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Estimation of Nutrient Uptake Requirements for Yams in India Based on QUEFTS Model

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Abstract

Yams (Dioscorea Spp.) yield in many parts of the world are very low compared to maximum or potential yields. Managing the spatial and temporal variability using modeling approach will be one of the ways to improve the yield. The Quantitative Evaluation of Fertility of Tropical Soils (QUEFTS) model was used for determining the region specific balanced NPK uptake requirements and recommendations for a target yield of yams. Published data from several field experiments dealing with N, P and K during the past 30 years across yam growing environments with wide range of soil and climatic conditions were used for calibration of QUEFTS model. The calibration of QUEFTS model for yams required estimation of the slope of two borderlines describing the maximum accumulation (a) and maximum dilution (d) of N, P and K in plant in relation to tuber yield. The study proposed the following ‘a’ and ‘d’ values for yam with harvest index above 0.40. The constants for minimum (a) and maximum accumulation (d) (kg tuber kg”1 nutrient) of N (137 and 363), P (1212 and 3509) and K (127 and 397) were derived as standard model parameters. The ratio of maximum dilution (d) to maximum accumulation (a) [d/a] for N (2.65) was less than that of P (2.90) and K (2.91), indicating that a specific yield of yam relied on a relatively narrow range of N uptake. Therefore, a precise N supply is more important for a stable tuber yield relative to P and K. The model predicted a linear increase in tuber yield, if nutrients are taken up at rate of 4.15, 0.45 and 3.95 kg of N, P and K per 1000 kg tuber. The average uptake ratio in total plant dry matter was 9.2:1:8.8. The optimal internal efficiencies for balanced nutrition were 240, 2222 and 253 kg N, P and K per kg of tuber.

Key words: Yam, QUEFTS, internal efficiency, indigenous nutrient supply, recovery efficiency

Introduction

Yams are important staples in tropical countries mainly West Africa, South East Asia, the Pacific Islands and the Caribbean. Yam is the third important tropical tuber crop after cassava and sweet potato and a good source of carbohydrate (Onyeka et al., 2006). As a food crop, yams provide major source of energy and meet the nutritional requirements and hence plays a major role in improving food and nutritional security. Globally yams are cultivated in an area of 8.56 million ha with a total production of 73.02 million tons and the average yield is 8.53 t ha^{-1} which is far below the potential productivity of 60-75 t ha^{-1} (Diby et al., 2008). Since 2000, the world’s annual yam production has increased by an estimated 26 million tons (66% increase) which shows the ever-increasing demand for yams to meet the food requirements of the people. There are wide variability in the average yield of yams in major yam growing countries which range from 0.60 to 29.17 t ha^{-1} (www.fao.orgs/faostat). Yams are efficient scavengers of soil nutrients. Adequate supply of nutrients can result in achieving good growth and yield potential. They are highly responsive to manures and fertilizers. *Dioscorea alata* L. a leading cultivated species has tuber of highly polymorphic shape and colour. *D. rotundata* Poir., a representative of under exploited resource among tropical root and tuber crops, can produce a tuber yield of 35 to 40 t ha^{-1} (Moorthy and Nair, 1989) with excellent tuber quality and is also feasible in diverse cropping systems. This crop is getting popularity in Indian farmers due to its high yie-ld potential and wide adaptability to various agro climatic regions (Suja and Sreekumar, 2014).

Published literature on cereals and tuber crops reported that further increase in yield and nutrient-use efficiency can be possible only by managing the large spatial and temporal variability existing in soil nutrient supply, nutrient-use efficiency and crop response to nutrients (Pingali et al., 1998 and Byju et al., 2012). Recent research conducted in various countries including India has demonstrated limitations of the blanket recommendations. Efficient production of crops depends on the provision of a balanced supply of N, P and K either from the soil or from fertilizer sources. The optimized application of nutrients to the crop is essential to maintain high yield and good soil health. The site specific nutrient management (SSNM) approach becomes meaningful when fertilizer nutrient requirements are formulated based on more generic, quantitative approaches, such as simulation models to estimate the relationship between yield and nutrient uptake (Maiti et al., 2006). Most of the simulation models describe the relationship between nutrient supply, uptake and crop yield, and those models address a single nutrient. In agricultural practices, at least the three macronutrients should be taken in to account.

The Quantitative Evaluation of Fertility of Tropical Soils (QUEFTS) model originally developed by Janssen et al. (1990), describes relationship between yield and nutrient uptake. The QUEFTS approach has been already applied in cereals like rice in Asia (Witt et al., 1999), West Africa (Hafele et al., 2003) and in India (Pathak et al., 2003), wheat in China (Liu et al., 2006) and maize in West Africa (Janssen et al.,1990; Saidou et al., 2003, Xu et al., 2013 and Shehu et al., 2019) and China (Liu et al., 2006) and cassava in West Africa (Ezui et al., 2016). The QUEFTS model was also calibrated and validated in India for site specific NPK recommendations for cassava, sweet potato, elephant foot yam and taro in major growing environments of India (Byju et al., 2012 and 2016; Kumar et al., 2016 and Jinimol and Byju, 2018).

