Research article

Variation in mineral element composition of landrace taro (*Colocasia esculenta*) corms grown under dryland farming system in South Africa

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ABSTRACT

Taro [*Colocasia esculenta* (L.) Schott] has the potential to address food and nutrition insecurity in sub-Saharan Africa. However, the nutrient content of taro is yet to be fully elucidated. The objective of this study was to evaluate mineral element content as a proxy for nutritional value of different taro genotypes. The study evaluated 14 taro accessions at Roodeplaat and Umbumbulu in South Africa based on their calcium (Ca), iron (Fe), potassium (K), magnesium (Mg), manganese (Mn), sodium (Na), phosphorous (P) and zinc (Zn) content. The accessions were planted in a randomized complete block design, replicated three times under field conditions. The mineral element content varied significantly (p < 0.05) among the genotypes. Genotypes Amad7-2, Umbu8 and Amad101 exhibited high Ca ($\geq$432 mg kg^{-1}), Fe ($\geq$32 mg kg^{-1}) and Mg ($\geq$229 mg kg^{-1}) across the locations. The first principal component (PC) accounted for 33.7% of the variation and was strongly associated with Zn (r = 0.94, p < 0.001) and P (r = 0.89, p < 0.001). The second PC explained 29.7% of the variation and was associated with Na (r = 0.83, p < 0.001), Mg (r = 0.76, p < 0.001) and K (r = 0.55, p < 0.05). Fe and Mn contributed below the 12.5% threshold to the PCs and were considered as less discriminatory among the accessions. The negative correlations among some of the mineral elements would be a challenge for selection and breeding of nutritious taro accessions. This information is essential to select superior local accessions based on their mineral element content for developing breeding populations and lines for improving nutrition quality among poor households in sub-Saharan Africa.

1. Introduction

Taro is an important root crop in the family *Araceae* (Kreike et al., 2004). The crop ranks among the most important root and tuber crops in terms of production after potato, cassava, sweet potato and yam (FAO, 2018a, b). The worldwide production of taro was estimated to be 10 639 850 metric tonnes on 1 660 170 ha (FAO, 2018a, b). It supplements cereal-based diets in Africa, Asia, Central America and the Pacific islands (Sharma et al., 2008). Its importance is underpinned by its relatively high productivity under resource-limited agro-systems such as those found in sub-Saharan Africa, where it is grown for its corms that are rich in carbohydrates, protein, minerals and vitamins (Sharma et al., 2008). The crop is particularly important in the poor regions of the world where malnutrition and hidden hunger are prevalent. Taro contains thiamin, riboflavin, iron, phosphorus, zinc potassium, copper, manganese and vitamins (Huang et al., 2007; Soudy et al., 2010), which boost the immune system and help human body to resist disease. Despite the importance and potential of taro to address nutrient deficiencies, most evaluation studies of taro were centered on agronomic traits such as maturity, height and yield. The South African Agricultural Research

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Council (ARC) evaluated different taro accessions grown by resource poor farmers in South Africa for growth and agronomic performance, and identified accessions that have genetic potential (Gerrano et al., 2019) to be included in the taro nutritional breeding programme (Figure 1 A and B). In order to achieve a need-driven breeding programme of taro that enhances food and nutritional security, due considerations must be given to the crop nutritional attributes including its macro- and micronutrient content.

Very little research has been carried out on genetic variation, genotype-environment interaction and genotype-trait association for mineral element content as a proxy for taro improvement programme in sub-Saharan Africa. As with most under-utilized crops, taro improvement is lagging compared to cereals such as maize and wheat. Understanding variability in mineral element content of taro will improve knowledge and contribute towards its improvement and addressing hidden hunger among vulnerable communities.

The widespread underutilization of taro is premised on lack of knowledge of its utilization and nutritive content. Assessing genetic variation in its mineral nutrient content will improve its utilization in nutritional breeding programs to enhance food security. One approach to establish the nutritional value of taro accessions is to conduct multi-environment trials to assess the effect of genotype × environment interaction (GEI) on nutrient content. Mineral element content varies with genotype, and the impact of environment has been recorded through its effect on soil nutrient accumulation, biosynthesis of assimilates and water potential, which affect the ultimate concentration of mineral elements in plant tissues (Mwenye et al., 2011; Alcantara et al., 2013). For instance, water deficit is known to foster high accumulation of carbon (C) compounds in the below ground parts (Poorter et al., 2012). Thus, drought could increase carbohydrate content of taro corms. However, drought will significantly reduce corm yield leading to food shortages. It is imperative to conduct multivariate studies to investigate the influence of genotype-environment on mineral element accumulation and the interrelationships among the test genotypes and variables, to improve selection strategies in taro improvement for food and nutritional security. Multivariate analysis provides a holistic approach for identifying genotypes with high performance in multiple traits for multiple trait selection. Application of multivariate analysis is common in crop science because it is robust in detecting variation in data set that may otherwise not be detectable by conventional univariate tools (Flores et al., 1998). This study evaluated mineral element composition of landrace taro genetic resources grown in dryland farming system in different agro-ecological conditions in South Africa.

