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Macro and Micro Nutrient Uptake Parameters and Use Efficiency in Cacao Genotypes as Influenced by Levels of Soil Applied K

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Authors' contributions

This work was carried out in collaboration between all authors. Authors YML and ME conducted the experiment, performed statistical analysis and wrote the first draft of the manuscript. Author ZH conducted the nutrient analysis and reviewed the manuscript. Authors DZ, RCS and VB contributed in designing and monitoring the experiment and revising the final manuscript. All authors read and approved the final manuscript.

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ABSTRACT

Aims: To evaluate the effects of soil K levels (deficit to excess) on nutrient uptake parameters (concentration, uptake, influx, transport and use efficiency ratios) of macro and micro nutrients in different cacao (*Theobroma cacao* L.) genotypes.
Methodology: Seedlings of three cacao genotypes (Amelonado, EET-400 and ICS 95) were grown for 90 days in a plant growth chamber with three levels of K (52, 156, and 469 mg K plant^{-1}) in the growth medium. The experiment was a split plot design with genotypes as the main plots and K levels as the subplots with three replications. Nutrient uptake parameters were investigated.
Results: Significant (P<0.01 and 0.05) K effects were observed on the nutrient uptake parameters of various macro and micro nutrients in cacao. Increasing K in the soil significantly increased K

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(P<0.01) and Zn (P<0.05) concentrations and significantly (P<0.01) reduced the P, Ca, Mg, and Mn concentrations in cacao plants. Overall uptake of P, Ca, Mg, Fe, and Mn decreased and uptake of N, K, Cu and Zn increased with increasing soil K levels. Increasing the K levels of the soil significantly at P<0.01 and P<0.05 increased the efficiency ratio (ER) for P, Ca, Mg, Mn and N respectively in cacao. Increasing K levels of the soil significantly (P<0.01 and 0.05) decreased ER for K and Zn respectively in cacao. For all of the soil K levels, Amelonado genotype was most efficient in utilization of absorbed Fe, Mn and Zn, whereas ICS 95 genotype was most efficient in utilization of absorbed N, P, Ca, Mg, B, and Cu.

Conclusion: At varying soil K levels, cacao genotypes used in this study showed significant differences in macro and micro nutrient uptake, nutrient influx and transport and nutrient use efficiency. Soil K levels have significant effects on nutrient uptake parameters of cacao.

Keywords: Cocoa genotypes; nutrient concentrations; nutrient uptake; nutrient influx; nutrient transport; nutrient use efficiency.

1. INTRODUCTION

Cacao (*Theobroma cacao L.*) is an important economic crop producing over 5 million tons of cocoa beans with a value of $10 billion worldwide and provides income for over 5 million smallholder farmers in the tropics [1,2]. Soils under cacao are often depleted and acidic because of long-term cultivation with minimal fertilizer input, loss of nutrients through erosion and leaching, and removal by the harvested crops [3]. Soils under cacao contain average around 156 mg K kg^{-1} soil [3] which is insufficient to support optimal cacao growth and attain high yields. Cacao has a high K requirement due to its growth habit, large pod size and the high K content in the pod husk [3-6].

Potassium is important to cacao and essential to higher plants, assisting with enzyme activation, protein synthesis, photosynthesis, stomatal movement, and phloem transport [7]. Potassium deficiency makes plants more susceptible to adverse environmental conditions like drought and cold [7,8]. At low soil K, a plant re-translocates K from older leaves to newer leaves. However, in response to severe K deficiency plant growth is retarded and re-translocation is prohibited as older leaves become highly chlorotic [7]. Potassium deficiency is associated with many physiological disorders and may result in a nutritional imbalance [9]. To be effectively absorbed and metabolized, potassium should never be allowed to become deficient in high yielding tropical tree crops where risk of soil exhaustion is much greater, as compared to temperate tree crops [10].

A limited number of nutrient studies have been reported with cacao seedlings and older trees [11-15]. Cabala-Rosand et al. [5] found that under field conditions the most common deficiencies in cacao were N, K, Zn, Fe and B. Current fertilizer recommendations for cacao are 100 kg K ha^{-1} yr^{-1} [10]; however due to economic considerations resource-poor farmers may not be able to provide this amount of fertilizer. Ofori-Frimpong et al. [16] identified genotypic variation in the responses of cacao to K fertilization.

