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REGULAR ARTICLE

Potassium release characteristics, potassium balance, and fingermillet (*Eleusine coracana* G.) yield sustainability in a 27- year long experiment on an Alfisol in the semi-arid tropical India

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Abstract

Aims In Alfisols, potassium (K) deficiency limits productivity, as these soils are poor in K-bearing minerals such as mica. As nutrient management practices greatly influence K nutrition of crops especially in the longer term, we evaluated the effects of 27 (1978–2004) years of cropping fingermillet (*Eleusine coracana* G.) under different manure and mineral fertilizer treatments on K release, balance and yield sustainability on K deficient Alfisols in the semi-arid tropical region of southern India.

Methods Fingermillet (variety: PR-202) was grown each year under rainfed conditions with 5 different nutrient management treatments: control (no amendment), 10 Mg ha^{-1} farm yard manure (FYM), 10 Mg ha^{-1} FYM +50 % NPK, 10 Mg ha^{-1} FYM +100 % NPK and 100 % NPK. Potassium release characteristics in the soil profile were determined using 1 N boiling HNO_3 (strong extracting solution), 0.01 M HCl (medium extracting solution) and 0.01 M $CaCl_2$ (mild extracting solution).

Results Continuous cropping of Alfisols for 27 years resulted in a decrease in K supplying capacity due to soil K depletion through crop K uptake. In soils without K addition, inherent soil supply could not meet the K requirement of fingermillet; thus, a negative K balance following 27 years of cropping affected K nutrition of the crop in all the treatments. As a result, the highest sustainable yield index (SYI) was observed using an integrated nutrient supply (combined application of nutrients from organic and inorganic sources), and the lowest index was obtained without K additions.

Conclusion For balanced nutrient management in cereal production systems, K nutrition needs urgent attention in the K deficient Alfisol region of southern India. Addition of any amount of organic manures available at field level offers an alternative strategy for maintaining soil K fertility to improve and sustain crop productivity.

Keywords K release · K balance · Soil reserve K · Yield sustainability · Rainfed fingermillet · Semi-arid tropics

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Introduction

Potassium (K) is an essential, major plant nutrient with numerous functions. It plays a major role in activating~60 enzymes, regulating stomatal function, controlling water relations especially under rainfed crop production, influencing the water balance of the plant system, and underpinning agronomic productivity and sustainability (Mengel 1985). Thus, severe depletion of K in soils under long term continuous cropping without supplemental K, leads to minimal exchangeable K. In this scenario, the K requirement of crop(s) is met from the reserve K fraction (Srinivasarao and Khera 1994; Srinivasarao et al. 2007). A negative K balance in soil under intensive cropping occurs because of low external input and large crop removal, leading to depletion of the non-exchangeable or reserve K (Subba Rao et al. 2010).

Alfisols and associated soils cover about 10 % of world soils. Alfisols are the common soil type in Europe (26.7 %), Australia (13.1 %), Africa (11.1 %), South America (10.1 %), North America (9.8 %) and Asia (5.4 %) (Eswaran et al. 2011). In India, Alfisols and associated soils mainly exist in the Southern Plateau. Degraded soils, with shallow effective rooting depth, low soil organic carbon (SOC) reserves, low water holding capacity, and multi- nutrient deficiencies traditionally support only single crop during the rainy season (June–October). However, farmer practices involve regular application of N and P, assuming that soils are rich in K and crop K needs can be met from soil K resources. These soils, with kaolinite as a dominant clay mineral and only traces of K supplying mica, are prone to severe K deficiency (Naidu et al. 1996). Mengel (1985) reported that K depletion is especially severe in cereal-based systems. Long-term continuous cropping of K mining cereals can exacerbate K deficiency, and severely reduce agronomic productivity. Therefore, judicious K management has emerged as a principal challenge for crop productivity and yield sustainability in Alfisols of the semi-arid tropics. Depletion of non-exchangeable K has also been observed in mica rich illitic alluvial soils; Inceptisols (Swarup and Chhillar 1986), and smectitic Vertisols (Srinivasarao et al. 2000). The depletion is aggravated by the omission of K and relatively higher rates of application of N and P under intensive production systems that generate higher demands in soils with low K reserves such as Alfisols. The dissolution and availability of K involves conversion of non-exchangeable K to available forms, while K sorption and fixation on clay particles makes it unavailable to plants (Martin and Sparks 1983; Dhillon and Dhillon 1992; Cox and Joern 1997; Srinivasarao et al. 2006). Most of the previous studies in India have been conducted on micaceous Inceptisols of the Indo-Gangetic plains and smectitic Vertisols or associated soils in central India (Swarup 1998; Srinivasarao et al. 2000, 2011). These soils are relatively high in K due to the dominance of K bearing and associated minerals in clay and silt fractions. Such studies are indeed limited in mica poor and kaolinite dominant Alfisols of southern India.

Fingermillet (*Eleusine coracana* G) is the most important small millet and it covers 12 % of world millet area, and is predominantly cultivated as staple food crop in more than 25 countries of Africa (eastern and southern) and Asia (from near East to far East) with Uganda, India, Nepal, and China as major producers. In India, it is cultivated on~1.8 million ha (Mha) Alfisols in southern Indian states of Karnataka, Andhra Pradesh and Tamil Nadu, but with highly variable productivity and production (http://www.icrisat.org/crop-fingermillet.htm). This crop has been cultivated for the last 3 decades on Alfisols of this region mostly under imbalanced supply of nitrogen and phosphorous and K application. Fingermillet is one of the high K demanding crops, and it requires a large amount of K to complete its life cycle. In the absence of external K application, soil K weathering is the major source for meeting the K requirement. However, rainfed Alfisols are deficient in K due to low contents of K bearing minerals in clay and silt fractions of the soil. Therefore, optimum K release from the soil to meet crop K needs is particularly important at critical plant growth stage of fingermillet. If K supplying capacity and K release rates from soil do not match K uptake, crop growth and production is severely affected. Average fingermillet yields vary widely between 0.6 to 5 Mg ha^{-1} with annual removals of 40 – 50 kg K ha^{-1} depending upon soil depth, rainfall and nutrient management practices (CRIDA 2010). Being a rainfed crop, both the amount of rainfall, and its distribution during the critical crop growth stages determines the grain yield level and K removal by the crop. Favourable distribution of rainfall results in higher crop yield, and removal of up to 120–150 kg K ha^{-1}; while under low rainfall or its unfavourable distribution, K removal is around 50 kg K ha^{-1}. Therefore rainfall amount and distribution determines crop yield and nutrient removal. As most farmers apply N and P regularly, yield under high rainfall depletes soil K reserves more than those with poor rainfall. Therefore the extent of soil K removal in rainfed dry ecosystem depends upon rainfall amount and its distribution. As a general practice some of the farmers apply variable amounts of farm yard manure (FYM) along with chemical fertilizers mostly without K and other nutrients. For sustainability of fingermillet yield, the understanding of the effects of continuous cropping on soil K supplying capacity is essential as Alfisols are deficient in K -rich mica clay minerals. Depletion of soil K reserves is a strong constraint to enhancing and sustaining productivity of a K -demanding crop like fingermillet in non-micaceous Alfisols where both readily available as well as soil reserve K levels are low. Absence of sufficient K supplementation, K removal exceeds the K input, and hence the resulting negative K balance leads to severe depletion of the K reserves. In fingermillet growing regions field level nutrient application practices vary from no inputs to various combinations of organic manure and chemical fertilizers without K and other nutrients.

Our hypothesis is integration of different K sources (INM) could result in better K release required for optimum K nutrition, thus higher plant K concentration and higher yields under continuous cropping in low K bearing Alfisols. With these considerations in view, the present study was conducted on K- deficient Alfisols to investigate trends in yield and K supply capacity, and K balance under 27 years of mono-cropping of fingermillet under different nutrient management practices especially relative to supply of K through mineral and organic sources.

Materials and methods

Site description

A long-term field experiment was conducted with fingermillet on an Alfisol located at farm of the Agricultural Research Station, University of Agricultural Sciences (Gandhi Krishi Vignan Kendra, GKVK, Bengaluru, Karnataka, India (13° 05′ 11.33″ N latitude, 77° 34′ 17.86″ E longitude and at 810 m above sea level). The experiment, established during the rainy season of 1978, was conducted under the aegis of the All India Coordinated Research Project on Dryland Agriculture (AICRPDA). The annual rainfall at the site during the experimental period ranged from 680 mm to 890 mm (SD=229.5; CV=24.8 %). The mean annual and crop season rainfall of the region is 780 mm and 593 mm, respectively. Soils of the experimental site are sandy loam in texture, containing 600, 50 and 350 g kg^{-1} sand, silt and clay and are classified as deep fine, kaolinitic, isohyperthermic, Typic Kandiustalfs (Srinivasarao et al. 2000).