The present study was aimed at describing the nutrient uptake and yield relations for yams grown in India. The specific objectives of this study were to determine the envelope functions describing relationships between tuber yield and nutrient (N, P, K) uptake in yams, quantify the balanced N, P and K uptake requirements of across a wide range of yields and environments and estimate the NPK fertilizer nutrient requirements.

Materials and Methods

Origin of data

Published data from several field experiments dealing with N, P and K during the years 1972 to 2004 across yams growing environments with a wide range of soil and climatic conditions were used for the study. Data from those experiments having different chemical fertilizer treatments were included in the study. Available data from these experiments were total uptake of N, P, and K, tuber yield and levels of applied fertilizers in different treatments. In the current study, the upper and lower 2.5% of the ranges of the yield and nutrient uptake data have been excluded from the analysis to remove outliers due to analytical errors.

Crop management practices

Data sets for calibration of QUEFTS model for yams were selected from field experiments having fertilized and unfertilized plots with different rates of NPK from different yam growing regions and years. All the experiments ensured adequate control measures for weed and pest management. Half of N and K and full dose of P were applied as basal dressing and the remaining half of N and K were applied 30-60 days after basal dose. The unfertilized plots received similar crop management practices except fertilizer application. The crop was harvested manually and total weights of tuber, leaves, and vines were calculated. Tuber yields were obtained at physiological maturity and yields were recorded. The weight of vines and leaves were also recorded. Tuber, vine and leaf samples were collected at the time of harvest for the estimation of N, P, and K uptake. All plant samples were oven dried at 65°C for 48 hrs until constant weight. Dried samples were ground in a stainless-steel Wiley Mill and N content was determined by the Kjeidahl method (Burmner and Mulvaney, 1982). The P content was estimated by the vanadomolybdophosphoric yellow colour method after tri acid digestion [nitric acid (HNO_3), perchloric acid ($HClO_4$), sulfuric acid (H_2SO_4); 9:3:1] and K content by a flame photometer using the same digest (Jackson,1972).

Model background

The original version of the QUEFTS model was developed by Janssen et al. (1990) as a tool for quantitative prediction of maize yields unfertilized tropical soils. This model assumes that yield is a function of N, P and K supply from the soil and fertilizer, taking into account the climate adjusted and variety specific potential yield of that region (Pathak et al., 2003). Based on this principle, the model calculates the potential availability of nutrients N, P and K and the interaction among them. This model furthermore illustrates a distinction between potential supply of nutrient (maximum quantity that is supplied from soil and fertilizer) and its actual uptake by that specific crop. When all other growth conditions are in optimum, the actual uptake of nutrient becomes equal to potential supply. A general assumption of the model is that yield is only a function of N, P and K supply and potential yield (Y_{max}) is determined by crop variety and climatic conditions. Two possible (minimum and maximum) yield levels can be estimated based on the final nutrient uptake. In these calculations, the ratio of yield and nutrient would be the minimum and maximum values as accumulation ('a') and dilution ('d'). When a particular nutrient is present in limited amount compared diluted within the plant and hence its concentration will be minimal. Then the internal efficiency will have its maximum value. Similarly, a particular nutrient is abundantly present compared to other nutrients, it gets accumulated within the plant, hence its concentration will be maximal and internal efficiency will be minimal.

Four steps are involved in QUEFTS calibration: (1) assessment of potential indigenous nutrient supply. We used nutrient uptake from unfertilized plots as indigenous nutrient supply, (2) determination of the uptake of N (UN), P (UP) and K (UK) as functions of potential supply of N (SN), P (SP) and K (SK), that is, supply from soil plus fertilizer, taking fertilizer nutrient-recovery efficiency into account (3) estimation of yield ranges as functions of actual uptakes of N, P, and K when they are maximally accumulated and maximally diluted. The internal efficiencies when they are maximally accumulated and diluted are designated as 'a' and 'd' respectively and (4) estimation of the final yield by combining three yield ranges (one each for N, P, and K) considering NPK interactions.

Using 'a' and 'd' values for N, P and K, fertilizer recovery efficiencies as REN (0.5), REP (0.2), REK (0.4) and some minimal values for INS (5.0), IPS (1.0), and IKS (5.0), the balanced NPK uptake requirements were derived under a set of constraints like yield target and yield potentials. Smailing and Janssen (1993) suggested maximizing the mean of uptake efficiencies, since it is impossible to maximize the uptake efficiency of all nutrients simultaneously. The ratio of UN/SN, UP/SP and UK/SK are considered as yield producing uptake efficiencies, and the mean of the three species formed the total yield producing uptake efficiency.

Step 3 and 4 of the model dealing with the relationship between tuber yield and the NPK uptake in total plant dry matter are modified by following studies;

1. The borderline describing the maximum and minimum accumulation of N, P and K in the total dry matter were fixed and their application to different criteria of data selection was studied.
2. The optimum uptake requirements of N, P and K (YN, YP and YK) at different potential yields (Y_{max}) were calculated.
3. The indigenous nutrient supplying capacity was estimated.

