ 2.18 Mt as K), eastern (~ 1.59 Mt as K), and southern region (~ 1.11 Mt as K), respectively. Apparent K balances were negative in each state, and the overall K mining for 16 states considered in the study was ~ 8.07 Mt (as K) (Satyanarayana and Tewatia 2009). Considering K input through fertilizers and manures and output through crop removal, Dutta et al. (2013) observed that K balances in most states were negative. In most states, K mining was more in 2011 than that in 2007 (Fig. 5). Their study showed increased K mining in the soils of the north (Punjab, Haryana, and Uttar Pradesh), east (Assam, Bihar, Orissa, Jharkhand, and Chhattisgarh), west and central parts (Gujarat, Rajasthan, and Madhya Pradesh) of India during 2011 as compared to 2007. Gross and net K balances for 2015–2016 for the entire country were ~ 12.3 and ~ 7.2 Mt (as K) on the negative side, respectively (Tewatia et al. 2017). The gross K balance was calculated considering inorganic fertilizer as input and crop K removal as output based on crop production and fertilizer consumption data, and nutrient uptake coefficients gathered from multiple sources (Tandon 2004; Tandon and Muralidharudu 2010; FAI 2016). They made two additional assumptions for the net balance: (i) net K uptake is 60% of gross K uptake, and (ii) fertilizer use efficiency is 70% for K. Information from the national database of the Soil Health Card Scheme (launched in 2015) for eight districts representing intensively cultivated areas of India revealed severe K deficiency in north-western India,

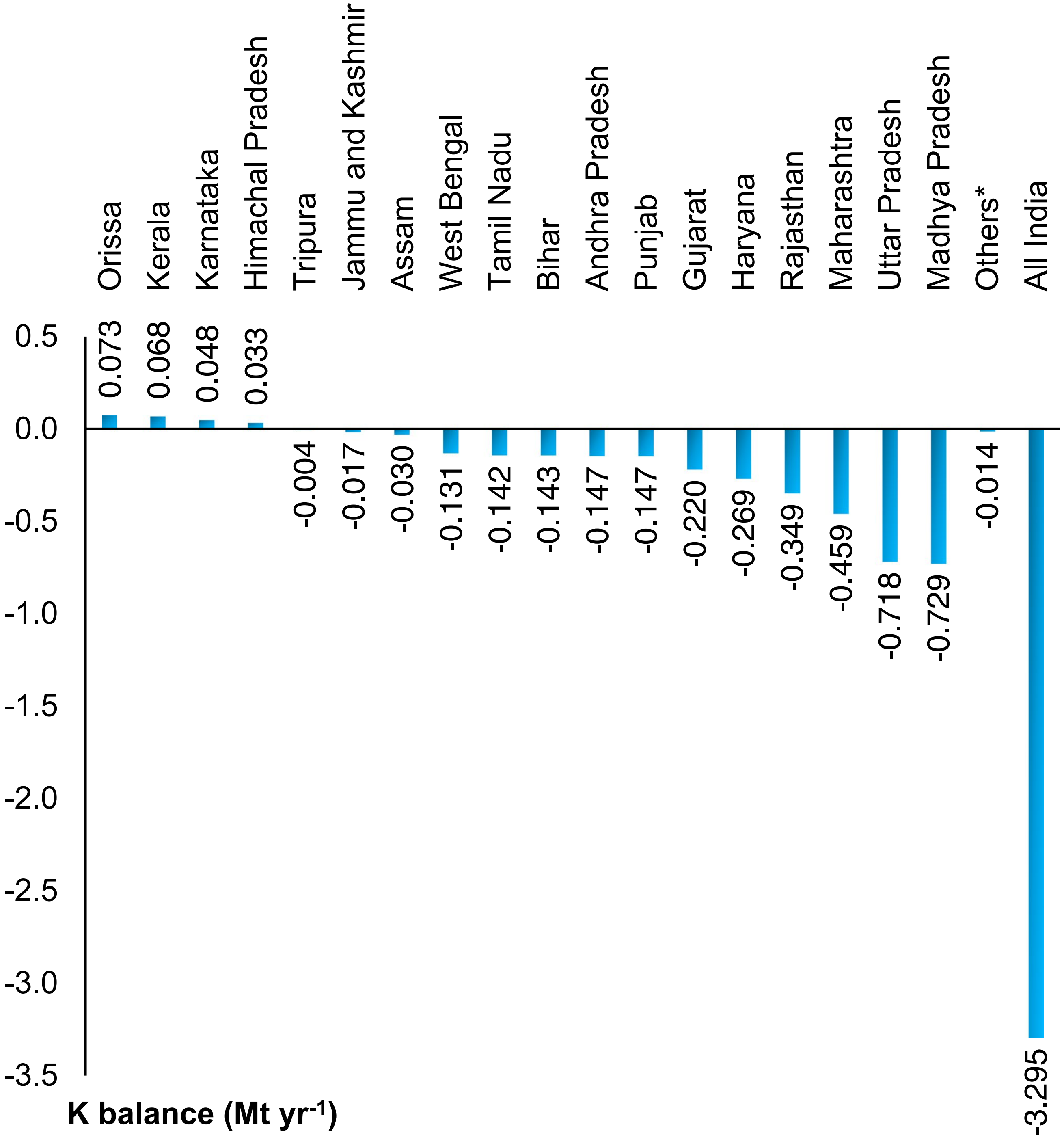
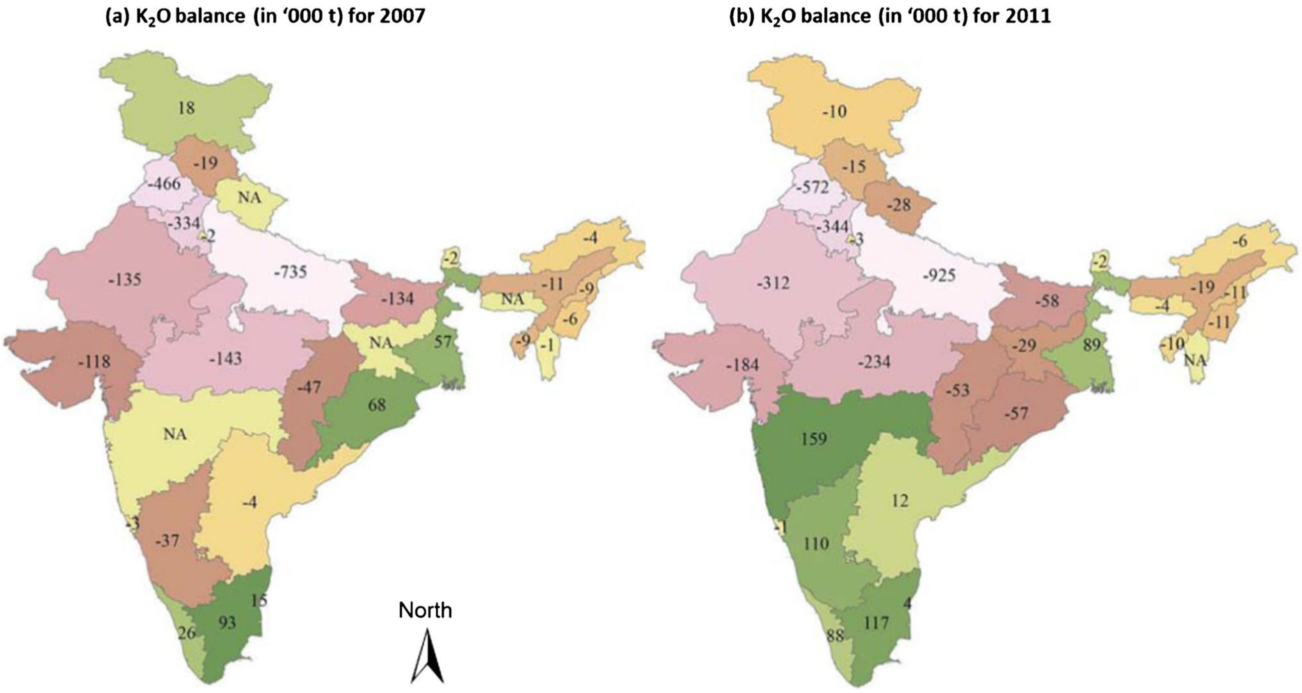