Cropping pattern and treatments

Fingermillet (variety: PR 202) was grown each year during the rainy season (June-October) over a 27-year period (1978–2004). Tillage consisted of one ploughing to an average depth of 0.15–0.20 m soon after rainfall in June, followed by blade harrowing. The seeding rate was 10 kg ha^{-1}. The experiment was laid out in a randomized block design with four replications on plots measuring 13 by 7 m. There were five treatments:

T1: Control (no amendments added)
T2: Farm yard manure (FYM) at 10 Mg ha^{-1} (only organic source)
T3: (FYM 10 Mg ha^{-1}+50 % NPK (integrated nutrient management or conjunctive use of organic manure and chemical fertilizers; INM$_{50}$)
T4: FYM 10 Mg ha^{-1}+100 % NPK (INM$_{100}$) and
T5: 100 % NPK (Sole mineral)

These five treatments broadly represent various nutrient application scenarios under which fingermillet is grown in India. Recommended rates of major nutrients (e.g., N, P and K at the rate of 50, 50 and 25 kg ha^{-1}, respectively) were applied using urea (46 % N), di-ammonium phosphate (46 % P_2O_5 and 18 % N) and potassium chloride (60 % K_2O). Fertilizer was applied alongside the crop row at the time of sowing. The FYM used contained 0.75 % N, 0.28 % P and 0.56 % K. The FYM also contained (mg kg^{-1}) 2.3 Zn, 3.9 Fe, 0.14 Mn and 0.4 Cu on a dry weight basis. FYM was applied and incorporated 2 weeks before sowing. Hand weeding was done two times during the third and sixth week after sowing. Recommended pest and disease management practices were followed as and when needed.

Soil sampling and analysis

Soil samples were collected after 27 years of cropping in February, 2005 from each plot at 0–0.2, 0.2–0.4, 0.4–0.6, 0.6–0.8 and 0.8–1.0 m depth with a core sampler (0.05 m in diameter, 0.08 m in length). Soil samples were air dried, gently ground and passed through a 2-mm sieve. Samples were analyzed in triplicate for basic soil properties following the standard protocols viz., pH (1:2, soil: water ratio), EC, organic carbon, $CaCO_3$, and cation exchange capacity (CEC) (through Na^+ replacement) (Jackson 1973). Textural analysis was determined by the hydrometer method (Bouyoucos 1927).

Extractable K forms

Different soil-K fractions were determined to represent readily available K to plant K uptake (0.01 M $CaCl_2$, 0.01 M HCl and 1 N NH_4OAc) and strongly held K (1 N boiling HNO_3), which is slowly released upon depletion of reading available K in soils. Thus four extractants used in the study were: 0.01 M $CaCl_2$-extractable K (mild extracting solution) (Woodruff and McIntosh 1960), 0.01 M HCl-K (moderate extracting solution), neutral 1 N ammonium acetate - K (Hanway and Heidel 1952), and 1 N boiling HNO_3-K (strong extracting solution) (Wood and De Turk 1941) to estimate various K fractions in soil samples collected from different depths. K contents in various extracts were determined using a flame photometer.

Crop yield and plant analysis

Fingermillet was harvested at maturity, and yield and yield parameters were determined. The latter included total biomass, grain and straw yield for respective treatments for each of the 27 crops. Grain yields were expressed on 14 % moisture content. Samples of grain and straw were oven dried and milled for further analysis. The concentration of K in the grains and straw was determined by acid digestion and analyzed by flame photometry at 548 nm (Bhargava and Raghupathi 2005).

Release characteristics

Potassium supplying parameters (i.e., step-K, cumulative-K and constant rate-K) were derived according to the procedure described by Haylock (1956). The K release patterns were obtained from the consecutive extractions of 0.01 M $CaCl_2$, 0.01 M HCl and 1 N boiling HNO_3 for all soil depths for each treatment. The constant amount of K released over successive extractions was taken as the constant rate-K. The step-K was estimated by the summation of values obtained after subtracting the constant rate-K values from K extracted in each extraction. The cumulative-K was estimated by the summation of values of K extracted in all extractions. The potential K release above the constant K supply was computed by the ratio of step-K to constant rate-K. Step K represents the potential soil K supplying capacity to the crop as judged by K uptake in successive crops grown on the same soil without K addition. Constant K represents a fraction of mineral K released upon depletion of most of the plant extractable K (both readily and slowly available); and it is a property of a particular mineral in clay and silt fractions in a soil.

Soil K balance

Soil K balance was computed by assessing K inputs into soil through different sources and outputs through crop K removal, assuming negligible loss by erosion or leaching. The contribution of K from the soil reserve pool was calculated by considering these attributes with initial (1978) and final (2005) K status in 0–0.2 m depth (representing root zone in the profile) using Eqs. 1 and 2.

$$\Delta\text{Available}{-}\text{K}\ (\text{NH}_4 OAc{-}\text{K}) = [\text{Initial K in 1978} + \text{K added for 27 years}]{-}[\text{Crop K removal}] \tag{1}$$

$$\text{Crop K removal}\Big/\text{uptake}\ \left(\text{in kg ha}^{-1}\right)$$
$$= \left[\left(\text{Grain yield in kg ha}^{-1} \times \text{grain K content in \%}\right) + \text{Stover yield in kg ha}^{-1} \times \text{Stover K content in \%}\right)\Big]\Big/100$$

$$\text{Contribution of non–exchangeable K} = \Delta NH_4OAc\text{–K–Available K in 2005} \quad (2)$$

Sustainable yield index (SYI)

Crop productivity was calculated by a sustainable yield index (SYI) using yield-data of 27 years. This was done to offset annual variations in the yield, and to highlight the performance of the treatments, during the entire experimental period. The SYI is defined by Eq. 3.

$$SYI = \frac{Y-\sigma}{Ymax} \quad (3)$$

where Y is the estimated average yield of a treatment across the years, σ is its estimated standard deviation, and Y_{max} is the observed maximum yield in the experiment during the years of cultivation (Singh et al. 1990).

Statistical analysis

Statistical analysis of data was performed using the Windows based SPSS program (Version 11.0, SPSS, Chicago, IL, USA 2001). The SPSS procedure was used to analyze variance and to determine the statistical significance of treatment effects. The Duncan multiple-range-test (DMRT) was used to compare treatment means.

Simple correlation coefficients and regression equations were developed to obtain the relationship between K supplying parameters determined by various extracting solutions (i.e., $CaCl_2$, HCl, HNO_3) for different soil-K forms, crop yield, K uptake, and SYI. Correlation coefficients were also computed between the seasonal rainfall (June – September) and the fingermillet yield. Statistical significance was assessed at the 95 % probability level. Regression models were developed from crop yields with individual treatment and monthly rainfall during the season.

$$Y = \acute{\alpha} \pm \beta_1 (RF_{June}) \pm \beta_2 (RF_{July}) \pm \beta_3 (RF_{August}) \pm \beta_4 (RF_{September}) \quad (4)$$

where Y is dependent variable (yield, kg ha^{-1}) and rainfall (RF, mm) is independent variable, ά is the intercept and βs are regression coefficients of monthly rainfall over years. Statistical significance of models was assessed on the basis of the coefficient of determination (R^2) and the standard error.

Results

Crop yields trends with rainfall and nutrient management

Rainfall received during the growing period was positively correlated with fingermillet grain yield over 27 years (R^2=0.11 to 0.25) (Table 1). Yield was negatively correlated with rainfall received in June and positively with that received in July, in all the treatments. Higher slope was found in case of July and August rainfall. The correlation of yield with rainfall received during the last two months of the growing season was variable.

The agronomic yield declined over 27 years irrespective of the nutrient management practices and rainfall. The relationship between yield and time series (Fig. 1) indicates that the decline in yield is much higher in 100 % NPK, followed by control and FYM 10 Mg ha^{-1}+100 % NPK; and the other two treatments FYM 10 Mg ha^{-1} and FYM 10 Mg ha^{-1}+50 % NPK maintained the yields at similar levels (where, y is yield in kg ha^{-1} and x is the duration in years). The lowest yield was obtained in the control and the highest in integrated nutrient management (INM) treatment (conjunctive use of organic manure and chemical fertilizers) comprising of 10 Mg ha^{-1} FYM and 100 % NPK. Yield gaps between the control and other nutrient management treatments widened with the duration of cropping (Fig. 1).

SYI also followed a similar trend as yield. A higher value of SYI was obtained with a combined use of organic and chemical sources of nutrients followed by 10 Mg ha^{-1} of FYM and 100 % NPK through chemical fertilizers (Fig. 2). In contrast, the lowest SYI was obtained in the control.

Table 1 Regression models showing association of fingermillet grain yield with season rainfall over 27 years (1978–2004)

Treatments	† R^2	Φ SE	Regression model
Control	0.25	672.9	$Y = 956.7 - 0.28 (RF_{June}) + 4.07(RF_{July}) - 3.56 (RF_{Aug}) - 0.37 (RF_{Sept})$
FYM 10 Mg ha^{-1}	0.19	514.0	$Y = 2890.2 - 1.18 (RF_{June}) + 2.16 (RF_{July}) - 1.6 (RF_{Aug}) - 1.5 (RF_{Sept})$
FYM 10 Mg ha^{-1}+50 % NPK	0.23	503.0	$Y = 2931.1 - 2.33 (RF_{June}) + 2.52 (RF_{July}) + 0.91 (RF_{Aug}) - 0.74 (RF_{Sept})$
FYM 10 Mg ha^{-1}+100 % NPK	0.11	624.2	$Y = 3168.1 - 0.21 (RF_{June}) + 2.75 (RF_{July}) - 1.25 (RF_{Aug}) + 0.02 (RF_{Sept})$
100 % NPK	0.23	847.6	$Y = 2344.3 - 0.78 (RF_{June}) + 4.03(RF_{July}) - 4.68 (RF_{Aug}) + 0.12 (RF_{Sept})$

† *R^2* Coefficient of détermination; Φ *SE* Standard error; *Y* dépendent variable (Yield=kg ha^{-1}); *RF* Independent variable (Rainfall=mm)

Changes in soil properties

The data on soil analyses indicated that except in FYM 10 Mg ha^{-1}+100 % NPK treatment the soil sample from the 0 – 0.2 m layer had lower pH than in the subsoil layers. Similarly, except in the control treatment, greater SOC concentration was observed in the surface layer than in the subsoil layers. There was no consistency found in EC in terms of depth (Table 2). The soils were acidic with pH ranging from 4.6 in the surface layer of 100 % NPK treatment to 5.3 in FYM 10 Mg ha^{-1}+100 % NPK treatment. The EC was higher in treatments with conjunctive use of NPK and manure than in the control.