The internal efficiency (IE, kg kg^{-1}) of a nutrient is defined as the amount of tuber yield in kg produced per kg plant N, P, or K uptake in total plant dry matter (oven-dry weight). The reciprocal internal efficiency (RIE, kg 1000 kg^{-1}) was calculated from average IE of all data and it is the amount of nutrient in the plant dry matter needed to produce 1 ton of tuber. The indigenous nutrient supply for a particular nutrient is defined as the amount of that nutrient taken up by the crop under optimal conditions when all other nutrients are supplied amply (Liu et al., 2005). The indigenous N supply was calculated as the N uptake in nitrogen unfertilized plots, and similarly P and K uptakes were calculated from plots that received no P and K fertilizer, respectively. The difference between N uptake in fertilized and unfertilized gives recovery efficiency of fertilizer N, whereas the P and K uptakes of plots that received no P and K fertilizer respectively, will give the recovery efficiency of fertilizer P and K.

Results and Discussion

Selection of data set for adjusting QUEFTS to yams

Internal nutrient use efficiency, fertilizer nutrient recovery efficiency and soil indigenous supply for yam were estimated using data set given in Table 1. The available data sets were analyzed using descriptive statistical analysis and the results were shown in Table 1. The average tuber yield was 18.39 t ha^{-1} and it ranged from 10.30 to 56.10 t ha^{-1}. The origin of data set from different field experiments across wide range of yam growing areas helps to include parameters of varied soil, climatic conditions and agro techniques. The average uptake of N, P and K were 76.66, 9.77 and 81.56 kg ha^{-1} respectively. Many studies showed the lowest nutrient uptake was recorded in nutrient omission plots whereas maximum uptakes were observed in plots with adequate or excessive nutrient supply. As nutrient concentration varies tremendously as reflected in the wide range of nutrient supplies and environmental conditions, the N, P and K uptake values ranged from 49.37 to 205, 5.14 to 57.30 and 44 to 259 kg ha^{-1} respectively. The average N, P and K applications were 76.47, 61.44 and 93.93 kg ha^{-1}respectively.

Across all observations, the average internal efficiency (IE) of N, P and K were 262.63, 2110.60 and 232.79 kg tuber yield kg^{-1} whereas the mean reciprocal internal efficiency (RIE) values were 4.34, 0.53 and 4.58 kg N, P and K removed t^{-1} of tuber with an uptake ratio of 8.18:1.0:8.64. When the internal efficiency values of N, P and K were analyzed from fertilized and unfertilized plots separately it could be observed that the values were greater in unfertilized plots for N, P and K and the values were greater in fertilizer plots for P. This is indicated that both N and K were limiting nutrients in those major yam growing areas. The range of harvest index in those studys was found to be 0.58 to 0.73 with a mean value of 0.66.

Evaluation of ‘a’ and ‘d’ values

The calibration of QUEFTS model requires the determination of the boundary lines of maximum accumulation (a) and minimum dilution (d) of N, P and K in plants as presented in Table 2. Determination of ‘a’ and ‘d’ values is important for the model calibration and for determination of N, P and K requirements for yam

Table 1. Descriptive statistics of data set used for estimation of internal efficiency, nutrient recovery efficiency and nutrient requirement

Parameters	Unit	n	Mean	SD*	Minimum	Maximum	Kurtosis	Skewness	CV* (%)
Tuber root yield	t ha^{-1}	86	18.39	7.64	10.30	56.10	10.45	2.80	41.55
Fertilizer -N	kg ha-^{1}	30	76.47	44.90	30.00	224.00	1.73	0.51	48.36
Fertilizer -P	kg ha-^{1}	36	61.44	8.67	60.00	112.00	-1.49	-0.23	39.10
Fertilizer -K	kg ha-^{1}	30	93.93	73.27	40.00	448.00	13.15	3.40	89.58
N uptake	kg ha^{-1}	86	76.66	31.56	49.37	205.00	6.39	2.31	41.17
P uptake	kg ha^{-1}	86	9.77	7.70	5.14	57.30	20.69	4.31	78.80
K uptake	kg ha^{-1}	86	81.56	36.63	44.00	259.00	8.97	2.86	44.92
IEN*		86	262.63	190.34	73.84	1932.32	71.71	8.11	72.47
IEP	kg kg^{-1}	86	2110.60	614.77	572.38	4819.51	4.11	0.70	29.13
IEK	kg kg^{-1}	86	232.79	51.82	66.88	435.45	2.94	0.23	22.26
RIE- N*		86	4.34	1.47	0.52	13.54	18.25	3.50	2.53
RIE- P	kg t^{-1}	86	0.53	2.93	0.21	1.75	11.50	2.93	13.29
RIE-K	kg t^{-1}	86	4.58	1.53	2.30	14.95	24.93	4.16	75.24
HI		72	0.66	0.03	0.58	0.73	0.34	-0.55	11.57
Tuber DM*	%	72	29.74	1.35	26.71	32.83	0.32	0.80	7.43

Notes. SD*, standard deviation; CV*, coefficient of variation; DM*, dry matter; IE*, internal efficiency; *HI, harvest index and *RIE, reciprocal internal efficiency