Fig. 4 K balance for 2000–01 in different states of India; K balance = K input (through fertilizer, compost, animal manure, crop residue, burned rice straw, rain, irrigation water) – K output (through crop uptake and other losses); *Others include Delhi, Chandigarh, Goa, Arunachal Pradesh, Manipur, Meghalaya, Mizoram, Nagaland, Sikkim, Dadra and Nagar Haveli, Daman and Diu, Andaman and Nicobar Islands (Adapted from Pathak et al. 2010).

where K deficiency was not anticipated previously due to the abundance of micaceous minerals (Patra et al. 2017). Notably, in these areas of north-western India, highly negative K balances were observed earlier (Dutta et al. 2013).

The K balances reported by different authors, as mentioned above, cannot be compared among each other as the input and output variables and sources of information were different across the studies. For the same reason, it


(a) K_2O balance (in '000 t) for 2007

(b) K_2O balance (in '000 t) for 2011

Fig. 5 Potassium balance (as K_2O, expressed in thousand tonnes) for (**a**) 2007 and (**b**) 2011 across different states of India; balances were calculated based on K input through fertilizer and manure and output through crop removal; NA: data were not available. (Dutta et al. 2013; reproduced with permission from Editor, African Plant Nutrition Institute).

cannot be said with certainty from the existing data that the K balance has become more negative in India over the years. Nonetheless, it is undeniable that significant K mining has been occurring in the agricultural soils of India for a long.

4 Implications of neglecting K fertilization: lessons from long-term experiments

Long-term fertilizer experiments (LTFEs) provide ideal platforms to assess the negative impacts of neglecting K fertilization on soil K supplying capacity and crop productivity, as the same may not become visible over the short-term. Therefore, the present discussion mainly highlights the findings of long-term experiments conducted in different parts of India, primarily representing Inceptisols, Alfisols, and Vertisols. These three orders account for over 60% of Indian soils (Sing and Chandran 2015). Equivalent situations in other parts of the world have also been briefly discussed.

4.1 Apparent K balance and depletion of soil K pools

Percent change per year (over initial content) in NH_4OAc-K as observed under NP (representing 100% recommended rate of N and P fertilizer application without K) in LTFEs at different locations reveal the decline in readily available K pools due to long-term neglect of K fertilization irrespective of soil orders (Fig. 6). The only exception was the Parbhani site, where a slight increase in NH_4OAc-K was observed. In general, the rate of decline (with respect to the initial value) was noticeably higher in Alfisols (-1.57% year^{-1}, an average of three locations) than Vertisols (-0.62% year^{-1}, an average of three locations) or Inceptisols (-0.61% year^{-1}, an average of three locations). Such variation among soil orders could be due to several factors, e.g., K balance, rate of replenishment of soil solution and exchangeable K pools by non-exchangeable K, and the initial content of NH_4OAc-K. Nonetheless, intensive cropping without K fertilization would decline soil K availability. Besides exchangeable K, long-term neglect of K fertilization under intensive cropping can also cause a noticeable decline in the non-exchangeable K content of soils (Table 4). As one would anticipate, the annual apparent K balance was negative under NP for each of the LTFEs located at New Delhi (Inceptisol), Ranchi (Alfisol), and Jabalpur (Vertisol). Although apparent, such negative K balances could cause a noticeable decline in exchangeable (30.9–47.4% across soil orders) and non-exchangeable K (12.9–24.2% across soil orders) compared with adjacent uncultivated soil (or reference soil) after more than four decades of intensive cropping (Table 4). As already discussed, most Indian farmers apply N at or more than recommended rates and P mostly at recommended rates. In