The lowest concentration of SOC in the profile was observed in the control (Table 2). In comparison, higher SOC concentration was observed in the surface layers of treatments involving integrated application of organic and chemical sources, followed by FYM. Concentration of $CaCO_3$ in the soil was also higher in the FYM 10 Mg ha^{-1}+100 % NPK treatment than that in the control, treatment with manure, and 100 % NPK (Table 2). The CEC was higher in FYM 10 Mg ha^{-1}+ 100 % NPK followed by FYM 10 Mg ha^{-1}+50 % NPK and FYM 10 Mg ha^{-1} than in the control (Table 2).

Soil extractable K forms and profile distribution after 27 years of cropping

Soil K extracted by different extracting solutions was in the order: HNO_3-K>NH_4OAc-K>HCl-K>$CaCl_2$-K (Table 3). Soil samples from the treatments that received nutrients from both organic and chemical sources were characterized by higher K for all the extracting solutions than that in the control. Among the different extractable K forms studied, HNO_3-K was the highest, followed by NH_4OAc-K, HCl-K and $CaCl_2$-K found in control and 100 % NPK+FYM 10 Mg ha^{-1} (Table 3). The extraction

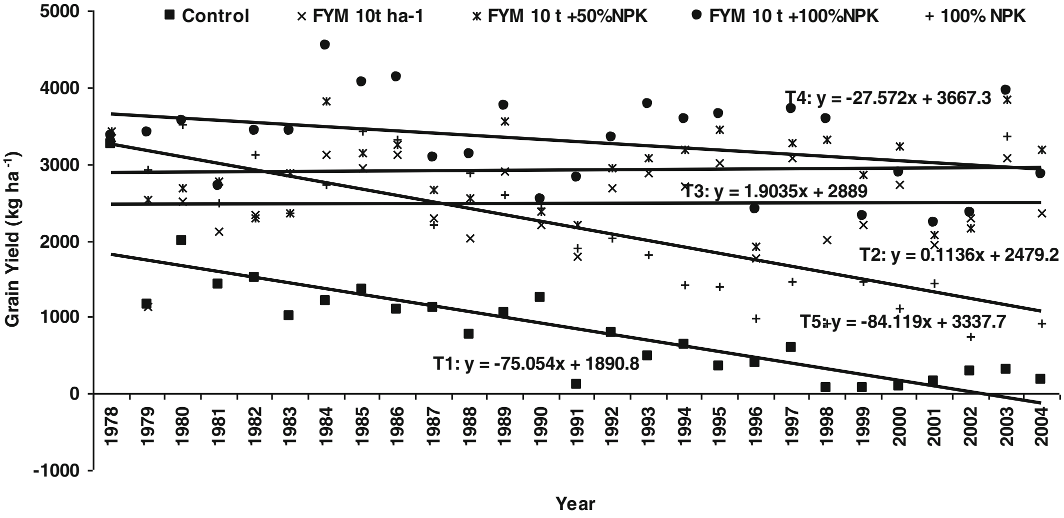

Fig. 1 Time series fingermillet grain yield trends under rainfed cropping of Alfisols during 27 years under various treatments in the SAT region of India

Fig. 2 Sustainable yield index (SYI) for fingermillet as influenced by various treatments during 27 years of continuous cropping of Alfisols of Southern India

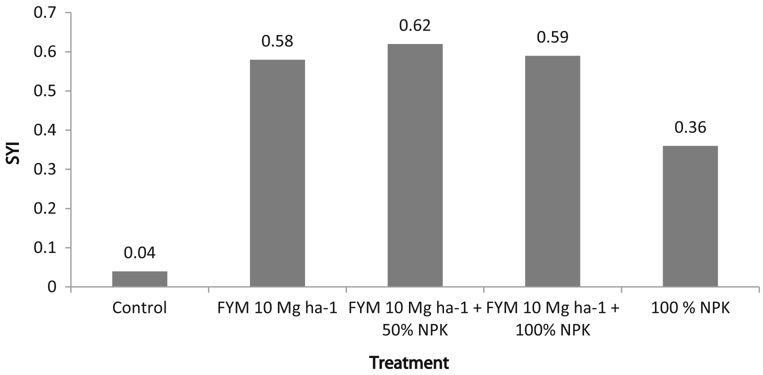

Table 2 Changes in soil properties of an Alfisol after 27 years of cropping with fingermillet in the semi-arid tropical (SAT) India

Treatment	Depth (cm)	pH (1:2)	EC (dS m^{-1})	Organic carbon (g kg^{-1})	$CaCO_3$ (g kg^{-1})	CEC (Cmol (+) kg^{-1})
Control	0–0.2	4.6 ± 0.18^{Ce}	$0.040 \pm na^{Ea}$	4.0 ± 0.21^{Ec}	2.1 ± 0.09^{Ba}	5.0 ± 0.20^{Cc}
	0.2–0.4	4.8 ± 0.17^{Bd}	$0.031 \pm na^{Db}$	4.2 ± 0.22^{Cb}	1.8 ± 0.06^{Ba}	5.5 ± 0.19^{Cb}
	0.4–0.6	5.2 ± 0.26^{Bc}	$0.028 \pm na^{Eb}$	4.3 ± 0.23^{Cb}	2.1 ± 0.07^{Ba}	5.6 ± 0.25^{Db}
	0.6–0.8	5.4 ± 0.22^{Ab}	$0.028 \pm na^{Eb}$	4.6 ± 0.24^{Ba}	0.7 ± 0.03^{Db}	5.8 ± 0.25^{Cb}
	0.8–1.0	5.6 ± 0.15^{Aa}	$0.029 \pm na^{Db}$	3.8 ± 0.20^{Bc}	2.0 ± 0.07^{Ba}	7.4 ± 0.33^{Ba}
	Mean	5.1 ± 0.22^{B}	$0.031 \pm na^{C}$	4.2 ± 0.22^{D}	1.7 ± 0.07^{B}	5.9 ± 0.18^{D}
FYM 10 Mg ha^{-1}	0–0.2	5.0 ± 0.17^{Bc}	$0.078 \pm na^{Ba}$	6.2 ± 0.33^{Ca}	2.0 ± 0.08^{Ba}	7.3 ± 0.32^{Bd}
	0.2–0.4	4.9 ± 0.20^{Bc}	$0.056 \pm na^{Cb}$	6.1 ± 0.32^{Aa}	2.1 ± 0.07^{Ba}	7.8 ± 0.27^{Ac}
	0.4–0.6	5.1 ± 0.18^{Bb}	$0.044 \pm na^{Dc}$	5.4 ± 0.29^{Bb}	1.5 ± 0.07^{Cb}	8.0 ± 0.32^{Ab}
	0.6–0.8	5.2 ± 0.25^{Ab}	$0.039 \pm na^{Dc}$	4.8 ± 0.25^{Ac}	1.2 ± 0.08^{Cc}	8.0 ± 0.24^{Bb}
	0.8–1.0	5.5 ± 0.27^{Aa}	$0.039 \pm na^{Cc}$	3.8 ± 0.20^{Bd}	1.6 ± 0.05^{Bb}	8.3 ± 0.37^{Aa}
	Mean	5.1 ± 0.22^{B}	$0.051 \pm na^{B}$	5.3 ± 0.28^{B}	1.7 ± 0.06^{B}	7.9 ± 0.28^{B}
FYM 10 Mg +50%NPK	0–0.2	5.5 ± 0.22^{Aa}	$0.073 \pm na^{Cb}$	6.7 ± 0.36^{Ba}	1.4 ± 0.08^{Ca}	7.5 ± 0.30^{Bb}
	0.2–0.4	5.5 ± 0.17^{Aa}	$0.065 \pm na^{Bc}$	6.3 ± 0.33^{Ab}	0.6 ± 0.06^{Cc}	7.8 ± 0.27^{Ab}
	0.4–0.6	5.5 ± 0.24^{Aa}	$0.077 \pm na^{Ab}$	5.3 ± 0.28^{Bc}	1.0 ± 0.02^{Db}	8.3 ± 0.37^{Aa}
	0.6–0.8	5.4 ± 0.24^{Ab}	$0.083 \pm na^{Aa}$	4.9 ± 0.26^{Ad}	1.4 ± 0.04^{Ca}	8.2 ± 0.25^{Aa}
	0.8–1.0	5.6 ± 0.20^{Aa}	$0.066 \pm na^{Ac}$	4.0 ± 0.21^{Be}	1.0 ± 0.05^{Cb}	7.5 ± 0.33^{Bb}
	Mean	5.5 ± 0.20^{A}	$0.073 \pm na^{A}$	5.4 ± 0.29^{B}	$1.1 \pm 0.0.4^{C}$	6.3 ± 0.22^{C}
FYM 10 Mg +100%NPK	0–0.2	5.6 ± 0.16^{Aa}	$0.088 \pm na^{Ab}$	7.1 ± 0.38^{Aa}	4.4 ± 0.04^{Ae}	9.3 ± 0.33^{Aa}
	0.2–0.4	4.9 ± 0.24^{Bd}	$0.099 \pm na^{Aa}$	6.5 ± 0.34^{Ab}	8.1 ± 0.19^{Ab}	7.5 ± 0.20^{Ac}
	0.4–0.6	5.4 ± 0.18^{Ab}	$0.065 \pm na^{Bc}$	5.7 ± 0.30^{Ac}	9.6 ± 0.24^{Aa}	7.8 ± 0.27^{Bc}
	0.6–0.8	5.4 ± 0.21^{Ab}	$0.064 \pm na^{Bc}$	5.1 ± 0.27^{Ad}	6.1 ± 0.42^{Ad}	8.5 ± 0.37^{Ab}
	0.8–1.0	5.2 ± 0.15^{Bc}	$0.061 \pm na^{Ac}$	4.2 ± 0.22^{Ae}	7.5 ± 0.18^{Ac}	8.2 ± 0.33^{Ab}
	Mean	5.3 ± 0.18^{A}	$0.075 \pm na^{A}$	5.7 ± 0.30^{A}	7.1 ± 0.33^{A}	8.3 ± 0.29^{A}
100 % NPK	0–0.2	4.3 ± 0.23^{Dc}	$0.048 \pm na^{Db}$	5.3 ± 0.28^{Da}	2.3 ± 0.25^{Ba}	5.2 ± 0.26^{Cc}
	0.2–0.4	4.0 ± 0.24^{Cd}	$0.059 \pm na^{Ca}$	5.0 ± 0.27^{Bb}	2.1 ± 0.08^{Ba}	6.0 ± 0.24^{Bb}
	0.4–0.6	5.3 ± 0.28^{Ab}	$0.050 \pm na^{Cb}$	4.5 ± 0.24^{Cc}	2.0 ± 0.08^{Ba}	6.0 ± 0.24^{Cb}
	0.6–0.8	5.4 ± 0.20^{Ab}	$0.044 \pm na^{Cc}$	4.6 ± 0.24^{Bc}	1.9 ± 0.08^{Bb}	8.3 ± 0.37^{Aa}
	0.8–1.0	5.6 ± 0.22^{Aa}	$0.052 \pm na^{Bb}$	3.9 ± 0.21^{Bd}	1.9 ± 0.08^{Bb}	6.3 ± 0.27^{Cb}
	Mean	4.9 ± 0.22^{B}	$0.051 \pm na^{B}$	4.7 ± 0.25^{C}	2.0 ± 0.07^{B}	6.4 ± 0.22^{C}