Studies related to genotypic response of cacao to varying soil K are very limited. Genotypes with high K use efficiency could reduce K fertilizer inputs and enhance crop yields. Generally, genotypes of cacao from the Amazon region are more nutrient demanding than genotypes that have been traditionally used outside the Amazon, such as Amelonado and un-shaded trees need more plant nutrients than shaded plants [5]. Cacao genotypes with improved K utilization at either deficient or excess soil K levels would be useful in producing superior cultivars with broader genetic diversity. Information is lacking concerning the influence of K levels in plants and their effects on nutrient uptake parameters. Low soil fertility in cacao growing regions is one of the main causes of poor pod yields [17]. To achieve sustainable cacao production and high yields requires appropriate and effective soil fertilization and management practices for various ecosystems where cacao is grown. The objectives of this study were to evaluate the effects of soil K levels (deficit to excess) on nutrient parameters (concentration, uptake, influx, transport) and nutrient use efficiency of macro and micro nutrients in different cacao genotypes.

2. MATERIALS AND METHODS

2.1 Cacao Genotypes and Seedling Preparation

Cacao pods of three genotypes (Amelonado, EET-400 and ICS 95) were received from Dr. Brian Irish, USDA-ARS Tropical Agriculture Research Station, Mayaguez, Puerto Rico. These cacao genotypes differ in their genetic makeup: Amelonado is a traditional type of lower Amazon Forastero from Brazil [18,19], ICS 95 is a Trinitario selection (cross between Forastero and Criollo) from Trinidad and EET-400 is the progeny of a hybrid cross between an Upper Amazon Forastero and an unknown genotype [18-20]. To remove any microbial contamination, seeds were separated from the pods, removed from the seed coats and soaked in 10% commercial bleach for two minutes, rinsed twice in sterile deionized-water, soaked in 90% ethanol for two minutes and rinsed twice in sterile deionized-water. Seeds were allowed to germinate on moist filter paper under laboratory conditions at 25ºC (±2ºC) for 48 hours until radicle emergence.

2.2 Plant Growth Conditions

Seeds with at least two mm radicle were planted in plastic pots (96 oz white polypropylene tub from Container Packing supply, Eagle, Idaho) containing 3 kg of Ottawa sand washed with deionized-water. Plants were grown in a climatically controlled growth chamber (Model GR-48, Environmental Growth Chambers, Chagrin Falls, OH). Light was provided by twenty Very High Output (VHO) fluorescent lamps (GE Part No F96T12/CW-1500) and six 60-watt incandescent lamps in each of two height-adjustable canopies to provide 14 hr day^{-1} of 600 µmol m^{-2} s^{-1} photosynthetic photon flux density (PPFD) at the plant canopy level. The day temperature was 30ºC with 75% RH and the night temperature was 28ºC with 75% RH. CO2 in the chamber was maintained at 400 cm^3 m^{-3}.

2.3 Sand-nutrition Solution Growth Medium

Each container was surface irrigated weekly with 100 ml of 1.5 mM Ca $(NO_3)_2{\cdot}4H_2O$ solution for the first 20 days. Beginning on the 21st day, a modified nutrient solution was used to provide essential nutrients and specific K levels. Macro- and micronutrient concentrations of this solution were: 6.0 N, 1.5 Ca, 1.7 Mg, 1.0 P (mmol L^{-1}) and 110 Fe, 20.6 B, 0.3 Zn, 0.16 Cu, 5.3 Mn and 0.49 Mo (µmol L^{-1}). These nutrients were provided using salts of $Ca(NO_3)_2{\cdot}4H_2O$, $Ca(H_2PO_4)_2{\cdot}H_2O$, $Mg(NO_3)_2{\cdot}6H_2O$, NH_4NO_3, H_3BO_3, $CuSO_4{\cdot}5H_2O$, $MnSO_4{\cdot}H_2O$, $(NH_4)6Mo_7O_{24}{\cdot}4H_2O$, $ZnSO_4{\cdot}7H_2O$, and Fe DTPA (Sprint 330, Becker Underwood, Inc., Ames, IA). From this nutrient solution, three solutions were prepared to achieve the three desired K treatments (to provide 52, 156, 469 mg K $plant^{-1}$ for 90 days growth) and K was applied as K_2SO_4. For all the treatments the solution pH was adjusted to 5.5 before being applied to the sand. Plants were irrigated with 100 ml of nutrient solution on every Monday and rinsed with 500 ml of DI-water on every Friday to reduce salt buildup.

2.4 Determination of Growth and Nutrient Uptake Parameters

An initial plant harvest was conducted from each of the genotypes on the 21st day after planting, just before initiation of the K treatments. Root lengths were determined by Comair Root Length Scanner (Hawker de Haviland, Victoria, Australia). The shoot samples were freeze dried and the dry biomass was recorded and the samples were saved for later analysis of elemental composition.