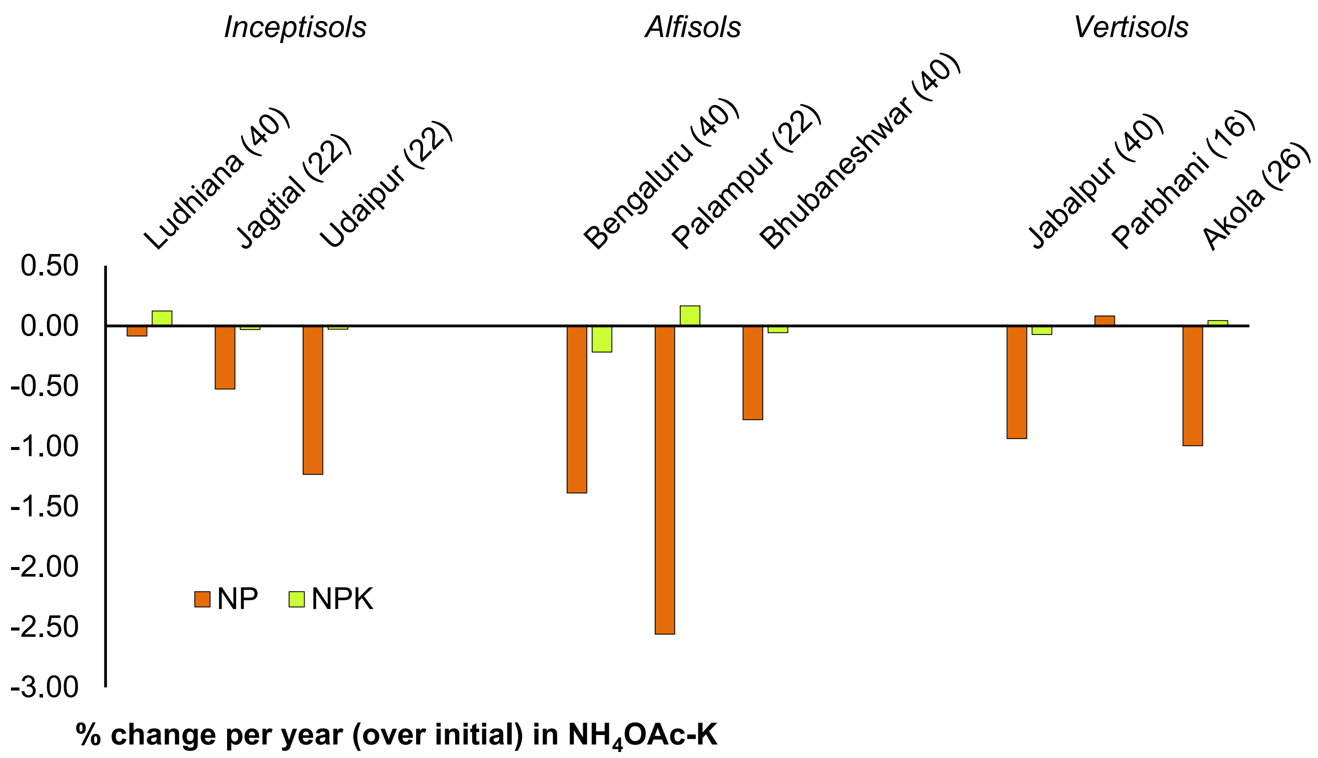


Fig. 6 Percentage of change per year (over initial) in NH_4OAc-K under intensive cultivation without or with K fertilization as observed in long-term fertilizer experiments at different locations representing Inceptisols, Alfisols and Vertisols; figures within parenthesis indicate the number of years of cultivation (i.e., the duration of the experiment considered), based on percent change per year was calculated. (Adapted from Singh et al. 2017).

comparison, K at much less than recommended rates or do not apply at all, and commonly do not return crop residues to the fields. Hence, based on the observations from LTFEs, it will not be wrong to speculate that most Indian soils have already lost a substantial part of their inherent K reserves, and the same will go on unchecked if proper K management is not given due cognizance.

Interestingly, even with K fertilization at recommended rates, there was a decline in NH_4OAc-K on multiple occasions (Fig. 6). Data from LTFEs spread across the country representing Inceptisols, Alfisols and Vertisols showed

Table 4 Annual apparent K balance and percent change in exchangeable and non-exchangeable K over adjacent uncultivated soil due to long-term cropping without or with K fertilization at three LTFE sites (Adapted from Singh et al. 2017; Das 2018b; Das et al. 2019c). [a]Textural class: sandy clay loam, [b]Clay, [c]Calculated based on apparent K balance of 34 years (for the Inceptisol) or 44 years (for the Alfisol and Vertisol) as reported by Singh et al. (2017), [d]EK, exchangeable K; NEK, non-exchangeable K (extracted by $NaBPh_4$ for 4 h), [e] % change over uncultivated soil = $100 \times \left[\frac{(\text{Value of a parameter under a given treatment} - \text{value of the parameter in uncultivated soil})}{\text{Value of the parameter in uncultivated soil}}\right]$.

Soil order	Location	Depth (cm)	Years of cropping	Cropping system	Annual apparent K balance (kg ha^{-1} $year^{-1}$)[c]		% Change over uncultivated soil[e]			
							EK[d]		NEK	
					NP	NPK	NP	NPK	NP	NPK
Inceptisol	New Delhi	0–15[a]	43	Maize-wheat	−248	−228	−30.9	−13.5	−13.2	−5.8
		15–30[a]					−31.4	−17.3	−23.6	−12.9
Alfisol	Ranchi	0–15[a]	42	Soybean-wheat	−63	−27	−47.4	−35.3	−22.8	−12.5
		15–30[a]					−39.7	−27.7	−12.9	−3.0
Vertisol	Jabalpur	0–15[b]	42	Soybean-wheat	−195	−209	−44.8	−20.8	−24.2	−25.7
		15–30[b]					−30.9	−13.5	−13.2	−5.8