Table 2. Constants of envelope functions relating tuber yield of yam to maximum accumulation (a) and dilution (d) of N, P and K in total dry matter

Parameters	Set 1		Set 2		Set 3		Set 4	
	a (2.5th)	d (97.5th)	a (5th)	d (95th)	a (7.5th)	d (92.5th)	a (10th)	d (90th)
N	137	363	137	363	137	363	137	363
P	1212	3509	1212	3509	1212	3509	1212	3509
K	127	397	127	397	127	397	127	397

growing areas. The data set used for the calibration of the model included crop data like plant N, P, and K uptake (kg ha^{-1}), tuber dry matter (%), harvest index, internal efficiencies (kg^{-1} kg^{-1}), and different fertilizer levels from different research papers covering the period from 1972 to 2004 in yam growing areas of the world. The ideal data set for calibration of QUEFTS model would not be influenced by any factor other than N, P and K from soil supply. Present study used only data set with a tuber yield >10 t ha^{-1} and excluded 2.5% of highest and lowest observations, when determining borderline values for dilution and accumulation of nutrients in plant tissue (set1, Table 2). This was done to get a data set where yam growth is not limited by factors other than N, P and K because calibration of QUEFTS needs a data set that is not influenced by any other factors than N, P and K supply from soil. The constants of 'a' and 'd' showing the internal efficiencies at maximum accumulation and dilution of N, P and K for the whole data set were calculated as 137, 1212 and 127; 363, 3509 and 397 (set1, Table 2).

The sensitivity of the developed relationship between tuber yield and N, P and K uptake was studied by 3 other sets of constants by deleting 5%, 7.5 % and 10% of the highest and lowest data respectively (set 2, set 3 and set 4, Table 2). Data set with different degrees of outlier exclusions were carried out for defining the border lines showing the relationship between tuber yield and nutrient accumulation in plant dry matter at maturity, by treating the upper and lower 2.5, 5, 7.5 and 10 percentiles of the internal efficiencies as outliers. The major component of the calibration of the QUEFTS model for yam is to determine the border lines of maximum dilution (d) and accumulation (a) of nutrients in plants and was illustrated by Figs. 1-3. The values obtained for all percentiles defining the envelope function coefficients 'a' and 'd' for N, P and K in set 1, set 2, set 3 and set 4 (Table 2) were same in our study.

Potential yield and nutrient requirement

Great variations exist in the potential yields of (Ymax) yam in growing areas in tropics. Using the internal efficiencies at maximum accumulation and dilution of the nutrients derived from the study, the QUEFTS model was run to generate optimum yield verses nutrient uptake curves for yield potential levels ranging from 20 to 70 t ha^{-1}. The uptake requirements at different yield potentials of yam showed that the relationship between yield and nutrient (N, P and K) uptake was found to be linear at lower yield targets, indicating that plant growth is mainly limited by NPK uptake (Fig. 4). A linear increase in tuber yield was suggested by the model with N, P and K uptake of 4.15, 0.45 and 3.95 kg N, P and K per 1000 kg tuber yield. Table 3 shows internal efficiencies and reciprocal internal efficiencies, which are constant up to a yield target 30 t ha^{-1}, which shows a balanced nutrient application. When yield target approaches the yield potential, internal efficiency values decreased drastically and reached to a minimum value. Irrespective of yield potential, the calculated NPK uptake ratios in total plant dry matter of yam were 9.2:1:8.7 in a linear part of relationship. The corresponding internal efficiency (IE) values for N, P and K were 240, 2222 and 253 kg kg^{-1}. The study showed that both NPK uptake and IE values of yam were closer to the data set used for developing the model. It is also observed that the linear part of the relationship is always 60 percent of the whole yield range. This indicated that maximizing the internal efficiencies (IEs) by balanced NPK application will result in profitable tuber yield closer to potential yield 70 t ha^{-1}.

Indigenous nutrient supply and fertilizer nutrients requirements

The QUEFTS model was run with varying indigenous nutrient supplies in order to get fertilizer nutrients requirements. The INS, IPS, and IKS values used were