At 90 days after K treatment initiation, plants were harvested and shoots were washed in de-ionized-water, blotted dry, freeze-dried and the dry biomass was recorded. All dried and harvested shoot samples were ground to pass a 0.55 mm sieve. Chemical analysis of the shoot was conducted by the Indian River Research and Education Center, University of Florida, Fort Pierce, FL. Chemical composition of macro (N, K, Ca, Mg, P) and micro (B, Cu, Fe, Mn, Zn) nutrients were determined by digesting 0.4 g of plant samples in 5 ml of 14 N HNO_3 in an AIM 500 Automatic Digestion System and diluting to 100 ml with deionized-water prior to analysis [21]. Element concentrations in the digested solutions were determined using an Inductively Coupled Plasma Optical Emission Spectrometer (ICPOES, Ultima JY Horiba Inc. Edison, NJ, USA). Total N in the plant samples was analyzed by the combustion method [22] using a CN analyzer (Vario MAX CN Macro Elemental Analyzer; Elementar Analysensysteme GmbH, Hanau, Germany).

Nutrient uptake parameters were determined by the following equations and details of the methods used for determination of plant growth, nutrient uptake and physiological parameters were described earlier [11,23].

Nutrient uptake (U, mg or µg shoot dry biomass^{-1}) = [(Conc.)(Ws_2)],

Where Conc. refers to the elemental concentration in plant (mg g^{-1} for macro and µg g^{-1} for micro nutrients), Ws_2 refers to the shoot biomass (g $plant^{-1}$) at final harvest.

Nutrient influx (IN, pmoles cm^{-1} s^{-1}) = $[(U_2-U_1)/(T_2-T_1)][(\ln Rl_2-\ln Rl_1)/(Rl_2-Rl_1)]$

Where U refers to the elemental content (uptake) in shoot (mmole $plant^{-1}$), T is time in seconds, and Rl is root length (cm $plant^{-1}$). Subscripts 1 and 2 refer to initial and final harvest times.

Nutrient transport (TR, pmole g^{-1} s^{-1}) = $[(U_2-U_1)/(T_2-T_1)][(\ln Ws_2-\ln Ws_1)/(Ws_2-Ws_1)]$

Where Ws refers to shoot biomass (g $plant^{-1}$). Subscripts 1 and 2 refer to initial and final harvest times.

Nutrient efficiency ratio (ER) = [mg of Ws_2/mg macro or µg micro of any given element in shoot]

2.5 Data Analysis

The experimental design was a split plot with genotypes as the main plots and K levels as the subplots. All experimental units were replicated three times. Results were subjected to analysis of variance using the general linear model (GLM) procedures of SAS (Ver. 9.2, SAS Institute, Cary, NC).

3. RESULTS AND DISCUSSION

3.1 Nutrient Concentrations

Exchangeable K in the soil is known to be important for cacao. Sufficient levels of K in soil for cacao were reported to be 0.40-0.55 meq K/100g soil (156 – 215 mg kg^{-1} soil) in Malaysia [24]. In Ghana, deficient levels of soil K were 0.2 meq K/100 g for cacao [25]. Soil K levels in the cacao growing region of Bahia varied from 0.14 to 0.2 meq K/100 g soil [5]. Our K treatment levels (52, 156, 469 mg K $plant^{-1}$) were equivalent to 0.04, 0.13, and 0.40 meq/100 g soil, respectively, so the soil K levels in the current study ranged from deficient to excess; however the highest level of soil K in the current study matches the highest soil K levels reported (>0.3 meq K/100 g) for South American soils [26]. The levels of K in the growth medium had significant ($P<0.05$) effects on concentrations of N, Cu, Fe, and Zn and had highly significant ($P< 0.01$) effects on concentrations of P, K, Ca, Mg, and Mn in cacao shoots (Table 1). With the exception of K and Zn, the concentrations of all the macro- and micro-nutrients in the shoots decreased as the K levels increased. No published findings exist in the literature relating to the effects of soil K levels on the concentrations of macro and micro nutrients in cacao. However, the effect of soil K on macro and micro nutrient concentrations in other crops is well documented [8,27-29]. Interactions between K and Mg were previously observed in coffee where a Mg/K ratio in the soil of 3 was optimal, but a Mg/K ratio >16 produced K deficiency symptoms in the plants [27]. The Mg/K ratios of growth medium in the present study were 0.75, 2.3, and 6.8 at the 56, 156, 469 mg K $plant^{-1}$ levels, respectively. Fageria [28] extensively covered the antagonistic interactions between K and Mg and Ca due to physiological properties of these ions in several plant species.