Capital and *small letters* within columns are significantly different for values of respective treatment and depth respectively at $P=0.05$ according to DMRT for the separation of means with HNO_3 showed nearly 6–8 and 20–30 times more K than those obtained by NH_4OAc-K and HCl-K, respectively, suggesting a superior K extraction efficiency of HNO_3. The distribution of soil extractable-K, particularly HCl-K and HNO_3 –K increased with depth, and comparatively higher values were obtained for deeper than shallow depth (0–0.2 m). Soils from plots receiving K through organic source contained greater extractable K than those that received only chemical fertilizers. Concentrations of HCl-K and HNO_3-K increased, and that of $CaCl_2$ –K decreased with increasing soil depth up to 0.4–0.6 m, followed by a slight increase thereafter in all treatments. Similar trend was observed for HCl-K, except that for the total amount of K extracted. In contrast, however, a decreasing trend with depth was observed in the case of NH_4OAc –K especially at lower depths.

Soil K supplying capacity

The long-term impact of nutrient management under fingermillet mono-cropping on K supplying capacity of the soil indicated that cumulative K release was higher in 1 N HNO_3 extraction, followed by that in 0.01 M HCl and 0.01 M $CaCl_2$ (Table 4). Significantly higher cumulative K in the surface 0–0.2 m depth was found in FYM 10 Mg ha^{-1}+100 % NPK treatment and the lowest was in the control. The values were intermediate for the other two (sole chemical fertilized or organic manure) treatments. Similar trends were also observed for K extracted by other extracting solutions. In general, however the K supplying capacity of the soil measured by HNO_3 extraction increased with the depth, indicating the uptake of non exchangeable K. The lowest value of the constant rate K was obtained with 0.01 M $CaCl_2$ extraction compared to that obtained by 0.01 M HCl and 1 N HNO_3.

Overall, the cumulative-K and step-K by 1 N HNO_3 extraction were significantly higher for 100 % NPK+FYM treatment, followed by 50 % NPK+FYM and 100 % NPK alone in 0–0.2 m soil layer. A parallel trend in K release among treatments was observed with HCl and $CaCl_2$ extraction (FYM 10 Mg ha^{-1}+100 % NPK>FYM 10 Mg ha^{-1}+50 % NPK>100 % NPK>FYM 10 Mg ha^{-1}>Control). The potential of K release beyond the supply of constant K, which is explained by step-K to constant rate-K ratio, was also greater in the combined use of NPK and FYM treatment. In comparison, the soil under control had the least K release potential for all the extracting solutions used.

Effects of K nutrition on crop yields and sustainable yield index (SYI)

Soil K fertility assessed as $CaCl_2$-K, HCl-K, NH_4OAc-K and HNO_3-K is significantly and positively related to fingermillet yield (Table 5). In general, extractable K was strongly correlated with total biomass yield for NH_4OAc-K, followed by $CaCl_2$-K, HCl-K and HNO_3-K. All the four extracting solutions and their supply parameters indicated good index values for SYI (Table 5). The NH_4OAc-K is most strongly related with SYI, followed by HCl-K, HNO_3-K and $CaCl_2$-K.

Soil K balance

A high amount of K was applied over 27 years in the FYM 10 Mg ha^{-1}+100 % NPK treatment, followed by FYM 10 Mg ha^{-1}+50 % NPK, FYM 10 Mg ha^{-1} and 100 % NPK treatments, respectively (Table 6 & Fig. 3). Significantly higher uptake of K was also observed with combined application of FYM and NPK than with FYM, 100 % NPK and control over 27 years of cropping. The change in available K (NH_4OAc-K) was determined (0–0.2 m depth) with reference to antecedent soil K status, K added, and K uptake by fingermillet cropping (Fig. 3). The computed difference in available K status was higher in 100 % NPK application treatment, followed by 10 Mg ha^{-1} FYM, control, 10 Mg ha^{-1} FYM+50 % NPK and FYM 10 Mg ha^{-1}+100 % NPK. The contributions from soil reserve K (non-exchangeable K) was computed to infer the impact of nutrient management practices on soil K mining under continuous cropping. Significantly large contribution of soil reserve K (non-exchangeable K) was observed in treatments receiving recommended rates of NPK followed by FYM 10 Mg ha^{-1}+50 % NPK, FYM 10 Mg ha^{-1}, FYM 10 Mg ha^{-1}+100 % NPK and control treatments (Fig. 3).

Impact of K release and supply parameters on crop yield and its sustainability

Impact of K supplying power of soil on crop growth and development, and ultimately on yield sustainability of fingermillet was studied by using K supply parameters such as cumulative –K and step-K in relation to total

Table 3 Changes in different forms of soil K in an Alfisol after 27 years of cropping with fingermillet in the SAT India

Treatment	Depth (m)	CaCl$_2$-K (mg kg^{-1})	HCl-K	NH$_4$OAc-K	HNO$_3$-K
Control	0–0.2	7.2±0.4^{Ea}	18.6±0.9^{Dd}	28±1.4^{Da}	170±8.5^{Dc}
	0.2–0.4	7.4±0.4^{Ca}	23.5±0.9^{Dc}	29±1.2^{Ca}	201±8.0^{Db}
	0.4–0.6	6.5±0.3^{Cb}	28.8±1.4^{Cb}	24±1.2^{Cc}	210±10.5^{Da}
	0.6–0.8	6.7±0.3^{Cb}	30.4±0.9^{Ca}	25±1.0^{Cc}	213±8.5^{Ca}
	0.8–1.0	6.5±0.3^{Db}	30.8±1.2^{Da}	27±1.4^{Db}	210±10.5^{Da}
	Mean	6.9±0.3^{D}	26.4±1.3^{D}	27±1.1^{C}	201±10.0^{D}
FYM 10 Mg ha^{-1}	0–0.2	10.6±0.4^{Da}	32.1±1.0^{Cc}	42±1.7^{Ba}	214±8.6^{Cc}
	0.2–0.4	9.4±0.5^{Bc}	32.1±1.6^{Cc}	36±1.4^{Bb}	244±12.2^{Ca}
	0.4–0.6	9.6±0.4^{Bb}	34.1±1.7^{Bb}	32±1.3^{Bd}	224±6.7^{Cb}
	0.6–0.8	9.8 ±0.4^{Bb}	36.5±1.5^{Ba}	34±1.0^{Bc}	222±8.9^{Cb}
	0.8–1.0	9.8±0.3^{Cb}	35.6±1.8^{Ca}	32±1.6^{Bd}	223±11.1^{Cb}
	Mean	9.8 ±0.5^{C}	34.1±1.4^{C}	35±1.8^{B}	226±6.8^{C}
FYM 10 Mg +50%NPK	0–0.2	14.6 ±0.7^{Ba}	36.1±1.8^{Bb}	44±1.8^{Aa}	234±11.7^{Bc}
	0.2–0.4	11.8 ±0.5^{Ab}	34.6±1.4^{Bb}	37±1.9^{Bc}	259±12.9^{Ba}
	0.4–0.6	12.0 ±0.6^{Ab}	34.9±1.7^{Bb}	39±1.6^{Ab}	245±9.8^{Bb}
	0.6–0.8	11.8±0.4^{Ab}	39.3±1.6^{Aa}	36±1.8^{Ac}	245±12.2^{Bb}
	0.8–1.0	11.8±0.5^{Bb}	38.9±1.6^{Ba}	34±1.7^{Bd}	235±9.4^{Bc}
	Mean	12.4±0.6^{A}	36.8±1.5^{B}	38±1.5^{A}	244±12.2^{B}
FYM 10 Mg +100%NPK	0–0.2	16.9±0.5^{Aa}	46.7±1.9^{Aa}	45±2.3^{Aa}	269±13.4^{Ab}
	0.2–0.4	11.9±0.6^{Ad}	36.7±1.1^{Ac}	38±1.1^{Ac}	276±13.8^{Aa}
	0.4–0.6	12.8±0.6^{Ac}	38.1±1.9^{Ac}	41±1.6^{Ab}	260±7.8^{Ac}
	0.6–0.8	12.2±0.5^{Ac}	40.2±2.0^{Ab}	37±1.9^{Ad}	259±12.9^{Ac}
	0.8–1.0	13.1±0.7^{Ab}	45.3±1.8^{Aa}	39±1.2^{Ac}	250±12.5^{Ad}
	Mean	13.4±0.5^{A}	41.4±2.1^{A}	40±2.0^{A}	263±10.5^{A}
100 % NPK	0–0.2	12.6±0.6^{Ca}	32.7±1.3^{Cb}	36±1.8^{Cb}	220±11.0^{Cc}
	0.2–0.4	12.1±0.5^{Ab}	33.4±1.7^{Bb}	40±1.6^{Aa}	260±10.4^{Ba}
	0.4–0.6	10.2±0.5^{Bd}	35.5±1.4^{Ba}	34±1.7^{Bc}	254±12.7^{Ab}
	0.6–0.8	11.6±0.5^{Ac}	36.5±1.8^{Ba}	32±1.3^{Bd}	252±12.6^{Ab}
	0.8–1.0	12.3±0.5^{Aa}	36.0±1.4^{Ca}	30±1.5^{Ce}	250±7.5^{Ab}
	Mean	11.8±0.6^{B}	34.8±1.4^{C}	34 ±1.7^{B}	247 ±9.9^{B}