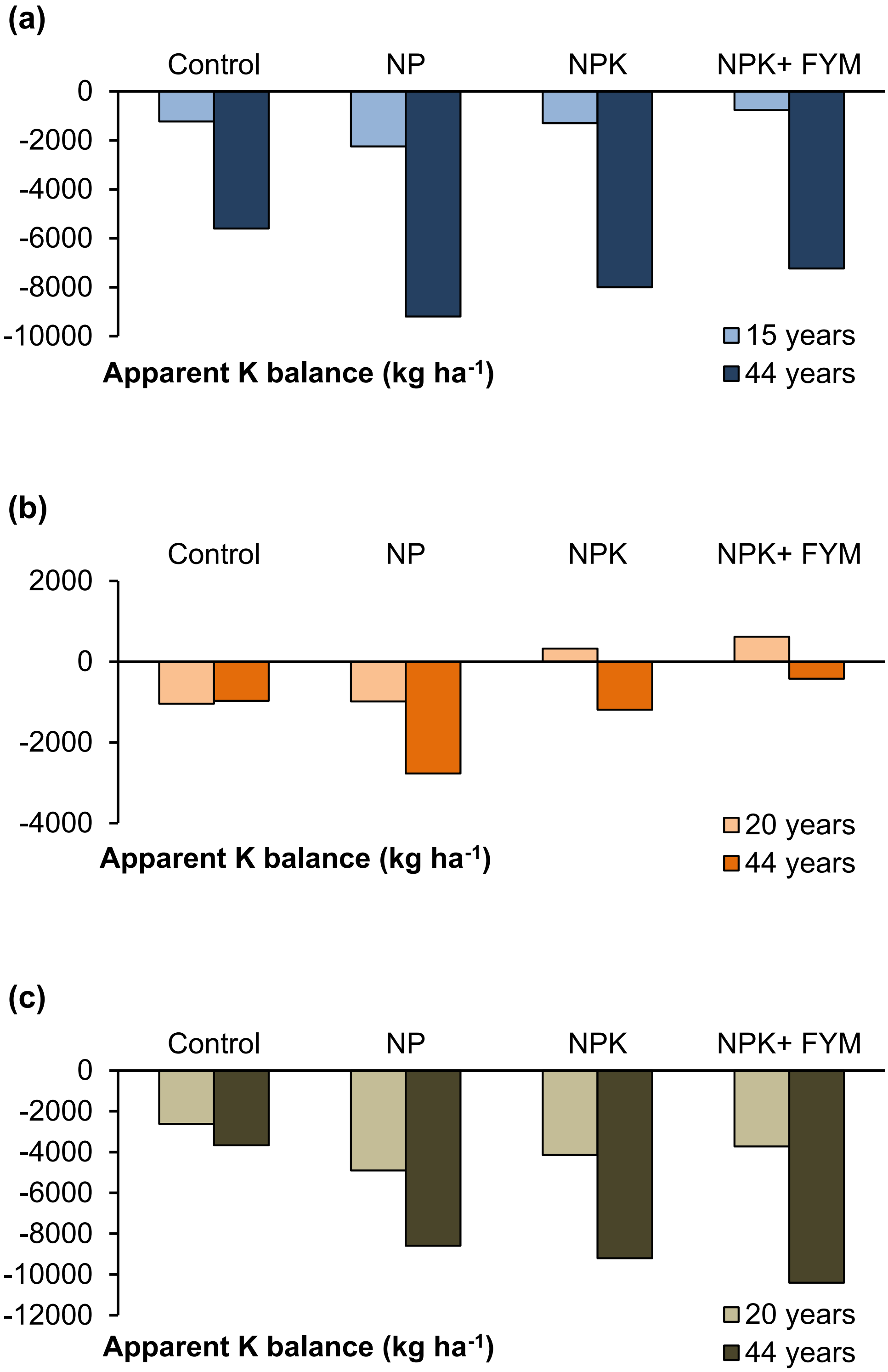


Fig. 7 Effect of nutrient management practices on apparent K balance observed in long-term experiments in (**a**) Inceptisols after 15 and 44 years; (**b**) Alfisols, and (**c**) Vertisols after 20 and 44 years. Control: no fertilizer or manure applied; NP: recommended rate of N and P applied through fertilizer; NPK: recommended rate of N, P and K applied through fertilizer; NPK + FYM: NPK + farmyard manure applied once in a year to the wet season crop; rates of N, P, K and FYM varied among locations (Adapted from Singh et al. 2017). Note: Inceptisols: 15-year data are from Jagtial, Telangana with rice-rice system and 44-year data are from Coimbatore, Tamil Nadu with finger millet-maize system. Alfisols: 20-year data are from Pattambi, Kerala with rice-rice system and 44-year data are from Ranchi, Jharkhand with soybean-wheat system. Vertisols: 20-year data are from Raipur, Chhattisgarh with rice–wheat system and 44-year data are from Jabalpur, Madhya Pradesh with soybean-wheat system.

negative apparent K balances not only when K fertilization was not done but also when K fertilizer at the recommended rate was applied without or with FYM (Fig. 7). The extent of negative K balance varied from one soil to another depending on the crop, its productivity in a particular soil, and the K fertilizer recommendation for that site. Generally, the more the productivity, the more is the K uptake, and the greater is the extent of negative K balance (Singh et al. 2017). In 10 LTFE sites (3 each with Inceptisols and Alfisols, and 4 with Vertisols), apparent K balance varied from – 26 to – 63, – 72 to – 245, and – 150 to – 248 kg ha^{-1} year^{-1} under NP in Alfisols, Vertisols, and Inceptisols, respectively. Under NPK, the respective ranges for Alfisols, Vertisols, and Inceptisols were 16 to – 60, – 108 to – 209, and – 87 to – 228 kg ha^{-1} year^{-1} (Singh et al. 2017). Overall soil fertility and crop productivity in Alfisols are generally lower than Inceptisols and Vertisols in India (Pal 2017), for which the extent of negative K balance was also lower there. Corresponding to negative apparent K balances, Das (2018b) and Das et al. (2019c) observed a decline in exchangeable as well as non-exchangeable K (compared with adjacent uncultivated soils) to the tune of 13.5–35.3% and 3–25.7%, respectively, at three LTFE sites under NPK treatment (Table 4). At those LTFEs, the impact of > 4 decades of intensive cropping with varying nutrient supply options on total K was non-significant (at $P = 0.05$) (Das 2018b; Das et al. 2019c), implying that structural K pool had negligible involvement in K supply to plants over the years.

In 9 of the above mentioned 10 LTFE sites, apparent K balances were negative even when FYM (which contains ~ 0.5% K) was applied (at the rate of 5–15 Mg ha^{-1} annually) along with the recommended rate of K fertilizer. In some instances, apparent K balance under NPK + FYM was more negative than NPK or even NP (Singh et al. 2017). For example, at the Jabalpur-LTFE site, apparent K balance averaged over 44 years was – 237 kg ha^{-1} year^{-1} under NPK + FYM as against – 209 and – 195 kg ha^{-1} year^{-1} under NPK and NP, respectively. Corresponding to that slightly lower non-exchangeable K contents were observed under NPK + FYM (852 and 895 mg kg^{-1} at 0–15 and 15–30 cm, respectively) as compared to NPK (868 and 903 mg kg^{-1} at 0–15 and 15–30 cm, respectively) or NP (886 and 920 mg kg^{-1} at 0–15 and 15–30 cm, respectively) after 42 years of intensive cropping (Das 2018b). Such a situation occurs when the increments in yields and associated K uptakes due to manuring are more than the additional K input from the FYM applied. Nonetheless, such decline in soil K pools, especially the non-exchangeable pool, even under recommended rates of K fertilization, underlines the inadequacy of current K fertilizer recommendations in maintaining the original soil K fertility status under conditions of long-term intensive cropping.

Sometimes, negative apparent K balance might correspond to an increase in NH_4OAc-K, as observed in a long-term experiment (27 years) conducted on a K-deficient Alfisol from southern India under finger-millet mono-cropping (Srinivasarao et al. 2014). Irrespective of treatments, which were control (no amendments), FYM, FYM + 50% NPK, FYM + 100% NPK and 100% NPK (no organic source), K removal by crop was more than that added through FYM or fertilizer or their combination. Despite, NH_4OAc-K increased by ~ 18% and ~ 39% (over initial content of ~ 59 mg kg^{-1}) under FYM + 50% NPK and FYM + 100% NPK, respectively after 27 years of cropping. Over that supplied through external inputs and the exchangeable K, non-exchangeable K pool met the crop K demand (Srinivasarao et al. 2014).

Li et al. (2017a) reported a decline in NH_4OAc-K after 25 years of wheat–maize cropping with heavy inputs of N and P fertilizers in an alluvial soil of China. They also observed greater depletions in the non-exchangeable pool with increasing N and P applications over unfertilized control in the surface layer (0–20 cm). However, long-term cropping with different fertilization or tillage had little impact on the structural K pool (Li et al. 2017a). After two decades of wheat–maize cropping in a light textured soil (Calcaric Cambisol) of China, Zhao et al. (2014) observed a significant depletion in non-exchangeable K at surface soil (0–20 cm) in no-K treatments (NP or NP + straw) compared with initial the content. In contrast, the same increased with K fertilizer addition (NPK or NPK + straw). Thus, long-term skipping of K input resulted in the transformation of interlayer K into available K, which was then taken up by the plants and removed from the soil with harvested biomass.

4.2 Alteration of clay minerals

Long-term neglect of K fertilization under intensive cropping can also alter clay minerals by transforming mica or illite to vermiculite, smectite, and interstratified minerals with lower layer charge. In an LTFE site at New Delhi (Inceptisol), after 43 years of intensive cultivation, mica content in clay at 0–15 cm of NP plot was found to be ~ 42% as against ~ 51% in NPK plot and ~ 54% in adjacent uncultivated soil (Das 2018b). In another LTFE located at Ranchi (Alfisol), at the end of 42 cropping cycles, lesser illite in NP (~ 8% at 0–15 cm and ~ 7% at 15–30 cm) as compared to NPK (~ 14% at 0–15 cm and ~ 10% at 15–30 cm) was observed in clay fraction (Das et al. 2019c). Associated with it, illite-kaolinite interstratified minerals under NP (~ 69%) were more than that under NPK (~ 59%) at 0–15 cm. At 15–30 cm, NP recorded more vermiculite-illite interstratified minerals (~ 10%) than NPK (~ 6%). A more alarming fact observed in this study was that the illite content of clay even under NPK + FYM was noticeably lower than adjacent uncultivated soil at 0–15 and 15–30 cm depths (Das et al. 2019c). Similarly, in the LTFE site at Jabalpur (Vertisol), after 42 years of cropping, mica content in clay (at 0–15 cm as well as 15–30 cm depths) showed a noticeable decline under NP (~ 15–19%), or NPK (~ 12%) or even NPK + FYM (~ 12–15%) as compared to adjacent uncultivated soil (~ 24–37%) (Das 2018b). In all those sites, apparent K balances were negative under NP, NPK and NPK + FYM (Singh et al. 2017). Although the contents of clay minerals reported in these studies were semi-quantitative, there is a clear indication that soil K mining under intensive cropping for a long time is likely to cause alterations in K-bearing clay minerals. Such alterations are manifested primarily as loss of micaceous minerals and their subsequent transformation into vermiculite or interstratified minerals like vermiculite-illite and illite-kaolinite. If allowed to go unchecked for a long time, alterations in micaceous minerals due to continued depletion of interlayer K could be irreversible and would have far-reaching adverse impacts on K supplying capacity in particular and soil health in general (Sanyal et al. 2014; Das et al. 2019c).