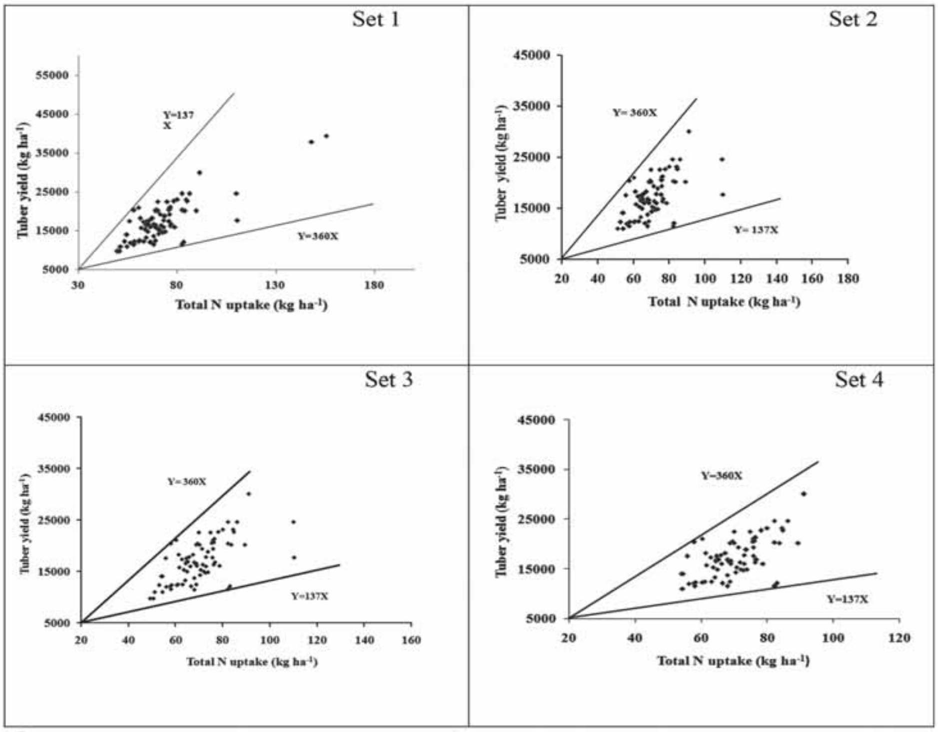

Fig. 1. The relationship between tuber yield and N uptake in yam. The regression lines in the left of each figure represent the boundary of maximum dilution (YND), while the lines on the right indicate the boundary of maximum accumulation (YNA). The slope of the boundary lines were calculated by excluding upper and lower 2.5th, 5th,7.5th or 10th percentiles of all internal efficiency data.

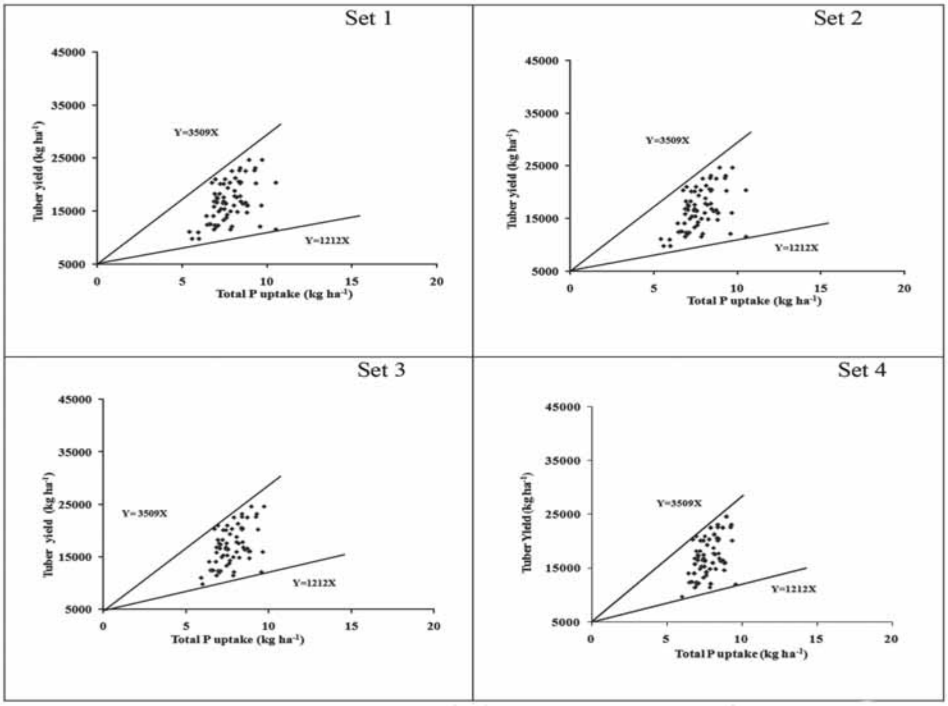

Fig. 2. The relationship between tuber yield and P uptake in yam. The regression lines in left of the each figure represent the boundary of maximum dilution (YND), while the lines on the right indicate the boundary of maximum accumulation (YNA). The slope of the boundary lines were calculated by excluding upper and lower 2.5th, 5th,7.5th or 10th percentiles of all internal efficiency data.

very low value to the level when FN, FP and FK requirements reached zero. When the value of indigenous nutrient supply of N, P and K was increased, the fertilizer nutrient requirement decreased linearly and reached minimum value. Fertilizer nutrient requirements were calculated for varying yield potentials ranging from 20-70 t ha^{-1}and the target yields of 20, 30, 40, 50, and 60 ha^{-1}. An increasing trend in fertilizer requirement was obtained due to increasing yield targets irrespective of Potential yield (Ymax) (Table 4-6). Tables 4-6 were explained the relationship between the indigenous nutrient supply and fertilizer N, P and K required for the growth of white yam.