Concentrations of nutrients in the leaves are considered better indicators of plant nutrition status, as compared to soil test values [7,29,30]. Overall, K concentrations in the shoots of all three cacao genotypes were 3.5, 9.1 and 18.1 mg kg^{-1} at 56, 156, 469 mg K $plant^{-1}$ levels, respectively (Table 1). From the published findings [5,31-34] for cacao grown in different ecological regions, nutrient concentrations in cacao have been grouped from marginal (low, deficient), adequate (sufficient, normal) and excess (high). Using such classifications of nutrient concentrations, shoot K concentrations observed in the current study ranged from deficient (10-13 mg kg^{-1}) to adequate (18.5 to >20 mg kg^{-1}). Most of the other plant nutrient concentrations in Table 1 were in the adequate (sufficient) to normal range, however concentrations of N, Mg and Mn were in the marginal (low) to sufficient range [5,31-34]. In all the genotypes, with the exception of N, K, and Zn concentrations, overall concentrations of other essential nutrients were reduced by increasing K levels of the growth medium from 56 to 469 mg K $plant^{-1}$ (Table 1). To date no previous studies have assessed such nutrient concentration relationships in cacao or cacao genotypes at varying soil K levels.

Table 1. Effect of soil K levels on shoot concentrations of macro and micronutrients in cacao genotypes

Genotype	K level (mg plant^{-1})	N	P	K	Ca	Mg	B	Cu	Fe	Mn	Zn
		---------------mg g^{-1}---------------					-----------------------µg g^{-1}----------------------				
Amelonado	52	14.6	1.54	3.39	8.25	4.35	140.3	10.24	85.0	18.80	14.81
	156	13.9	1.55	8.76	6.88	3.15	116.8	7.27	51.7	14.14	13.78
	469	15.2	1.26	18.43	4.81	2.11	124.1	10.29	70.9	12.70	18.92
EET-400	52	15.6	1.97	4.15	10.79	4.85	135.7	11.29	99.2	21.51	16.27
	156	13.4	1.54	9.89	7.59	3.29	127.8	8.48	109.8	19.82	15.29
	469	14.0	1.23	18.27	5.60	2.25	119.8	9.65	108.9	15.61	18.61
ICS 95	52	14.0	1.73	2.92	9.23	4.46	136.3	8.59	126.1	20.90	15.04
	156	12.9	1.52	8.51	6.69	3.12	122.6	6.38	68.0	16.87	13.92
	469	13.2	0.96	17.54	4.22	1.83	123.1	9.28	95.1	14.93	26.03
Significance											
Genotype (G)		NS	NS	NS	**	NS	NS	NS	**	**	NS
K level (K)		*	**	**	**	**	NS	*	*	**	*
G * K		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
LSD $_{0.05}$		2.9	0.58	3.61	2.59	0.81	40.6	6.48	51.9	5.52	13.60

, significant at P ≤ 0.05 or 0.01, respectively. NS = Not significant*

Depending on the levels of soil K different relationships were observed between shoot concentrations of various macro and micro nutrients (Table 2). At soil K of 52 mg K plant^{-1} (deficit) positive significant (P<0.05) relationships were observed between shoot concentrations of N and concentrations of Ca, Cu and Zn; concentrations of K and Mg, P and Cu; concentrations of Mg and Zn; concentrations of Cu and Mn, and concentrations of Mn and Zn (Table 2). However, highly significant (P<0.01) positive relationships were observed between concentrations of Ca and Mg and P; and concentration of Cu and Zn. At soil K of 469 mg K plant^{-1} (excess) significant (P<0.05) positive relationships were observed between concentrations of N and K, and negative relationships between concentrations of Ca and Cu. However highly significant (P<0.01) positive relationships were observed between concentrations of K and Cu, concentrations of Ca and Mg, and concentrations of Mg and P; and highly significant (P<0.01) negative relationships between concentration of Ca and Zn. To date no previous studies have assessed relationships between concentrations of macro (N, P, K, Ca, Mg) and micronutrients (B, Cu, Fe, Mn) at varying levels of soil K and therefore it was not possible to draw any conclusion on the effect of K concentrations in shoot on the level of other nutrients.

3.2 Nutrient Uptake (U)

Uptake (U) gives an indication of the amount of nutrient accumulated in the plant. Uptake of any element is the product of concentration x dry-matter of shoot. Fig. 1 shows the influence of K levels on shoot and root growth of three cacao genotypes. In all the genotypes, increasing K had highly significant (P<0.01) effects on the uptake of P, K, Ca, Mg, and Mn (Table 3). Overall, in all three genotypes increasing K supply decreased the uptake of P, Ca, Mg, Fe, and Mn in the shoots, while the uptake of N, K, Cu and Zn in the shoots increased. There are no published evidences in the literature showing the positive or negative effects of K supply on the uptake of macro or micronutrients in cacao. Antagonistic interactions between K levels in plants and the uptake of Mg^{2+} and Ca^{2+} have been reported in other crops [9,35-37]. Low levels of K in other crops favor the uptake of Mg^{2+} and Ca^{2+} [38] and K also regulates the uptake of Cu, Fe, Mn, Zn in plants depending on the conditions [9]. Positive interactions of K with uptake of N, P, Fe and Cu and the negative effects of K on uptake of Ca, Mg, B in other crops has been documented [28].