Capital and *small letters* within columns are significantly different for values of respective treatment and depth respectively at P=0.05 according to DMRT for the separation of means

biomass yield, grain yield, straw yield and SYI. Soil K forms (e.g., CaCl$_2$-K, HCl-K and HNO$_3$-K) significantly influenced crop growth and increased grain, straw and biomass yields. Though, different K forms were significantly correlated with crop yields, the highest correlation coefficient of K uptake was obtained with the HNO$_3$ extractable K (non-exchangeable K) (r=0.95, P<0.001), and of SYI with the NH$_4$OAc-K (r=0.97, P<0.001). Similarly yield attributes were also strongly related to the K supply parameters.

Discussion

Effect of rainfall availability and pattern, nutrient management strategies and K nutrition on fingermillet yield trends

Skewed trends in grain yield in selected years over 27 years may be due to the differences in time, distribution and intensity of rainfall among years. Aberrant weather conditions and their impact on water and

Table 4 Variable K release capacity of soils as evaluated by diverse extractants following 27 years of cropping and fertility management in Alfisols of Southern India

Treatment	Depth (m)	1 N HNO$_3$				0.01 M HCl				0.01 M CaCl$_2$			
		Cumulative – K#	Constant – K*	Step-K$	Step-K/Constant-K¥	Cumulative – K	Constant – K	Step-K	Step-K/Constant-K	Cumulative – K	Constant – K	Step-K	Step-K/Constant-K
Control	0–0.2	546.4^{De}	12.0^{Ab}	402.4^{Dd}	33.5^{Da}	153.2^{Dc}	9.0^{Aa}	45.6^{Dd}	5.2^{Dd}	62.4^{Eb}	2.2^{Ca}	40.4^{Ec}	18.4^{De}
	0.2–0.4	629.9^{Ed}	18.8^{Aa}	404.3^{Dd}	21.5^{Dd}	175.2^{Da}	8.8^{Ab}	68.8^{Da}	7.8^{Ca}	71.2^{Ca}	1.8^{Cc}	53.2^{Ca}	29.6^{Aa}
	0.4–0.6	686.0^{Dc}	18.8^{Aa}	460.4^{Dc}	24.5^{Bc}	156.4^{Dc}	8.8^{Ab}	51.0^{Dc}	5.8^{Cc}	60.7^{Dc}	1.6^{Dd}	44.7^{Db}	27.9^{Cb}
	0.6–0.8	716.2^{Eb}	18.8^{Ba}	490.6^{Eb}	26.1^{Db}	163.0^{Cb}	8.8^{Ab}	58.0^{Cb}	6.6^{Bb}	60.6^{Dc}	2.0^{Bb}	40.6^{Dc}	20.3^{Ed}
	0.8–1.0	722.1^{Ea}	18.8^{Ba}	496.5^{Da}	26.4^{Bb}	165.6^{Db}	8.8^{Ab}	59.6^{Db}	6.8^{Cb}	58.4^{Dd}	1.8^{Cc}	40.4^{Ec}	22.4^{Dc}
	Mean	660.1^{D}	17.4^{B}	450.8^{D}	25.9^{C}	162.7^{D}	8.8^{A}	56.6^{E}	6.4^{D}	62.7^{D}	1.9^{C}	43.9^{E}	23.3^{D}
FYM 10 Mg ha^{-1}	0–0.2	629.6^{Cd}	12.0^{Ab}	485.6^{Cd}	40.5^{Ca}	175.9^{Cb}	9.0^{Aa}	68.3^{Cc}	7.8^{Cc}	83.2^{Da}	3.0^{Aa}	53.2^{Da}	17.7^{Dc}
	0.2–0.4	728.6^{Db}	18.8^{Aa}	503.0^{Cb}	26.8^{Cb}	186.1^{Ca}	8.8^{Ab}	79.7^{Ca}	9.1^{Ba}	73.2^{Cb}	2.2^{Bb}	51.2^{Dc}	23.3^{Cb}
	0.4–0.6	723.8^{Cc}	18.8^{Aa}	498.2^{Cc}	26.5^{Bb}	174.1^{Cb}	8.8^{Ab}	68.7^{Cc}	7.8^{Bc}	72.0^{Cb}	2.0^{Bc}	52.0^{Cb}	26.0^{Da}
	0.6–0.8	729.5^{Db}	18.8^{Ba}	503.9^{Db}	26.8^{Db}	172.0^{Bc}	8.8^{Ab}	67.0^{Bc}	7.6^{Bc}	72.0^{Cb}	2.0^{Bc}	52.0^{Cb}	26.0^{Da}
	0.8–1.0	739.9^{Da}	18.8^{Ba}	514.3^{Ca}	27.4^{Bb}	178.7^{Cb}	8.8^{Ab}	72.7^{Cb}	8.3^{Bb}	72.8^{Cb}	2.0^{Bc}	52.8^{Db}	26.4^{Ca}
	Mean	710.3^{C}	17.4^{B}	501.0^{C}	28.7^{B}	177.4^{C}	8.8^{A}	71.2^{C}	8.1^{C}	74.6^{C}	2.2^{B}	52.2^{D}	23.3^{D}
FYM 10 Mg +50%NPK	0–0.2	662.8^{Bd}	12.0^{Ab}	518.8^{Bd}	43.2^{Ba}	187.8^{Bb}	9.0^{Aa}	80.2^{Bb}	9.1^{Bb}	106.4^{Ba}	2.8^{Ba}	78.4^{Ba}	28.0^{Bb}
	0.2–0.4	772.8^{Cc}	18.8^{Aa}	547.2^{Bc}	29.1^{Bb}	194.6^{Ba}	8.8^{Ab}	88.2^{Ba}	10.0^{Aa}	98.8^{Ab}	2.6^{Ab}	72.8^{Ab}	28.0^{Bb}
	0.4–0.6	785.1^{Ba}	18.8^{Aa}	559.5^{Ba}	29.8^{Ab}	180.4^{Bc}	8.8^{Ab}	75.0^{Bc}	8.5^{Ac}	85.2^{Ad}	1.8^{Cd}	67.2^{Bc}	37.3^{Ba}
	0.6–0.8	788.3^{Ca}	18.8^{Ba}	562.7^{Ca}	29.9^{Bb}	179.1^{Ad}	8.8^{Ab}	74.1^{Ac}	8.4^{Ac}	98.0^{Ab}	2.6^{Ab}	72.0^{Ab}	27.7^{Cc}
	0.8–1.0	782.4^{Cb}	18.8^{Ba}	556.8^{Bb}	29.6^{Ab}	184.3^{Bb}	8.8^{Ab}	78.3^{Bb}	8.9^{Bb}	90.2^{Ac}	2.4^{Ac}	66.2^{Bc}	27.6^{Bc}
	Mean	758.3^{B}	17.4^{B}	549.0^{B}	31.5^{A}	185.2^{B}	8.8^{A}	79.1^{B}	9.0^{B}	95.7^{A}	2.4^{A}	71.3^{B}	29.2^{B}
FYM 10 Mg +100%NPK	0–0.2	703.7^{Ae}	12.0^{Ad}	559.7^{Ad}	46.6^{Aa}	222.1^{Aa}	9.0^{Aa}	114.5^{Aa}	13.0^{Aa}	113.4^{Aa}	2.8^{Ba}	85.4^{Aa}	30.5^{Ab}
	0.2–0.4	807.1^{Ac}	18.8^{Ac}	581.5^{Ab}	30.9^{Ab}	199.8^{Ab}	8.8^{Ab}	93.4^{Ab}	10.6^{Ab}	99.9^{Ab}	2.6^{Ab}	73.9^{Ab}	28.4^{Bc}
	0.4–0.6	799.4^{Ad}	18.8^{Ac}	573.8^{Ac}	30.5^{Ab}	186.4^{Ac}	8.8^{Ab}	81.0^{Ac}	9.2^{Ac}	87.6^{Ad}	1.8^{Cd}	69.6^{Ad}	38.7^{Aa}
	0.6–0.8	857.0^{Ab}	21.4^{Ab}	600.2^{Aa}	28.0^{Cc}	182.8^{Ac}	8.8^{Ab}	77.8^{Ac}	8.8^{Ac}	98.4^{Ab}	2.6^{Ab}	72.4^{Ac}	27.8^{Bc}
	0.8–1.0	864.6^{Aa}	24.1^{Aa}	575.4^{Ac}	23.9^{Cd}	198.1^{Ab}	8.8^{Ab}	92.1^{Ab}	10.5^{Ab}	92.9^{Ac}	2.4^{Ac}	68.9^{Ad}	28.7^{Ac}
	Mean	806.4^{A}	19.0^{A}	578.1^{A}	30.4^{A}	197.8^{A}	8.8^{A}	91.7^{A}	10.4^{A}	98.4^{A}	2.4^{A}	74.0^{A}	30.3^{A}
100 % NPK	0–0.2	628.0^{Cd}	12.0^{Ab}	484.0^{Cd}	40.3^{Ca}	179.7^{Cb}	9.0^{Aa}	72.1^{Cc}	8.2^{Cc}	89.2^{Ca}	2.8^{Ba}	61.2^{Cc}	21.9^{Cd}
	0.2–0.4	781.5^{Bc}	18.8^{Aa}	555.9^{Bc}	29.6^{Ac}	190.3^{Ba}	8.8^{Ab}	83.9^{Ba}	9.5^{Ba}	89.3^{Ba}	2.2^{Bb}	67.3^{Ba}	30.6^{Ab}
	0.4–0.6	784.2^{Bc}	18.8^{Aa}	558.6^{Bc}	29.7^{Ac}	175.1^{Cc}	8.8^{Ab}	69.7^{Cc}	7.9^{Bc}	78.8^{Bb}	2.8^{Aa}	50.8^{Ce}	18.1^{Ee}
	0.6–0.8	812.2^{Ba}	18.8^{Ba}	586.6^{Ba}	31.2^{Ab}	173.3^{Bc}	8.8^{Ab}	68.3^{Bc}	7.8^{Ac}	77.8^{Bb}	1.2^{Cd}	65.8^{Bb}	54.8^{Aa}
	0.8–1.0	792.3^{Bb}	18.8^{Ba}	566.7^{Ab}	30.1^{Ab}	184.0^{Bb}	8.8^{Ab}	78.0^{Bb}	8.9^{Bb}	78.1^{Bb}	2.0^{Bc}	58.1^{Cd}	29.1^{Ac}
	Mean	759.6^{B}	17.4^{B}	550.4^{B}	31.6^{A}	180.5^{B}	8.8^{A}	65.2^{D}	7.4^{C}	82.6^{B}	2.2^{B}	60.6^{C}	27.6^{C}