The calibration of QUEFTS model for yam required estimation of the slope of two borderlines describing the maximum accumulation and maximum dilution of N, P and K in plant in relation to tuber yield. The study proposed to use aN = 137, dN = 363, aP = 1212, dP = 3509, aK = 127, dK = 391 as standard parameters in QUEFTS model for yam with harvest index above 0.40. The constants of 'a' and 'd' showing the internal efficiencies at maximum accumulation and dilution of N, P and K values were

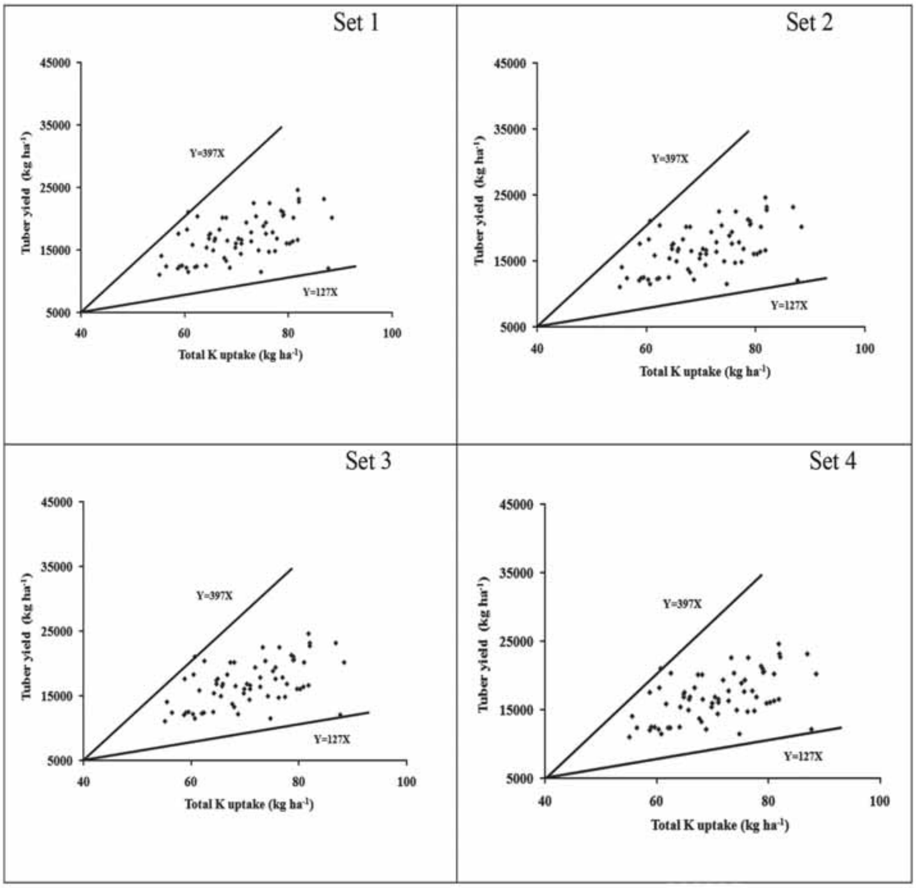

Fig. 3. The relationship between tuber yield and K uptake in yam. The regression lines in the left of each figure represent the boundary of maximum dilution (YND), while the lines on the right indicate the boundary of maximum accumulation (YNA). The slope of the boundary lines were calculated by excluding upper and lower 2.5th, 5th,7.5th or 10th percentiles of all internal efficiency data.

standardized for other tuber crops like cassava as 35, 250, 32 and 80, 750, 102 (Byju et al., 2012), elephant foot yam as 130, 900, 100 and 460, 2100, 170 (Byju et al., 2016), sweet potato as 40, 96, 30 and 80, 272, 85 (Kumar et al., 2016) and for potato 24, 164, 25 and 108, 469, 63 (Kumar et al., 2018) respectively.

In the present study step wise exclusion of data set did not affect the slope values. But previous studies in maize (Witt et al., 1999), cassava (Byju et al., 2012) sweet potato (Kumar et al., 2016), elephant foot yam (Byju et al., 2016) and taro (Jini mol and Byju, 2018) showed that slope of each boundary line forming envelope functions changed due to exclusion of the data. Many studies reported that step wise exclusion of extreme data affected the slope of the internal efficiencies of nutrients to a great extent. But optimal nutrient requirements calculated by QUEFTS model for all data sets were similar in a study by Liu et al. (2006). Pathak et al. (2003) and Setiyono et al. (2010) used the 2.5th percentiles of nutrient internal efficiencies for defining the final envelope function coefficients in rice and maize respectively. Hence the present study used the data set with 2.5th percentiles of nutrient internal efficiencies for defining the final envelope function coefficients (Set 1,