Genotype had a significant effect at P<0.01 and P<0.05 on the uptake of Fe and Mn, respectively (Table 3). However, uptake of Fe and Mn by the Amelonado genotype was lower relative to other two genotypes, possibly indicating less demand for these nutrients. Rengel and Damon [39] reported genotypic differences in K uptake for many important crops, but our study did not identify significant genotypic differences in K uptake. Cabala-Rosand et al. [5] suggested that Amazon varieties require more nutrients than Amelonado varieties. In our study the ICS 95 Trinitario type had the greatest nutrient uptake. Overall, Amelonado, which is a typical lower Amazon Forastero selection, had the lowest nutrient uptake. EET-400 displayed moderate nutrient uptake. Understanding of nutrient demand by any given genotype will assist in designing fertilizer management practices for higher economic yields.

3.3 Nutrient Influx (IN)

Determination of nutrient influx (IN) provides an indication of the ability of the roots to absorb minerals from the soil. Increasing the K application rate significantly (P<0.01 and 0.05) increased the IN for K, Zn, N, Cu and Fe respectively and decreased significantly (P<0.01) the IN of Ca and Mg, regardless of genotype (Table 4). Even though K levels had no significant effects on IN of B, higher K increased the IN of B in all genotypes tested. The IN of N, P, K, Ca, Mg, B, Cu, Fe, and Mn differed significantly (P<0.01 and P<0.05) among genotypes, with ICS 95 having lower IN for all the essential elements than the other two genotypes. There are no publication exists in literature relating to the effects of K on IN of macro and micro nutrients in cacao and its genotypes.

3.4 Nutrient Transport (TR)

Transport (TR) indicates the ability of plants to translocate nutrients from the roots to the shoots. Genotypes that have higher capacity to translocate root absorbed nutrients to the shoot could increase nutrient levels in shoot to adequate to sufficiency level thereby prevent nutrient deficiency in crops grown in low fertility soils. In all the genotypes, increasing K application rate significantly (P<0.01 and 0.05) increased for TR of K and Zn respectively. However, increasing applied K levels significantly decreased (P<0.1 and 0.05) the TR of P, Ca, Mg, Mn, and Fe respectively (Table 5). Genotype significantly at P<0.1 and P<0.05 affected the TR of Ca, Cu, Fe, Mn and N, P, K, Mg respectively. Among the three genotypes, ICS 95 had the lowest TR for N, P, K, Mg and Cu, whereas Amelonado had the lowest TR for Ca, Fe and Mn. There are no known publication exist in literature reporting the cacao genotypic or K levels effects of TR of macro and micro nutrients in cacao.