[#] Cumulative K: ∑(K extracted in all the extractions), [*] Constant-K: Constant amount release of K over. [$] Step-K: ∑ (K extracted in each extraction-constant rate K) successive extractions.[¥] Step-K/Constant-K: Potential K release above constant K supply

Capital and *small letters* within columns are significantly different for values of respective treatment and depth respectively at P=0.05 according to DMRT for the separation of means

Table 5 Association of soil K extracted by different extractants and K release attributes with grain yield, straw yield, crop K uptake yield sustainability of fingermillet on Alfisols of Southern India

Soil K in different media of extractants		Total biomass yield	Grain yield	Straw yield	Crop K uptake	SYI
		kg ha^{-1}				
CaCl$_2$-K		0.94 ***	0.87	0.85 ***	0.97 ***	0.62 ***
HCl-K		0.91	0.92 ***	0.90 ***	0.93 ***	0.70 ***
NH$_4$OAc-K		0.96 ***	0.95 ***	0.96 ***	0.82 ***	0.97 ***
HNO$_3$-K		0.91 ***	0.92 ***	0.90 ***	0.95 ***	0.69 ***
K release characteristics						
Media of extraction	Soil K supplying parameters					
CaCl$_2$-K	Cumulative-K	0.89 ***	0.90 ***	0.88 ***	0.97 ***	0.70 ***
	Step-K	0.82 ***	0.83 ***	0.81 ***	0.94 ***	0.60 ***
HCl-K	Cumulative-K	0.78 ***	0.80 ***	0.77 ***	0.85 ***	0.53 **
	Step-K	0.79 ***	0.80 ***	0.78 ***	0.85 ***	0.53 **
HNO$_3$-K	Cumulative-K	0.96 ***	0.97 ***	0.96 ***	0.97 ***	0.79 ***
	Step-K	0.96 ***	0.97 ***	0.96 ***	0.97 ***	0.79 ***

*** Significant at $P<0.001$

nutrient availability at critical crop growth stages under different nutrient management practices also contributed to the variations in yield trends. However, the application of organic amendments alone or in combination with chemical fertilizers lead to lower negative to positive slopes in yield trends which supports our hypothesis. The climate of the south Indian semi-arid tropics (rainy season consisting of 3 to 4 months) is characterized by frequent dry spells caused by erratic rainfall distribution. Thus, the adoption of an INM strategy (addition of organic manure along with chemical fertilization) under dry regions may alleviate climatic and soil-related constraints (i.e., low soil water retention and low soil fertility). Soil fertility management in this experiment positively influenced these two productivity constraints. Heavy rainfall received during June with poor distribution (one or two isolated storms) can adversely affect seed germination, reduce

Table 6 The contribution of non-exchangeable K to total K removal by crop and K balance following 27 years of fingermillet cropping on Alfisols

Treatment	Initial K (in 1978) kg ha^{-1}	K added	K removed [a]	Δ NH$_4$OAc-K [b]	Available K (in 2005) [c]	Contribution of non-exchangeable K [d]
Control	133	0^{E}	728^{E}	-595^{C}	67^{D}	662^{E}
FYM 10 Mg ha^{-1}	133	1350^{C}	2088^{C}	-605^{B}	121^{C}	726^{C}
FYM 10 Mg ha^{-1}+50%NPK	133	1688^{B}	2407^{B}	-587^{C}	157^{B}	743^{B}
FYM 10 Mg ha^{-1}+100%NPK	133	2025^{A}	2684^{A}	-526^{D}	185^{A}	711^{D}
100 % NPK	133	675^{D}	1800^{D}	-992^{A}	72^{D}	1064^{A}

[a] K uptake by fingermillet over 27 years continuous cropping

[b] Expected soil available K status (NH$_4$OAc-K)

[c] Actual available K status in 2005

[d] Soil K supply from reserve sources (mineral and clay interlayer K)

Different capital letters within columns are significantly different at $P=0.05$ according to DMRT for the separation of means

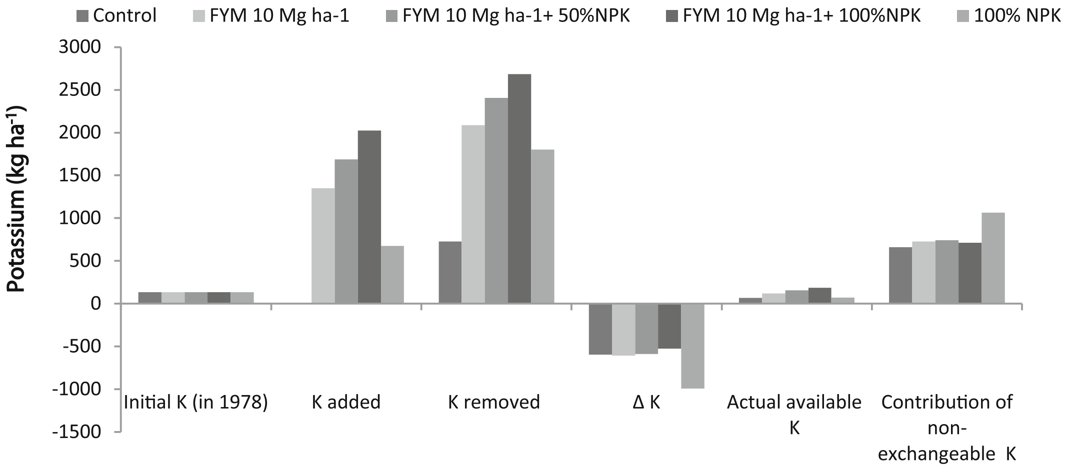

Fig. 3 The K balance in Alfisols as affected by various treatments after 27 years of cropping with fingermillet in the SAT India

crop stand and decrease agronomic yield (negative slope values). Rainfall received during July had a positive impact on crop yield (positive slope values) in all the treatments including the control because of moisture supplementation at initial crop growth period boosts crop vigor. The regression analyses of grain yields with rainfall during the months of August and September showed mixed responses despite the occurrence of critical crop stages during these months. Thus, the distribution of rainfall is more important than the total amount received in any month, growing season, or year. Further, K availability is also a critical factor influencing plant physiological factors (e.g., root growth and proliferation) such as tolerance to drought and heat stress prevalent in the semi-arid regions (Kirkby et al. 2009). Optimum K nutrition improved rainwater capture (Hermann et al. 1994), protection against tissue dehydration (Sen-Gupta et al. 1989), regulation of stomata opening and closing, detoxification of oxygen radicals and enhanced translocation of photosynthates (Cakmak 2005) probably led to better growth and crop quality (Kumar et al. 2006; Pettigraw 2008) and improved sustainable yields. Under extremely low K fertility, crop growth in the soil is retarded without optimum supply of K. Further, the input of K through chemical fertilizers or organic manure is minimal to the crops grown on Alfisols under rainfed conditions.