Fifteen years of cropping (with various summer and winter season crops) in a field without K addition followed by exhaustive cropping in a greenhouse (different crops in succession) again without K input led to the depletion of non-exchangeable K pool and resulted in the transformation of illite to vermiculite in a Brazilian Ultisol (Moterle et al. 2016). They observed that growing crops without K input practically deteriorated the illite. After 32 years of cultivation with a rotation of soybean, maize, wheat, and oats (*Avena strigosa*) on a Brazilian Oxisol, Firmano et al. (2020) observed a decrease in the crystallinity of K-bearing 2:1 phyllosilicates in the clay fraction under no K fertilization for the entire period.

Overall, K-exhaustive conditions induced by long-term cropping with no or inadequate K input result in a noticeable decrease in exchangeable and non-exchangeable pools but have a small or negligible effect on the structural pool associated with primary minerals. Under constant exhaustion of K in soil, plants create a strong gradient in the rhizosphere, which can promote the release of K^+ from edge/wedge as well as deep interlayers of K-bearing 2:1 minerals, especially in the clay separates, thereby causing their alteration into other minerals. At the same time, such changes are mostly irreversible.

5 Sustainable management of potassium in agriculture

Developing effective K management strategies that could help reduce K losses and somehow return the depleted K to the soil to meet crop demand is vital for agricultural sustainability. Various aspects of K management are discussed hereunder:

5.1 Correct evaluation of soil K available for crops

An efficient K fertilizer recommendation would ensure optimal quantity and suitable proportions of K supply to meet crop requirement, help develop the desired balance of K in soil, and assure higher use efficiency of K and other nutrients (e.g., N). Presently, recommendations of K fertilizer rates are based on the crop to be grown and soil K fertility assessed by neutral normal NH_4OAc, which extracts the water-soluble and exchangeable fractions only. Such recommendations have often been found inadequate under intensive cultivation and unsuccessful in highlighting cropping-induced changes in soil K (Singh et al. 2017; Das et al. 2018; 2019c, d). This is due to the contribution of the non-exchangeable pool of K in soil towards plant uptake, which assumes more importance in soils low in NH_4OAc-K (Dhar and Sanyal 2000; Ghorban 2007). This is why some earlier workers have also included non-exchangeable K to evaluate better the available K (Rao et al. 1993; Srinivasarao et al. 2001). To include the non-exchangeable pool of K in defining soil K status, Srinivasarao et al. (2007) classified many Indian soils into low, medium and high categories based on exchangeable and non-exchangeable K pool sizes, where the non-exchangeable K was extracted by boiling nitric acid method. Li et al. (2015b) observed that the $NaBPh_4$ method is way more specific to non-exchangeable K than the conventional boiling nitric acid method, as, in the former, $>99\%$ of extracted K is released through cation exchange as against ~ 85–87% of extracted K released through cation exchange (the rest through the dissolution of the mineral structure) by boiling nitric acid method. In the future, researchers should opt for the $NaBPh_4$ method, instead of the conventional nitric acid method, to categorize soils for their non-exchangeable K status and ensure sufficient extraction time so that no part of interlayer K is missed out. Besides, upcoming research should focus on fractionation of the entire non-exchangeable pool based on plant availability (Wang et al. 2016).

The $NaBPh_4$ extraction method, though more specific than boiling nitric acid towards non-exchangeable K (Li et al. 2015b), and many times showed better predictions of plant K uptake than NH_4OAc (Cox et al. 1999; Bilias and Barbayiannis 2017; Bilias et al. 2021), is not entirely flawless. This method cannot predict the actual quantity of diffusion derived non-exchangeable K that plants can uptake (Núñez and Morón 2017), a problem common to all methods involving chemical extraction (Logan and Chaney 1983; Menon et al. 1989). In this context, cation exchange resins might prove useful in appropriately assessing the availability of soil K to plants. Cation exchange resins with high CEC can act as a sink for soil solution K and the non-exchangeable K released for plant uptake (Helmke and Sparks 1996). The amount of K extracted with H-saturated resin could be comparable with that extracted by acid treatment, but it is far less dangerous than acid extraction with respect to the breakdown of mineral structure (Arvieu and Chaussidon 1964). In the past, cation exchange resins have shown their ability to mimic plant K uptake by reflecting solution K activity and diffusion rate (Schaff and Skogley 1982; Skogley and Schaff 1985; Buck et al. 2016). Recently, Bilias et al. (2021) observed that K extracted by H-resin could predict plant K uptake from soils containing K-fixing 2:1 clay minerals with good accuracy ($r^2 = 0.63$ or 0.69, $p < 0.001$). More or less similar prediction accuracy ($r^2 = 0.65$ or 0.67, $p < 0.001$) was obtained with $NaBPh_4$ with extraction time of 1 or 5 min. Thus, to aim for the plant available part of non-exchangeable K, one can choose between $NaBPh_4$ with a short extraction period (i.e., 1 or 5 min) and H-saturated resin; whereas, to estimate the entire non-exchangeable K reserve, $NaBPh_4$ method with sufficient extraction time (10–20 days) should be the approach. Extraction of soil K with low molecular weight organic acids, e.g., citric, oxalic, malic, and tartaric, can also mimic the action of plant roots. The hydronium (H_3O^+) ions generated by dissociation of organic acids can replace K^+ from planar sites and clay inter-layers; acid's anionic part complexes the K^+ in solution and inhibits sorption on the solid phase. Hosseinpur et al. (2014) studied K release up to 168 h using 0.01 M citric acid. The associated release rate constants were significantly correlated with bean (*Phaseolus vulgaris*) yield, and K uptake studied over 15 different soils of Iran.