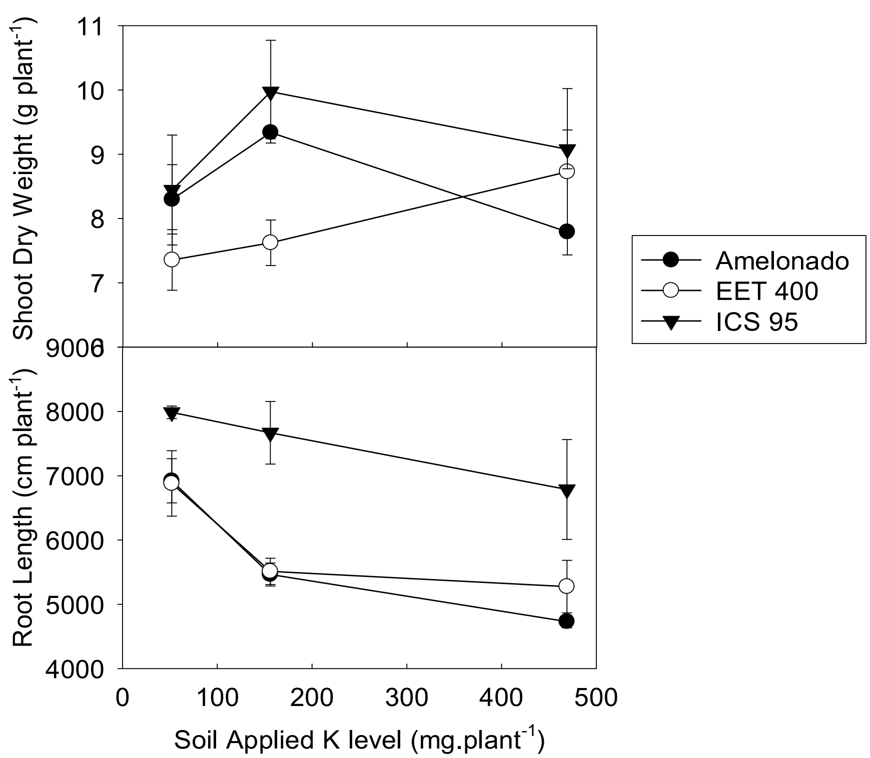

Fig. 1. Shoot growth (g dry matter plant^{-1}) and root length (cm plant^{-1}) of cacao genotypes influenced by soil K levels

Table 2. Pearson's correlations of concentrations of macro and micronutrients in cacao shoots influenced by soil K levels (52, 156, 469 mg K plant^{-1})

	N	K	Ca	Mg	P	B	Cu	Fe	Mn
52 mg K plant^{-1}									
K	0.66NS								
Ca	0.77*	0.64NS							
Mg	0.84**	0.77*	0.91**						
P	0.66NS	0.71*	0.86**	0.90**					
B	-0.51NS	0.10NS	-0.39NS	-0.31NS	-0.26NS				
Cu	0.75*	0.79*	0.58NS	0.79**	0.52NS	-0.01NS			
Fe	-0.46NS	-0.30NS	0.02NS	-0.08NS	0.01NS	0.26NS	-0.22NS		
Mn	0.50NS	0.36NS	0.65NS	0.62NS	0.38NS	-0.16NS	0.68*	0.29NS	
Zn	0.77*	0.58NS	0.56NS	0.70*	0.49NS	-0.34NS	0.82**	-0.19NS	0.73*
156 mg K plant^{-1}									
	N	**K**	**Ca**	**Mg**	**P**	**B**	**Cu**	**Fe**	**Mn**
K	0.33NS								
Ca	0.36NS	0.37NS							
Mg	0.36NS	0.63NS	0.57NS						
P	0.33NS	0.64NS	-0.21NS	0.47NS					
B	-0.20NS	0.19NS	0.03NS	-0.16NS	0.24NS				
Cu	0.54NS	0.72*	0.49NS	0.32NS	0.32NS	0.18NS			
Fe	-0.06NS	0.72*	0.56NS	0.32NS	0.09NS	0.33NS	0.75*		
Mn	-0.15NS	0.74*	0.57NS	0.60NS	0.20NS	0.19NS	0.54NS	0.88**	
Zn	0.10NS	-0.04NS	0.44NS	-0.31NS	-0.30NS	0.50NS	0.27NS	0.30NS	0.09NS
469 mg K plant^{-1}									
	N	**K**	**Ca**	**Mg**	**P**	**B**	**Cu**	**Fe**	**Mn**
K	0.74*								
Ca	-0.16NS	-0.48NS							
Mg	0.30NS	0.05NS	0.81**						
P	0.28NS	-0.11NS	0.79*	0.90**					
B	-0.28NS	-0.62NS	0.09NS	-0.31NS	-0.19NS				
Cu	0.65NS	0.86**	-0.69*	-0.25NS	-0.40NS	-0.46NS			
Fe	-0.32NS	0.06NS	-0.02NS	-0.10NS	-0.40NS	-0.18NS	0.19NS		
Mn	-0.61NS	-0.53NS	0.52NS	0.24NS	0.10NS	0.24NS	-0.57NS	0.58NS	
Zn	0.09NS	0.58NS	-0.85**	-0.52NS	-0.58NS	-0.38NS	0.62NS	0.10NS	-0.28NS

**, ** Significant at 0.05 and 0.01 levels of probability; respectively. NS = Not significant*

Table 3. Soil K levels on shoot uptake of macro and micronutrients in cacao genotypes

Genotype	K level (mg plant^{-1})	N	P	K	Ca	Mg	B	Cu	Fe	Mn	Zn
		--------------mg plant^{-1}--------------					---------------------μg plant^{-1}------------------				
Amelonado	52	120.8	12.7	28.0	68.1	36.0	1165	85.1	694.6	156.8	123.8
	156	129.8	14.5	81.8	64.2	29.4	1089	67.8	483.1	132.1	128.6
	469	118.5	9.8	143.6	37.5	16.5	967	80.2	552.6	99.0	147.5
EET-400	52	114.3	14.3	30.2	78.9	35.4	1001	80.7	733.7	156.9	118.0
	156	102.2	11.8	75.3	57.7	25.0	979	64.2	832.2	150.3	116.9
	469	121.7	10.8	158.9	50.1	19.9	1042	83.4	947.5	136.2	154.7
ICS 95	52	118.2	14.7	24.7	77.5	37.6	1145	71.1	1044.5	173.8	127.2
	156	128.1	14.9	84.0	67.0	31.1	1214	62.9	670.4	167.0	139.3
	469	120.1	8.7	159.0	38.4	16.6	1119	84.0	868.4	135.7	234.0
Significance											
Genotype (G)		NS	NS	NS	NS	NS	NS	NS	**	*	NS
K level (K)		NS	**	**	**	**	NS	NS	NS	**	*
G * K		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
$LSD_{0.05}$		45.8	5.9	46.8	28.6	10.3	496	44.8	455.0	53.8	108.4