In the present study, fingermillet yield was much higher in years with higher rainfall at critical plant growth stages. With greater yields, however, crops deplete more soil K particularly without external K application. Thus rainfall, crop yields, and soil K depletion interactions determine whether crop K needs at critical growth stages are met by soil K or not (Srinivasarao et al. 2009). Under continuous cropping, soil K contribution is comparatively higher if crop K needs do not match external K application. Incorporation of FYM along with NPK application improved SYI by reducing drought stress (Singh et al. 2010). Application of FYM along with NPK application improved the water retention capacity of soil and soil moisture which helped to cope better under drought conditions. Also a combination of FYM and chemical fertilizer supplied higher amount of nutrients which helped to increase SYI. The importance of maintaining an optimal supply of K for adaptation to drought is also recognized (Sen-Gupta et al. 1989; Kant and Kafkafi 2002; Cakmak 2005).

Continuous application of NPK alone may also have resulted in deficiency of other critical nutrients such as Zn, which could be the reason for higher reduction in fingermillet grain yield. Very low grain and biomass yield in control with soil as the only nutrient resource also showed considerable yield reduction with time. Luxurious vegetative growth under excessive nutrient supply in years with less than optimum rainfall led to reduced crop yields.

Soil K fertility, K release and movement in the soil profile

Soils were low in both available K (NH_4OAc-K<50 mg kg^{-1}) and non-exchangeable-K

(< 300 mg kg^{-1}) even after 27 years of cropping in different nutrient management treatments (Srinivasarao et al. 2011). Thus, K nutrition is one of the important constraints limiting fingermillet productivity and soils could no longer supply K at daily replenishment rates required by the fingermillet.

The distribution of different extractable forms of K in the soil profile under a range of nutrient management treatments showed that control plots had lower reserves, suggesting non replenishment of K in these soils against crop removal. Lower K release with $CaCl_2$ extraction shows that the exchangeable K is the sole supply, and it reflects the plant available reserve. The enrichment of K in the deeper soil layers in treatments with chemical or organic fertilizer application may be due to a downward movement of K by eluviation (Ganeshamurthy 1983). Similar observations were made under groundnut grown on Alfisols at Anantapur, India (Srinivasarao et al. 2010). The leaching of soluble K along with percolating rain water to deeper layers is generally high in light-textured soils. Continuous cultivation for 27 years of acidic and kaolinitic Alfisols, with meager amounts of K supplying mica, depleted K reserves and exacerbated soil–related constraints to crop productivity (Sharpley 1990; Wulff et al. 1998). The differences in K release among different extraction solutions could be attributed to differences in their nature of reaction in soil. In 0.01 M $CaCl_2$, the K^+ ions on the surface mineral structure are exchanged by Ca^{+2} in the $CaCl_2$ solution. Because of larger size of Ca^{2+} ions and hydrogen energy (Rich 1968), it does not exchange easily with K further in the interlayer. The HCl solution possesses protons, which facilitate the exchange of H^+ ions with K^+ ions of minerals. Once exchange positions are filled with H^+, further exchange from highly selective sites of minerals is difficult with dilute acid solution. As hydrated NH_4^+ and K^+ ions have similar sizes, extractability of 1 N NH_4OAc is higher than that by 0.01 M $CaCl_2$ (Martin and Sparks 1983). The K fraction released with the boiling HNO_3 is higher than that by the other two extraction solutions; and this trend may be due to the extraction efficiency of HNO_3 in the release of the interlattice K into soil solution. This process of K release indicates that the maintenance of exchangeable K level occurs through release from the non-exchangeable sources. Thus, the magnitude of exchangeable K at any point reflects both K^+ release and plant available levels. The fraction of K released with $CaCl_2$ extraction occurs via the replacement of K ions on the exchange complex by Ca^+ in the $CaCl_2$ solution (Srinivasarao et al. 1999). The trend of ascendancy of different soil-K forms, as influenced by various nutrient management treatments, is shown in Fig. 4.

Apparently, higher amount of K release in the FYM 10 Mg ha^{-1} +100 % NPK treatment by all extracting solutions was due to higher K input (904 mg kg^{-1}) received by the treatment mentioned than that in other treatments. The higher amount of K released is also attributed to the process of structural K released through increasing the area of exchangeable surfaces, and due to the accelerated weathering of the interlayer K by application of FYM (Bhattacharyya et al. 2006). No differences were observed in the constant rate –K in profile of soil under different treatments as this is primarily influenced by the mineralogical composition of soil (Srinivasarao et al. 2000). Higher K release through combined application of both organic and inorganic nutrient sources was reported by Srinivasarao et al. (1999) and Singh et al. (2002).

Soil K balance during 27 years of fingermillet mono-cropping

The higher magnitude of depletion in 100 % NPK treatment was due to more K removal than the input. The magnitude of exchangeable (readily available) and non-exchangeable (slowly available) K in soils is influenced by long-term fertility management and K removal by the crop. Keeping aside the data from the 100 % NPK treatment, the magnitude of non-exchangeable K was on par in soils under other treatments (Table 6). The increase in magnitude of depletion of K from these plots was due to application of

Fig. 4 The trend of ascendancy of different soil-K forms, as influenced by various nutrient management treatments

Soil K forms	Dominance among different nutrient management practices
$CaCl_2$-K	FYM 10t ha^{-1}+ 100% NPK > FYM 10t ha^{-1}+ 50% NPK > 100% NPK > FYM 10t ha^{-1} > Control
HCl-K	FYM 10t ha^{-1}+ 100% NPK > FYM 10t ha^{-1}+ 50% NPK > 100% NPK > FYM 10t ha^{-1} > Control
NH_4OAc-K	FYM 10t ha^{-1}+ 100% NPK > FYM 10t ha^{-1}+ 50% NPK > FYM 10t ha^{-1} > 100% NPK > Control
HNO_3-K	FYM 10t ha^{-1}+ 100% NPK > 100% NPK > FYM 10t ha^{-1}+ 50% NPK > FYM 10t ha^{-1} > Control
	High → **Low**

fertilizer N, which favored better crop growth, leading to increased crop demand for K. Indeed, the amount of K removed by plants depends on the agronomic production, soil type and retention/removal of crop residues (Singh et al. 2005). Higher plant root growth favored by K availability (Kirkby et al. 2009) at different critical phonological stages increases uptake of K, especially by the K exhaustive fingermillet (Subba Rao et al. 2010; Srinivasarao et al. 2007, 2011).

Relatively lower magnitude of K depletion from plots fertilized with both manure and fertilizers was due to additional supply of K from the manure. When compared to other treatments, unfertilized plots had the lowest K uptake, but an equivalent removal of K was the contribution from the soil reserve. The crop K requirement under continuous cropping is initially met from available K fractions. Any additional crop K need is mostly met from non-exchangeable K (Srinivasarao and Khera 1994; Srinivasarao et al. 1998). Lack of any recycling of crop residues might be the reason for higher K depletion from soil K reserve after 27 years of mono-cropping.

Impact of K release and supply parameters on crop yield and its sustainability

Strong relationship with K uptake and non-exchangeable K and of SYI with the NH_4OAc-K indicate that the long-term sustainability of yield is strongly affected by the soil non-exchangeable K release capacity as the major K removal by crop is replenished from this K source in soil; and the grain yield is influenced by the readily available or exchangeable K. Deficiency of K is widespread in crops cultivated on highly weathered tropical upland soils, which are low or deficient in K bearing minerals (Ramanathan and Krishnamoorthy 1978). Deficiency of K in fingermillet grown in the unamended control treatment might have perturbed normal physiological activities of plants and adversely affected growth of the high K-demanding fingermillet as soil K replenishment rates are far below the crop K requirements. Productivity of guinea grass (*Pannicum spp.*) grown on selected K deficient Oxisols and Ultisols in Thailand, was also severely reduced (Darunsontaya et al. 2012). Yet, the productivity was drastically improved when these soils were supplied with higher amounts of exchangeable K (NH_4OAc-K), and water soluble K. Indeed, there exists a strong linear correlation between NH_4OAc-K and cumulative –K uptake by plants, highlighting the importance of NH_4OAc-K (Darunsontaya et al. 2012). The forms and the availability of soil K to plants mainly depends on clay mineralogy, K buffering capacity of the soil, the supply of other nutrients and crop management practices (Srinivasarao et al. 1998).

Conclusions

Our results indicate the importance of K management to enhancing and sustaining high yields of fingermillet, a K demanding crop, grown on K-deficient Alfisols in southern India where both readily available as well as weatherable soil reserve K levels are low. In the absence of sufficient K fertilization, K removal exceeds the input, and the negative K balance leads to severe depletion of the soil K reserves. Thus in predominantly non-micaceous soils, the depletion of soil reserve K are a strong constraint to enhancing productivity of fingermillet and other millet-based systems. In the present study continuous cropping of fingermillet for 27 years with high amounts of organic manure (10 Mg FYM ha^{-1}) and contribution of organic manure+50 % NPK showed positive yield trends. As chemical fertilizer use at the farm level has decreased due to recent escalation of K fertilizer price in India over the past years, farmers tend to not apply K, further aggravating K nutrition of crops. Addition of organic manures may be helpful in rainfed regions in addition to fertilizers for improved water retention in the soil during intermittent dry spells and amelioration of other emerging secondary and micronutrient deficiencies for sustainable millet production in K deficient Alfisols.