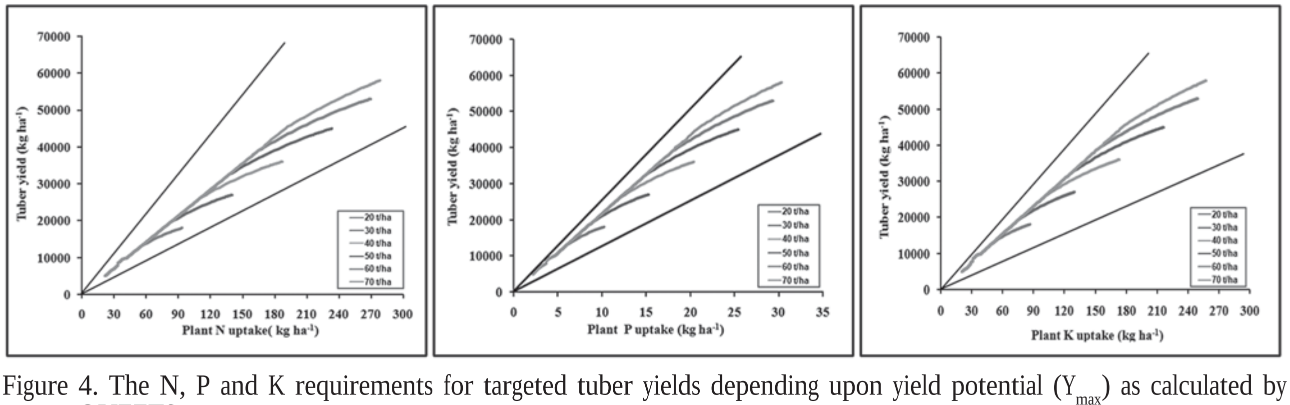

Figure 4. The N, P and K requirements for targeted tuber yields depending upon yield potential (Y_{max}) as calculated by QUEFTS

Table 3. NPK uptake requirements, internal efficiencies (kg tuber/kg nutrient) and reciprocal internal efficiency (kg nutrient/ 1000 kg tuber) for yam as calculated by QUEFTS for certain targeted yields

Yield t ha^{-1}	Required nutrient uptake (kg ha^{-1})			Internal efficiency (kg tuber kg^{-1} NPK removed)			Reciprocal Internal efficiency (kg 1000 kg $^{-1}$)		
	N	P	K	N	P	K	N	P	K
5	21	2	20	238	2500	250	4.20	0.40	4.00
10	43	4	42	233	2500	238	4.30	0.40	4.20
15	64	6	64	234	2500	234	4.27	0.40	4.27
20	83	9	79	240	2222	253	4.15	0.45	3.95
25	104	12	99	240	2083	253	4.16	0.48	3.96
30	125	14	118	241	2143	254	4.17	0.47	3.93
35	150	17	142	233	2059	246	4.29	0.49	4.06
35.5	154	17	145	231	2088	245	4.34	0.48	4.08
36	157	17	148	229	2118	243	4.36	0.47	4.11
36.5	160	18	151	228	2028	242	4.38	0.49	4.14
37	163	18	154	227	2056	240	4.41	0.49	4.16
37.5	167	19	157	225	1974	239	4.45	0.51	4.19
38	170	19	160	224	2000	238	4.47	0.50	4.21
38.5	174	19	164	221	2026	235	4.52	0.49	4.26
39	177	20	167	220	1950	234	4.54	0.51	4.28
39.5	182	20	170	217	1975	232	4.61	0.51	4.30
40	185	21	174	216	1905	230	4.63	0.53	4.35

Note: The model was run using standard model parameters (Table 2). The potential yield was set to 50 t ha^{-1}. Yield is expressed on fresh weight basis.

Table 4. The balanced N fertilizer requirements for targeted yam tuber yields 20, 30 and 40 t ha^{-1} with respect to soil indigenous nutrient supply (INS) as calculated by QUEFTS

INS (kg ha^{-1})	Fertilizer requirement for varying yield target (kg ha^{-1})		
	Yield target (t ha^{-1})		
	20 t ha^{-1}	30 t ha^{-1}	40 t ha^{-1}
20	138	227	354
25	128	217	344
30	118	207	334
35	108	197	324
40	98	187	314
45	88	177	304
50	78	167	294
55	68	155	284
60	58	145	274
65	48	137	264
70	38	127	254
80	18	107	234
90		87	214
95		77	204
100		67	194

Note: The N requirements for targeted tuber yields depending upon yield potential (Y_{max}) as calculated by QUEFTS. (Y_{max}) was fixed as 50 t ha^{-1}.

Table 2). The ratio of maximum dilution and maximum accumulation (d/a) for N (2.65) was less than that of P (2.90) and K (2.91), indicating that a specific yield of yam relied on a relatively narrow range of N uptake. Therefore, a precise N supply is more important for a stable tuber yield formation relative to P and K (Zang et al., 2019).