**, ** Significant at 0.05 and 0.01 levels of probability; respectively. NS = Not significant*

Table 4. Soil K levels on influx (IN) of macro and micronutrients in cacao genotypes

Genotype	K level (mg $plant^{-1}$)	N	P	K	Ca	Mg	B	Cu	Fe	Mn	Zn
		-----pmol (cm root)$^{-1}$ sec^{-1}----					----pmol (cm root)$^{-1}$ sec^{-1} (* 10^3)----				
Amelonado	52	0.53	0.023	0.039	0.107	0.092	6.626	0.075	0.770	0.176	0.104
	156	0.67	0.032	0.150	0.120	0.089	7.351	0.068	0.622	0.175	0.127
	469	0.63	0.023	0.299	0.077	0.054	7.216	0.092	0.795	0.143	0.166
EET-400	52	0.50	0.027	0.045	0.125	0.091	5.696	0.077	0.811	0.177	0.103
	156	0.53	0.026	0.139	0.107	0.075	6.623	0.070	1.094	0.198	0.119
	469	0.63	0.024	0.306	0.095	0.061	7.240	0.094	1.270	0.183	0.166
ICS 95	52	0.40	0.022	0.027	0.099	0.078	5.313	0.040	0.947	0.155	0.088
	156	0.47	0.023	0.109	0.088	0.066	5.811	0.034	0.622	0.153	0.099
	469	0.50	0.014	0.235	0.056	0.039	5.868	0.057	0.877	0.134	0.200
Significance											
Genotype (G)		**	*	*	**	**	*	**	**	**	NS
K level (K)		*	*	**	**	**	NS	*	*	NS	**
G * K		NS	NS	NS	NS	NS	NS	NS	*	NS	NS
LSD $_{0.05}$		0.21	0.013	0.089	0.047	0.027	2.942	0.052	0.458	0.064	0.120

**, ** Significant at 0.05 and 0.01 levels of probability, respectively. NS = Not significant*

Table 5. Soil K levels on transport (TR) of macro and micronutrients in cacao genotypes

Genotype	K level (mg $plant^{-1}$)	N	P	K	Ca	Mg	B	Cu	Fe	Mn	Zn
		------------------------pmol (g dry shoot)$^{-1}$ sec^{-1}--------------------------									
Amelonado	52	464.4	20.0	33.3	91.9	78.9	5.67	0.064	0.660	0.149	0.087
	156	457.2	21.1	98.8	79.1	58.7	4.85	0.045	0.410	0.115	0.084
	469	477.4	15.6	202.9	52.6	36.9	4.91	0.063	0.540	0.097	0.113
EET-400	52	504.3	26.7	44.0	121.6	89.1	5.56	0.075	0.791	0.173	0.100
	156	437.7	20.9	112.1	86.3	60.9	5.29	0.056	0.883	0.161	0.096
	469	468.4	16.9	216.8	65.8	42.7	5.09	0.067	0.903	0.130	0.122
ICS 95	52	440.5	22.1	26.8	101.3	79.6	5.41	0.041	0.976	0.159	0.089
	156	422.7	20.2	94.9	76.8	57.9	5.09	0.030	0.544	0.134	0.087
	469	425.1	11.5	196.9	47.1	32.6	4.99	0.048	0.753	0.115	0.167
Significance											
Genotype (G)		*	*	*	**	*	NS	**	**	**	NS
K level (K)		NS	**	**	**	**	NS	NS	*	**	*
G * K		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
LSD $_{0.05}$		92.9	8.3	41.5	28.8	14.2	1.74	0.043	0.403	0.041	0.089

**, ** Significant at 0.05 and 0.01 levels of probability; respectively. NS = Not significant*

3.5 Nutrient Efficiency Ratios (ER)

Efficiency Ratios (ER) are useful for assessing the ability of plants to use absorbed nutrients. The ER of essential nutrients differs widely between crop species and among cultivars within a species [30]. In addition, genotypes or cultivars within a species can be rated as Efficient or Inefficient at utilizing absorbed nutrients [23,30]. This is important because plants with high ER values (Efficient) for essential nutrients might grow well and produce higher yields on infertile soils [11,23,30].