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References

Bhargava BS, Raghupathi HB (2005) Analysis for plant materials for macro and mmicronutrients. In: Tandon HLS (ed) Methods of analysis of soils, plants, waters, fertilizers and organic manures. Fertilizers Development and Consultation Organization, New Delhi, p 204

Bhattacharyya R, Prakash V, Kundu S, Ghosh BN, Srivastava AK, Gupta H (2006) Potassium balance as influenced by farmyard manure application under continuous soybean-wheat cropping system in a Typic Haplaquept. Geoderma 137:155–160

Bouyoucos GJ (1927) The hydrometer as a new method for the mechanical analysis of soils. Soil Sci 23:343–354

Cakmak I (2005) The role of potassium in alleviating detrimental effects of abiotic stresses in plants. J Plant Nutr Soil Sc 168:521–530

Cox AE, Joern BC (1997) Release kinetics of non-exchangeable potassium in soils using sodium tetraphenylboron. Soil Sci 167:588–598

CRIDA (2010) Annual Report, Central Research Institute for Dryland Agriculture, Hyderabad, India

Darunsontaya T, Suddhiprakarn A, Kheoruenromne I, Prakongkep N, Gilkes RJ (2012) The forms and availability to plants of soil potassium as related to mineralogy for upland Oxisols and Ultisols from Thailand. Geoderma 170:11–24

Dhillon SK, Dhillon KS (1992) Kinetics of release of potassium by sodium tetraphenyl boron from some topsoil samples of Red (Alfisols), Black (Vertisols), and Alluvial (Inceptisols and Entisols) soils of India. Fert News 32:135–138

Eswaran H, Reich PF, Padmanabhan E (2011) World soil resources, opportunities and challenges. In: Lal R, Stewart BA (eds) World soil resources and food security. Adv Soil Sci 29–52

Ganeshamurthy AN (1983) An estimate of the uptake of the subsurface soil K of crops in two long-term experiments. J Agr Sci (Cambridge) 101:495–497

Hanway JJ, Heidel H (1952) Soil analysis methods as used in Iowa State College, Soil Testing Laboratory. Iowa Agric 57:1–13

Haylock OF (1956) A method for estimating the availability of non-exchangeable potassium transactions. 6th International Congress. Soil Sci 1:403–408

Hermann L, Hebel A, Stahr K (1994) Influence of microavailability in sandy Sahelian soils on millet growth. J Plant Nutr Soil Sc 157:111–115, http://www.icrisat.org/crop-fingermillet.htm. Date of access: 25th June, 2012

Jackson ML (1973) Soil chemistry analysis, 2nd edn. Prentice Hall of India Pvt. Ltd, New Delhi

Kant S, Kafkafi U (2002) Potassium and abiotic stresses in plants. In: Paschicha NS, Bansal SK (eds) Potassium for sustainable crop production. Potash Research Institute of India, Gurgaon and International Potash Institute, Basel, pp 233–251

Kirkby EA, LeBot J, Adomowicz S, Romheld V (2009) Nitrogen in physiology and agronomic prospective and implications for the use of different nitrogen forms. Proc Inter Fert Soc 653:1–48

Kumar N, Kavino M, Kumar AR (2006) Balanced fertilization for sustainable yield and quality in tropical fruit crops. In: Benbi DK, Brar MS, Bansal SK (eds) Balanced fertilization for sustaining crop productivity. International Potash Institute, Horgen, pp 387–405

Martin HW, Sparks DL (1983) Kinetics of non-exchangeable potassium release from two Coastal Plain soils. Soil Sci Soc Am J 47:883–887

Mengel K (1985) Dynamics and availability of major nutrients in soils. Adv Soil Sci 2:65–131

Naidu LGK, Reddy RS, Prakasa Rao EVS, Krishnam P, Nasre RA (1996) Potassium deficiency in crops- An emerging problem in red and lateritic soils. J Potassium Res 12:23–29

Pettigraw WT (2008) Potassium influences on yield and quality production for maize, wheat, soybean and cotton. Physiol Plant 133:670–681

Ramanathan KM, Krishnamoorthy KK (1978) Potassium dynamic in red soils. In: Sekhon GS (ed) Potassium in soils and crops. Potash Institute, India, pp 69–79

Rich CI (1968) Hydroxy interlayers in expansible layer silicates. Clays Clay Miner 16:15–30

Sen-Gupta A, Berkowitz GA, Pier PA (1989) Maintenance of photosynthesis at low leaf water potential in wheat. Plant Physiol 89:1358–1365

Sharpley AN (1990) Reaction of fertilizer potassium in soils of different mineralogy. Soil Sci 149:44–51

Singh M, Tripathi AK, Damodar Reddy D (2002) Potassium balance and release kinetics of non-exchangeable K in a Typic Haplustert as influenced by cattle manure application under a soybean-wheat system. Aust J Soil Res 40:533–541

Singh M, Wanjari RH, Subba Rao A (2010) Long-term fertilizer experiments: Impact on Productivity and Sustainability of Crops in Alfisols of India. In: Brar MS, Mukhopadhyay SS (eds) Potassium Role and Benefits in Improving Nutrient Management for Food Production, Quality and Reduced Environmental Damages. IPI-OUAT-IPNI International Symposium, Bhubaneswar, 5th – 7th, November, 2009, pp 99–105

Singh RP, Das SK, Bhaskara Rao UM, Narayana Reddy M (1990) Sustainability index under different management. Annual Report. Central Research Institute for Dryland Agriculture, Hyderabad, India

Singh Y, Singh B, Timsina J (2005) Crop residue management for nutrient cycling and improving soil productivity in rice based cropping systems in the tropics. Adv Agron 85:269–407

SPSS (2001) Statistical package. Version 11.0 for Windows. SPSS Inc, Chicago

Srinivasarao C, Bansal SK, Subba Rao A, Takkar PN (1998) Kinetics of exchangeable potassium desorption from twenty two benchmark soils of India. J Indian Soc Soil Sci 46:357–362

Srinivasarao C, Khera MS (1994) Potassium replenishment capacity of some Ustrochrepts at their minimal exchangeable K in relation to clay mineralogy. J Plant Nutr Soil Sc 157:467–470

Srinivasarao C, Rupa TR, Subba Rao, Singh SP, Bansal SK (2006) Kinetics of non-exchangeable potassium release from important benchmark soils of India: effects of mineralogy, soil depth and extraction media. Commun Soil Sci Plan Anal 36:1–19

Srinivasarao C, Satyanarayana T, Venkateswarlu B (2011) Potassium mining in Indian agriculture: input and output balance. Karnataka J Agric Sci 24:20–28

Srinivasarao C, Subba Rao A, Rupa TR (2000) Plant mobilization of reserve potassium from fifteen smectitic soils in relation to mineralogy and soil test potassium. Soil Sci 165:578–586

Srinivasarao C, Swarup A, Subba Rao A, Rajgopal V (1999) Kinetics of non-exchangeable potassium release from Topaquept as influenced by long-term cropping, fertilization and manuring. Aust J Soil Res 37:317–328

Srinivasarao C, Vittal KPR, Venkateswarlu B (2009) Role of potassium in water stress management in dryland agriculture. In: Brar MS, Mukhopadhyay SS (eds) Potassium role and benefits in improving nutrient management for food production, quality and reduced environmental damages. Proceedings of the IPI-OUAT-IPNI International Symposium, Bhubaneswar, Orissa, India, pp. 199–213

Srinivasarao C, Vittal KPR, Kundu S, Gajbhiye PN, Vijayasankarbabu M (2010) Twenty years of continuous cropping, fertilization and organic manure application effects on forms of potassium and kinetics of non-exchangeable K release in the profile of an Alfisol under arid conditions. Commun Soil Sci Plant Anal 41:783–796

Srinivasarao C, Vittal KPR, Tiwari KN, Gajbhiye PN, Kundu S (2007) Categorization of soils based on potassium reserves and production systems: implications in K management. Aust J Soil Res 45:438–447

Subba Rao, Srinivasarao C, Srivastava S (2010) Potassium status and crop response to potassium on the soils of agro-ecological regions of India. IPI Research Topics 20. International Potash Institute, Horgen, p 185

Swarup A (1998) Emerging soil fertility management issues for sustainable crop production in irrigated systems in long-term soil fertility management through integrated plant nutrient supply. In: Swarup A, Damodar Reddy D, Prasad RN (eds) Indian Institute of Soil Science, Bhopal, India, pp 54–68

Swarup A, Chhillar RK (1986) Build up and depletion of soil phosphorus and potassium and their uptake by rice and wheat in a long-term field experiment. Plant Soil 91:161–170

Wood LK, De Turk EE (1941) The absorption of potassium in soils in non-replaceable forms. Soil Sci Soc Am J 5:152–161

Woodruff CM, McIntosh JL (1960) Testing soil potassium. Transactions of the 7th International Congress of Soil Science 3: p 80

Wulff F, Schulz V, Jungk A, Claassen N (1998) Potassium fertilization on sandy soils in relation to soil test, crop yield and K-leaching. J Plant Nutr Soil Sc 161:591–599