Fixation and release of K play an important role in K supply to plants in soils having considerable amounts of 2:1 minerals in the clay fraction, which is not considered in the existing K fertilizer recommendation methods (Das et al. 2018; Bilias and Barbayiannis 2019a, b). Thresholds of K fixation and release in the soil can help decide the rate of K fertilization for crop production. Datta and Sastry (1989) and later Datta (2005) described the methodology for the determination of fixation threshold level (FTL) and release threshold level (RTL) of soils. The FTL is the level of soil solution or exchangeable K, beyond which K fixation into the non-exchangeable pool starts. In contrast, RTL is the level of soil solution or exchangeable K, below which release from non-exchangeable pool initiates (Datta 2005). Based on this approach, the K fertilization rate that could maintain soil solution or exchangeable K at an optimal level between the FTL and RTL seems viable. It would support K nutrition of plants without causing mining from or fixation into the non-exchangeable pool (Das et al. 2018; Datta 2005). This approach could be improved further by considering the actual K requirement of the crops to be grown. Li et al. (2016) developed a soil bioavailability grading system for K based on plant growth indices and soil K release rate. They built a relationship between the potential soil capacity for sustainable plant growth and the availability of K without additional K fertilizer to describe the release of K in soil.

Recently, exchangeable and non-exchangeable K extraction methods were clubbed with quantity-intensity (Q/I) parameters, CEC, and illite-K to establish an approach based on the thermodynamic parameters obtained from Q/I relationships for predicting the availability of K (Bilias and Barbayiannis 2019a). However, despite better accuracy being provided by the Q/I technique than the existing method for predicting soil K availability, generating multipoint-Q/I relationships is laborious and time-taking and is not fit for routine soil testing. Fortunately, it has been possible to predict different Q/I parameters with a single-point (using 10 mg K L^{-1} in 0.01 M $CaCl_2$ for equilibration) method for a wide variety of soils (concerning K status), where CEC and Gapon selectivity coefficient could further increase the accuracy of prediction (Bilias and Barbayiannis 2020).

5.2 Sources of K in agriculture

5.2.1 Fertilizers

Conventional fertilizer sources, e.g., muriate of potash (MOP) and sulphate of potash (SOP), are often relied upon for meeting the immediate need of plants for K. However, for K fertilizers, India is entirely dependent on imports, which is a massive burden on the national exchequer. Moreover, though K from the water-soluble fertilizers (e.g., MOP, SOP) is readily available to plants, it is also prone to leaching losses, mainly in sandy soils with low clay and organic matter content (Alfaro et al. 2004). Besides, K mineral reserves used in K fertilizer production are not infinite and might get exhausted amid the increasing demand created by intensive cultivation. Hence, sustainable alternative sources of K should be searched to achieve self-sufficiency in K nutrition in Indian agriculture. This calls for a gradual transmission from K fertilizers to indigenous K sources such as crop residues, manures, wood ash, distillery wastes, coir waste, and indigenous low-grade K-bearing minerals, to replenish the soil K (Aziz et al. 2010; Basak and Sarkar 2017). Some of the non-conventional sources of K and their effectiveness in growing crops are outlined in Table 5.

5.2.2 Crop residues

Crop residues containing 1% or more K, e.g., rice straw (~ 1.75% K), wheat straw (~ 1% K), sugarcane bagasse (~ 1.2% K), oat straw (~ 1.5% K), and tobacco (*Nicotiana* spp.) stems (~ 7% K), can serve as a sustainable alternative source of K in agriculture (Basak and Sarkar 2017). After harvesting grain crops, around 50–70% of total biomass is left as residues, which would add a substantial amount of K therein if returned to the soil. However, decomposition and subsequent release of nutrients from straw are time-taking processes in the field, so the positive effects of straw-return on soil K status and crop yields may not be visible over short-term periods (Brunetto et al. 2011; Partey et al. 2011). Nevertheless, over the long term, straw-return could alleviate soil K depletion under intensive cropping, enhance soil K status and increase crop yields (Zhao et al. 2014). Crop residues could be directly incorporated into the soil, converted to compost or biochar before soil application, or retained on the surface as a part of conservation agriculture to use them as K source (Singh and Sidhu 2014; Katyal 2020).

Table 5 Performance of alternative sources of K with respect to crop response. [a]K supplied through muriate of potash (MOP), [b]FYM farmyard manure, [c]KSB potassium solubilizing bacteria.

Source of K	Location	Soil/medium properties	Crop	Treatment	Salient findings	Reference
Organics						
Crop residue (wheat straw and cotton residue)	Nanjing, China	Clay loam, pH 5.7, exchangeable K 134 mg kg^{-1}	Wheat and cotton	Wheat straw (0.9 Mg ha^{-1}) and cotton residue (0.7 Mg ha^{-1})	98% increase in crop K uptake over control where no residue or K fertilizer was added	Sui et al. (2017)
Seaweed (*Kappaphycus alvarezii*) extract	Jharnapani	Clay loam, pH 4.8, available K 124 mg kg^{-1}	Soybean	Foliar spray of extract (15%)	Enhanced grain and straw yields over control with highest K uptake	Rathore et al. (2009)
Minerals						
Waste mica	New Delhi	Clay loam (Hazaribagh, Jharkhand) pH 6.13, available K 61.4 mg kg^{-1}	Sudan grass	Waste mica (100 mg kg^{-1})	Significantly higher K uptake and biomass yield over control	Basak and Biswas (2010)
Polyhalite	Northern Vietnam	Silt loam, pH 5.0, total K 0.58 g kg^{-1}	Cabbage	MOP[a] and polyhalite at 1:1 ratio for supplying 120 kg K_2O ha^{-1}	Increased profit by 64% over farmers' practice by significantly reducing K fertilizer requirement and increasing yield	Tien et al. (2021)
Organics + microbial culture						
Crop residue + FYM[b] + biofertilizer	Kanpur, Uttar Pradesh	Sandy loam, pH 8.1, available K 81 mg kg^{-1}	Maize-wheat	100% crop residue incorporation + FYM (5 Mg ha^{-1}) + biofertilizer	Significantly higher crop K uptake over control	Venkatesh et al. (2017)
Mineral + microbial culture						
Waste mica + KSB[c] (*Bacillus pseudomycoides*)	Jorhat, Assam	Sandy clay loam, pH 4.84, exchangeable K 73.5 mg kg^{-1}	Tea	Waste mica (50 kg K_2O ha^{-1}) + KSB (500 L ha^{-1})	Significantly higher K uptake, plant growth and exchangeable K content in soil over application of waste mica without KSB	Pramanik et al. (2019)

5.2.3 Manures and composts

Organic manures and composts, though they are used mainly to enhance organic matter content and overall fertility of soils, can also act as alternative sources of K depending on their K content, which varies primarily based on their ingredients and preparation method (Hue and Silva 2000; Das et al. 2015; Basak and Sarkar 2017). For instance, farmyard manure or FYM (~ 0.5% K), poultry manure (~ 1.5–3% K), pig manure (~ 0.5–1.2% K), urban/rural composts (~ 0.5–2% K), night soil (~ 0.4% K), oil cakes (~ 0.8–1.4% K), fish meal (~ 1.5% K), etc., could be used to boost up soil fertility and to supplement K fertilizers in agriculture (Hue 1995; Tandon 1995; Basak and Sarkar 2017). Furthermore, field experiments have shown the positive influence of NPK + FYM in maintaining K-supply and available K fractions in soils better than that of imbalanced fertilization (without K) (Jadhao et al. 2018; Das et al. 2018; 2019c).