Increasing the K levels of the soil significantly at $P<0.01$ and $P<0.05$ increased the ER for P, Ca, Mg, Mn and N respectively in cacao (Table 6). Increasing K levels of the soil significantly at $P<0.01$ and $P<0.05$ decreased ER for K and Zn respectively in cacao. The ER for K of cacao at the lower K level compares favorably with tomato and is higher than some other crops [30].

Genotype significantly at $P<0.01$ and $P<0.05$ affected the ER for K, Fe, Mn and N respectively. ICS 95 was most efficient in the utilization of absorbed N, Ca, Mg, P, B, and Cu, while Amelonado was more efficient in the utilization of absorbed Fe, Mn and Zn at all K levels. High ER for most of the essential nutrients of these cacao genotypes makes them very effective in utilization of absorbed nutrients in low fertility soils. The lower values of ER for EET-400 suggest that it is less efficient in utilizing absorbed nutrients relative to the other two genotypes.

Table 6. Soil K levels on macro and micronutrients use (ER) efficiency ratios in cacao genotype

Genotype	K level (mg plant^{-1})	N	P	K	Ca	Mg	B	Cu	Fe	Mn	Zn
		----mg shoot / mg element in shoot----					mg shoot / mg element in shoot) (* 10^4)				
Amelonado	52	68.7	659.2	295.5	121.7	230.3	0.72	9.78	1.23	5.35	6.87
	156	72.0	647.5	114.2	145.5	317.4	0.87	13.91	1.96	7.07	7.38
	469	65.9	842.1	54.9	229.7	478.3	0.81	10.26	1.45	8.05	5.86
EET-400	52	64.6	515.1	247.1	93.4	208.2	0.74	10.01	1.01	4.70	6.40
	156	74.5	648.1	101.2	132.1	304.8	0.79	12.07	0.93	5.08	6.58
	469	71.8	820.8	54.9	181.3	448.8	0.84	10.48	0.93	6.43	5.78
ICS 95	52	72.3	580.7	344.2	109.5	224.8	0.75	11.89	0.82	4.84	6.67
	156	77.7	669.2	118.8	149.9	320.6	0.82	15.86	1.49	5.95	7.61
	469	75.7	1060.2	57.6	238.8	548.2	0.81	10.81	1.08	6.74	4.05
Significance											
Genotype (G)		*	NS	**	NS	NS	NS	NS	**	**	NS
K level (K)		*	**	**	**	**	NS	**	**	**	*
G * K		NS	NS	**	NS	NS	NS	NS	*	NS	NS
LSD $_{0.05}$		13.8	345.4	56.2	101.6	100.7	0.24	6.07	0.59	2.01	4.19

**, ** Significant at 0.05 and 0.01 levels of probability; respectively. NS = Not significant*

Inter and intra specific variations in ER in many crop species have been reported [23,28,30]. Intra specific differences in ER of cacao have been reported [11,12,14] Mineral nutrient use efficiencies are known to be under genetic and physiological control and can be modified by plant interactions with environmental variables [30,40-42].

4. CONCLUSION

Cacao (*Theobroma cacao* L.) is an important economic crop for many tropical countries. Adequate levels of soil K are essential for good growth and achieving high cocoa bean yields. Soils under cacao invariably have low levels of plant available K to support good cacao growth.

Significant effects of K were found in the concentration, uptake, transport, influx and efficiency ratios of macro and micro nutrients in cacao. Increasing K in the soil significantly increased the K and Zn concentrations and reduced the P, Ca, Mg, and Mn concentrations in cacao plants. Concentrations of K had significant negative correlations with shoot concentrations of Ca, Mg, P, B, and Mn. Overall uptake of P, Ca, Mg, Fe, and Mn decreased and uptake N, K, Cu and Zn increased with increasing soil K levels. Significant increases in efficiency ratios for N, P, Ca, Mg, B and Mn, and decreases in efficiency ratios for K and Zn were observed with increasing soil K levels. Overall soil K levels, cacao genotype Amelonado was more efficient in utilization of absorbed Fe, Mn and Zn and ICS 95 genotype was most efficient in utilization of absorbed N, P, Ca, Mg, B and Cu relative to the other genotypes. The three cacao genotypes used in this study had similar responses of growth and nutrient uptake parameters to varying growth medium K levels. Understanding of K nutrition and its use efficiency could be useful in the development of suitable fertilizer management practices and further assist in breeding of cacao varieties efficient in utilization of soil K in environments with a limited supply of available K.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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