The QUEFTS model was calibrated for varying yield targets with respect to potential yields in order to get NPK uptake requirements. The model predicted a linear increase in tuber yield, if nutrients are taken up at rate of 4.15, 0.45 and 3.95 kg of N, P and K per 1000 kg tuber respectively. The average uptake ratio in total plant dry matter was 9.2:1:8.8. The corresponding values of N, P and K uptakes were 17.6, 2.2 and 15.6 kg for cassava (Byju et al., 2012), 18, 4 and 24 for sweet potato (Kumar et al., 2018) and 12.97, 2.75 and 17.47 kg for taro per 1000 kg tuber yield / cormal yield respectively (Jinimol and Byju, 2018). In present study - the values for N, P and K requirements were lower compared to the values reported above since the tuber yield was reported on fresh weight basis. Zang et al. (2019) reported the corresponding values as 1.34, 0.30 and 1.93 in radish. The P uptake was relatively lower than N and

Table 5. The balanced fertilizer requirements for targeted yam tuber yields from 20, 30 and 40 t ha^{-1} with respect to soil indigenous nutrient supply (INS) as calculated by QUEFTS

IPS (kg ha^{-1})	Fertilizer requirement for varying yield target (kg ha^{-1})		
	Yield target (t ha^{-1})		
	20 t ha^{-1}	30 t ha^{-1}	40 t ha^{-1}
5	21	43	76
6	18	38	72
7	13	33	71
8	6	26	67
9	2	23	56
10	-1	19	55
11		8	52
12		9	42
13		4	37
14			34
15			32
16			20
17			17
18			13
19			12
20			7
21			2
22			-3

Note: The P requirements for targeted tuber yields depending upon yield potential (Y_{max}) as calculated by QUEFTS. (Y_{max}) was fixed as 50 t ha^{-1}.

K in present study. Yams are highly efficient in extracting phosphorus from the soil and seldom need additional requirement. The response of P fertilization to yam growth was reported to be very low in many studies and hence P is not a limiting factor in view of low requirement (Kabeerathumma et al., 1991). Irizarry and Rivera (1985) reported that *D. rotundata* Poir. utilized 10.5 kg N, 1.4 kg P and 11 kg K in order to produce every ton of edible dry matter production. Earlier studies showed that the N, P and K uptakes are in the range of 148-205, 13-25 and 112-215 kg ha^{-1} for the yield levels of 13-37 t ha^{-1} (Sobulo, 1972; Obigbesan and Agoola, 1978; Irizarry et al., 1985; and Kabeerathumma et al., 1987). Diby et al., 2008 observed the increasing trend of nutrient uptake in yams with fertilizer application. Kabeerthumma et al. (1991) reported the ratio of NPK uptake in *D. alata* L. and *D. rotundata* Poir. as 1:13:1.23 and 1:15:1.23 respectively. Obigbesan and Agoola (1978) also reported similar nutrient uptake ratio for yams.

Table 6. The balanced fertilizer requirements for targeted yam tuber yields from 20, 30 and 40 t ha^{-1} with respect to soil indigenous nutrient supply (INS) as calculated by QUEFTS

IKS (kg ha^{-1})	Fertilizer requirement for varying yield target (kg ha^{-1})		
	Yield target (t ha^{-1})		
	20 t ha^{-1}	30 t ha^{-1}	40 t ha^{-1}
20	153	254	398
25	140	241	386
30	129	230	374
35	115	216	361
40	103	204	348
45	90	191	336
50	78	179	323
55	65	166	311
60	53	154	298
65	40	141	286
70	28	129	274
80	3		248
85			233
90			221
95			208
100			196

Note: The K requirements for targeted tuber yields depending upon yield potential (Y_{max}) as calculated by QUEFTS. (Y_{max}) was fixed as 50 t ha^{-1}.

Irrespective of different yield potentials, the N, P and K uptake was same until the yield come close to maximum potential yield. Similar observations were found in the studies of Witt et al. (1999) and Pathak et al. (2003). These observations were also reported in other tuber crops such as cassava (Byju et al., 2012) and elephant foot yam (Byju et al., 2016).

At greater yield targets that are closer to yield potential, there was great reduction in the internal efficiency values and similar observations were reported previously in rice (Witt et al. 1999), wheat and maize (Liu et al. 2005), maize (Shehu et al. 2019), cassava (Byju et al. 2012), sweet potato (Kumar et al. 2016) and taro (Jinimol and Byju 2018). The results indicate that maximizing the nutrient efficiencies by balanced NPK application will give more profit to farmers than aiming for greater targets closer to potential yield.

The wider gap between actual and potential yields indicates that further yield increase could be possible only through managing the spatial and temporal variations in soil nutrient supply. The effective fertilizer recommendation should consider crop needs and nutrients already available in the soil (Witt et al., 1999). Several studies showed the existence of large field variability in terms of soil nutrient supply, nutrient use efficiency and crop responses (Wang et al., 2001; Dobermann et al., 2002). The current generalized fertilizer recommendation (Blanket recommendation) which was developed years ago is no longer valid and it fails to account for the variations in crop needs for supplemental nutrients.

Conclusion

Data sets involving yam yield and nutrient uptake were built up for analyzing the relationship between them, and to evaluate the optimal nutrient requirements using the QUEFTS model. Regardless of yield potentials, the model predicted a linear increase in tuber yield if nutrients were taken up in balanced amounts of 4.15 kg N, 0.45 kg P and 3.95 kg K per 1000 kg tuber until the yield reached about 60% of the potential yield. Suggesting an average NPK ratio of 9.2:1:8.8. The N, P and K removal by tuber was also simulated by QUEFTS model for the development of fertilizer recommendation. The NPK fertilizer requirements for different potential yield situations were also calculated. The results need to be validated in major yam growing regions.

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