5.2.4 Minerals

Suggestions to use silicate rocks bearing K-containing minerals as sources of K are not new. Tectosilicates like orthoclase (~ 16% K), microcline (~ 16% K); and phyllosilicates like muscovite (~ 12% K), biotite (~ 6–10% K), phlogopite (~ 7–10% K), glauconite (~ 5–8% K) are some of the K containing minerals which can prove useful as alternative K source (Shirale et al. 2019). Direct use of these rocks is sometimes considered more acceptable and cost-effective instead of using them to produce K fertilizers (Manning 2010). However, due to the very low solubility of silicate rocks, if applied directly, the rate of release of K from such sources could be far less than what is required for proper plant nutrition. Bio-activation through K solubilizing or silicate dissolving microorganisms could help attain a desirable K release rate from these sources. Though K bearing minerals are far less effective than conventional fertilizers (e.g., MOP, SOP) in terms of providing readily available K, the former could supply enough amount of K over a long-term period to fetch agronomic benefits, especially in highly weathered soils prone to leaching (Basak and Sarkar 2017). Milled syenite (silicate rock with K-feldspar as the dominant mineral) has been described as a possible K source from which plants can obtain K conveniently (Manning et al. 2017). Studies on phyllosilicate minerals as K sources revealed that biotite and vermiculite could be applied directly, while illite can be used effectively combined with conventional soluble K sources (Li et al. 2015a). In India, some low-grade indigenous K-bearing minerals can be used as an alternative source of K for growing crops, especially in highly weathered soils, e.g., Alfisols, Oxisols, which are inherently low in K reserves (Basak and Sarkar 2017). One such example is glauconite-rich greensand, which can be used as a slow-release K fertilizer more effectively in acid soils. As of 1 April 2015, India had ~ 2500 Mt of glauconite reserves (Anonymous 2018). This could be used in combination with other K sources for K supply to crops. Around 16% improvement in potato yield was observed with greensand application in a coarse-textured soil with low organic matter (Heckman and Tedrow 2004). Another such indigenous K source could be waste mica (~ 6.5–10% K), generated in huge quantities as a by-product of the electrical industry. With proper modification through biological or chemical means, waste mica can be effectively used in agriculture as a K source (Nishanth and Biswas 2008). Waste mica applied directly after grinding could improve biomass yield of Sudan grass (*Sorghum vulgare* var. Sudanese) compared with no fertilization, whereas with suitable bio-inoculation, waste mica could further increase the biomass yield (Basak and Biswas 2009). Besides silicates, a potential K source for use in agriculture could be polyhalite, which is found in sedimentary marine evaporates. It contains ~ 12% K apart from ~ 12% Ca, ~ 6% Mg, and ~ 19% S (Sirius Minerals 2016). It showed a beneficial effect on yield and oil content of mustard (*Brassica nigra*) (Tiwari et al. 2015); also increased yields and quality of produce in cauliflower (*Brassica oleracea* var. botrytis) and cabbage (*Brassica oleracea* var. capitata) than fertilization with equivalent amounts of soluble fertilizers (Satisha and Ganeshamurthy 2016). India has around 16,000 Mt of polyhalite reserves (Anonymous 2018). This highlights the vast scope of this mineral for use in agriculture as a K source.

5.2.5 Potassium solubilizing bacteria

Potassium solubilizing bacteria (KSB) can facilitate the release of insoluble K through complex formation and exchange reactions from the fixed K or the structural pools (Meena et al. 2015; Ahmad et al. 2016; Etesami et al. 2017). A wide array of species in genera *Bacillus*, *Burkholderia*, *Acidithiobacillus*, *Paenibacillus*, and *Pseudomonas* have shown promising results in solubilizing unavailable and slowly available K for meeting crop K requirements (Sheng and Huang 2002; Sheng and He 2006; Uroz et al. 2007; Sangeeth et al. 2012). These bacteria can be applied without or with a K source like waste mica for satisfactory results (Basak and Biswas 2009; Nath et al. 2017). Several pot-culture studies (e.g., Han and Lee 2005; Badr et al. 2006; Sugumaran and Janarthanam 2007; Basak and Biswas 2009, 2010) and a few field studies (Badr 2006; Supanjani et al. 2006) have shown the positive effect of KSB on increasing yields and K uptake by crops. However, in our opinion, application of KSB without any external K source like waste mica could have a detrimental effect on soil health as KSB would dissolve or alter the K-bearing minerals present in soil and cause soil K mining. Furthermore, even though they are applied in association with an external K source, it is still unclear if the solubilization is limited only to the added K source. In this regard, future studies should attempt to quantify both the positive and negative effects of using KSB without or with an external K source (e.g., waste mica or glauconite) on soil health and crop performance.

5.3 Time and method of application

The timing of K fertilizer application is mostly crop- and site-specific. Since K is relatively immobile in the soil, K fertilizers are usually added during land preparation before sowing. However, the mobility of K ions within the soil can be affected by the heterogeneity of soil types in terms of CEC and texture. Owing to its luxury consumption, recommendations for K are based on a combination of factors viz. targeted yield of a crop, status of soil K, climatic conditions, management practices, the stage and season of plant growth. Although heavy dressing of K every few years might be more effective, a frequent light application can be more advantageous in reducing the luxury consumption of K in some plants. This could also help in reducing excessive K loss by leaching and fixation before plant uptake (Brady and Weil 2012).

Generally, K fertilizers are broadcasted and mixed with surface soil. Band placement is recommended only in soils with a low level of available K or in soils with high K-fixing capacity (Subba Rao and Brar 2009). The split application appears as an alternative to basal application in some situations (Mahfuza et al. 2008). In addition, cotton and other high K-requiring crops benefit from pre-plant soil application and/or mid-season side-dressing (Singh et al. 2021). Adjusting the time and method of K application can improve K use efficiency in farming systems that use foliar or fertigation techniques. Fertigation using a drip irrigation system can increase water and K use efficiency (Volenec et al. 2021). Because of infrastructural limitations, such approaches are best for high-value plantation crops, e.g., fruit trees. Fertigation in fruit trees resulted in similar downward movement of K in the soil as that of broadcasting, but the lateral movement of K was better with fertigation than broadcasting (Neilsen et al. 1999). Deep placement (~ 8–10 cm) of K fertilizer can be effective in high rainfall areas prone to runoff losses, e.g., pocket method, where fertilizer is put in or around planting pockets (Aune et al. 2017). Band placement of K fertilizer is more efficient than broadcasting in soils having high K fixing capacity (Anonymous 1998).

5.4 Economics of K fertilizer use

Depending on crop and soil characteristics, response to applied K varies widely. Inadequate or no K fertilization not only affects the soil K fertility but could also cause yield declines and associated economic losses. Numerous studies on the integration of K, N and P have shown a remarkable increase in productivity and net return (Table 6). Long-term experiments at various locations in India showed that crop response to applied K fertilizer varied from 2 to 18% of total NPK response in Inceptisol sites, 2–28% of total NPK response in Vertisol sites, but as high as 26–88% of total NPK response in the sites having Alfisol (Singh and Wanjari 2018). On-farm nutrient response studies in the IGP by Majumdar et al. (2012) showed that no application of K decreased average yields of rice, wheat, and maize to the tune of 622, 715 and 700 kg ha^{-1}, respectively, and the corresponding economic return in these crops was reasonably high. For instance, the return for every INR invested on K was INR 5.5 for rice, INR 4.5 for wheat, and INR 3.3 for maize (Majumdar et al. 2012). However, the profitability of K fertilizer use depends on yield increment per unit K input, the unit cost

Table 6 Effect of K application on yield and economics in various crops/ cropping systems. ^{a}Value of increased return = Net return on yield with K – Net return on yield without K; INR Indian rupee, ^{b}System productivity, ^{c}Pooled data of 2 years (2008–09 and 2009–10).

Crop/cropping system	Location	Yield without K (t ha^{-1})	Yield with K (t ha^{-1})	% Yield increase over no K	Value of increased return (INR ha^{-1})^a	Reference
Maize-wheat	New Delhi	9.0^b	11.3^b	25.4	32,760	Raghavendra et al. (2020)
Finger-millet	Ramanagara, Karnataka	3.38	3.98	17.7	8555	Sundaresh and Basavaraja (2017)
Rice	Katni, Madhya Pradesh	3.91	5.98	52.9	66,800	Panwar et al. (2018)
	Indo Gangetic Plain	4.08	4.70	15.2	6210	Majumdar et al. (2017)
Hybrid rice	Kakdwip, West Bengal	4.08	7.56	85.3	28,600	Banerjee et al. (2018)
Wheat	Bichpuri, Agra	8.5^c	9.7^c	14.3	8479	Kumar et al. (2015)
Groundnut	Bhubaneswar, Odisha	1.25	1.56	24.8	11,638	Mohapatra et al. (2013)

of K input, and the price fetched per unit of crop output. Farmers, particularly those in developing countries, are generally assumed not to make extensive use of fertilizer unless the price of the additional output is more than twice the cost of nutrient input (benefit: cost or B: C ratio > 2) (Shand 2007). Under shortage of credit and high interest rates and/or severe climatic risks, farmers go for only those inputs having a very high B: C ratio. However, complete dependence on the B: C ratio can be misleading as high ratios can occur with low yields caused by low nutrient application levels like that observed with K. Hence, even if not as fertilizer, adequate K input at least through other means must be there to maintain the soil health under intensive cropping systems to ensure sustainability. Moreover, crop response to applied K often increases over time, so establishing economic returns of K fertilization from one-year data would be unwise. Therefore, the long-term application of adequate K inputs in agriculture would surely help maintain soil health, fetch better farm income, and contribute towards agricultural sustainability.

6 Suggestions for stakeholders

Based on the preceding discussion, the following suggestions can be made to decide upon the future line of work on soil K dynamics and K management of intensive agricultural systems in India:

(i) Research should be carried out to develop precise methods of determining K requirement during crop growth for different soil types and climates, through conducting small field trials with different K levels and monitoring leaf K content with cheap portable sensors (like Horiba® Cardy K^+ meter). This follows from the fact that portable specific ion electrodes provide a quick and cost-effective way of assessing K concentration in plant tissue and soil solution at the field level (Gangaiah et al. 2016).

(ii) The K balance sheets reported in India are primarily apparent rather than actual as only K removal by the harvested portion of crops and input through fertilizers or manures is considered. At the same time, factors like losses through leaching or erosion and additions through irrigation water, rainfall, capillary rise, etc., are mostly ignored. In the future, researchers should attempt to prepare more accurate K balance sheets by including all the probable input and output pathways. Such balance sheets would be specific to a particular crop or cropping system and the soil type.

(iii) The existing K fertilizer recommendations should be refined by including non-exchangeable K. Suggestions to have non-exchangeable K in soil testing for proper assessment of soil K supplying capacity under intensive cropping and more reliable fertilizer recommendation are not new. However, as already discussed, the conventional method of using boiling nitric acid is not exclusive to the non-exchangeable pool only but also includes some structural K by mineral dissolution. Hence, the $NaBPh_4$ method would be a better choice for including the non-exchangeable K in soil testing. Nonetheless, the latter method has to be calibrated for major soil types of India to accurately measure the contribution of the non-exchangeable pool in plant K uptake. Ion-exchange resins should also be tested to determine the actual plant-available K in various soil types of India by calibrating with crop K uptake.

(iv) For more appropriate K management under intensive cropping and predict future K fertilizer requirements for different agro-ecological regions of India, soils should be characterized for non-exchangeable K reserve and its plant available part (for the dominant crops of the region), preferably through the $NaBPh_4$ method (for reasons discussed earlier). The same has to be linked to the K-bearing minerals present in different size-separates of soil.

(v) Greenhouse studies should be conducted with different soil types of India to generate information on clay mineral changes caused by varying levels of soil K depletion under nutrient-exhaustive cropping. Moreover, one should compare soil samples under different fertilization and manuring treatments with the adjacent uncultivated soils from long-term experiments spread across the country to quantify the changes in clay minerals due to prolonged cropping and variation in K balance.

(vi) Even with the inclusion of non-exchangeable K in soil testing, the actual ill effects of long-term K removal might go unnoticed. Moreover, the K fractions do not account for the release-fixation behavior of soils, which are very important from the K management point of view. For these reasons, Das et al. (2018) suggested examining parameters like thresholds of K release and fixation, K release rate, and fixation capacity at least once in ten years to keep track of the harmful effects of soil K depletion. We further add that the changes in K-bearing minerals, at least in the clay separates, should be monitored once in a decade.

(vii) Extensive greenhouse and field trials should be carried out throughout India to explore and evaluate the different non-conventional sources for their effectiveness in supporting K nutrition of existing cropping systems.

(viii) Lastly, provisions should be made for incentives to farmers who retain or incorporate crop residues in the field. Returning crop residues to the field would essentially reduce the removal of native soil K under intensive cropping. At the same time, it will refrain farmers from burning the crop residues, thereby, help in reducing air pollution.

7 Conclusions

From the above discussion, we can conclude the following:

(i) K balance remained largely negative for a long in most states and all dominant cropping systems in India, primarily due to negligence towards K application through fertilizer or other sources.
(ii) Undoubtedly, intensively cultivated soils of India have been continuously undergoing K mining.
(iii) Continuous K mining for a long time can deplete various K pools, especially the exchangeable and the non-exchangeable pool, implying an adverse impact on fertility and overall soil health. Moreover, long-term soil K mining can cause irreversible changes in the K-bearing minerals. All these, together, pose a potential risk to agricultural sustainability.
(iv) The existing K fertilizer recommendations for major cropping systems appeared insufficient on multiple occasions and need revision.
(v) Efforts to include parameters related to non-exchangeable K, release-fixation, quantity-intensity, etc., have been made to improve the existing soil K fertility assessment method, which needs further corroboration.
(vi) Application of adequate K input through either commercial fertilizer or alternative sources like crop residues, manures, and K-rich minerals, or their suitable combination, must be made to meet the crop demand under intensive cultivation to boost up crop yields, maintain soil health, and fetch more farm income in the long run.

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