2. Materials and methods

2.1. Plant material and site description

Fourteen accessions of taro (Table 1) were selected from the previous study for yield, and yield related as well as growth traits (Gerrano et al., 2019). The accessions were diverse in their original sources, which included accessions collected from rural areas of KwaZulu-Natal Province in South Africa and introductions from other origin. The accessions were planted at two sites, ARC-Roodeplaat and Umbumbulu. The ARC-Roodeplaat research farm (25°59″ S, 28°35″ E, 1168 m alt) is located in Gauteng Province, while Umbumbulu (29°59″ S, 30°42″ E, 548 m alt) is in KwaZulu-Natal Province. Roodeplaat has a semi-arid cool climate and 400–750 mm annual rain fall. The mean minimum and maximum temperatures for the area are 14 °C and 30.31 °C, respectively (Shegro et al., 2013). The site is dominated by clay soil. Umbumbulu receives between 800 and 1200 mm of rain per year and has a mean temperature of 20 °C (Chimonyo et al., 2016), which are favorable conditions for taro production. The experiments at each site were planted in the summer cropping season of 2016.

2.2. Planting

The land was ploughed to 30 cm depth and prepared with a disc prior to planting. The experimental layout was a randomized complete block design with three replications at each site under field conditions. Each genotype was planted on 9 m^2 plot consisting of three 3 m rows at a population density of 16,667 plants per hectare. Five plants were planted per row at 30 cm constant intervals. The plots were separated by 1.5 m paths to minimize interference for field evaluation (Gerrano et al., 2019). The middle rows and middle three plants (eliminating border effects) were harvested for sampling of corms for nutritional analysis. Irrigation and weeding were carried out as necessary. The crops at both sites were not fertilized. The crops were grown to full maturity before harvesting (Figure 1 A). The harvested corms were washed, peeled to remove the skin and cortex, and sliced into small chips. The chips were freeze-dried and used for mineral element analysis.

2.3. Mineral element analysis

The analysis involved three replicates of freeze-dried taro genotypes corms. The dried chips were ground into a fine powder using a combination of an electric blender and mortar and pestle. The 5 g fine powders from each accession were digested in a microwave using the procedure described by Kristl et al. (2002). After digestion, the samples were prepared in solution and then diluted to 25 mL with distilled water. Similarly, blank solutions were prepared for comparisons. The Ca, Mg, and Zn concentrations were determined by flame atomic absorption spectrometry (AAS). The flame atomic emission spectrometry (AES) was used for K concentration, while Fe and Mn were determined by electrothermal atomic absorption spectrometry (ETAAS). P was determined by a vanadate–molybdate method. Each taro genotype harvested from the field was analyzed for each mineral element content, which was expressed in mg kg^{-1}.
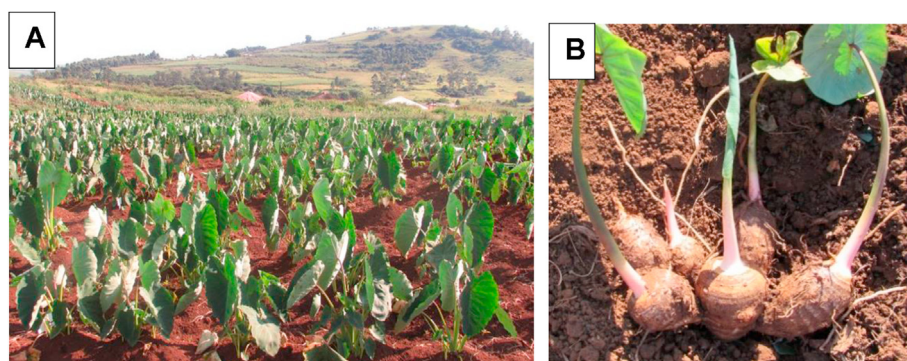

Figure 1. Taro planted at the farmer's experimental field (A) and the cormels (B).

Table 1. Taro accessions collected from different sources in South Africa.

Accession	Source
3053/5118	KZN
Aamd2053	KZN
Amad101	Malaysia
Amad2914	KZN
Amad2919	KZN
Amad3053	KZN
Amad47	KZN
Amad56	KZN
Amad6_8	KZN
Amad7_2	KZN
Umbu5	KZN
Umbu7	KZN
Umbu8	KZN
Umbu9	KZN

KZN = KwaZulu Natal.

2.4. Data analyses

The data were subjected to Analysis of Variance (ANOVA) and means separated by the Fisher's Least Significant Difference (LSD) in R software using the "nlm" and "lm" packages. Subsequently, the Pearson Correlation, Principal Component and Hierarchical Analyses were conducted to deduce trait and genotype associations. A combination of R packages including FactoMineR, factoextra, devtools, ggpubr, tidyverse and cluster were used for data manipulation and constructing univariate and multivariate graphs. All the statistical tests were performed at 5% level of significance using R (R CoreTeam, 2019). Mean values, standard errors, minimums, maximums and coefficients of variation were computed for each mineral element.

3. Results

3.1. Variation and genotypic mean performance

The mineral element concentration among the accessions varied widely (Table 2). The mean values for Ca and K content were 358.6 mg kg^{-1} and 1451.0 mg kg^{-1}, respectively. Zinc and Mn had means of 6.9 mg kg^{-1} and 3.9 mg kg^{-1}, respectively, with Zn showing wider variation from 1.5 to 21.6 mg kg^{-1} compared to 1.3–7.3 mg kg^{-1} exhibited by Mn. Fe is one of the trace elements that are important in proper functioning of the body. The concentration of Fe in this study also varied from 21.6 to 45.4 mg kg^{-1}. The accessions exhibited significant differences in mineral nutrient content and there were differential responses in mineral element content to environmental conditions (Table 3). There was a significant interaction effect between genotype and environment (G x E) on all the mineral elements evaluated (Table 3). Total coefficient of variation in

mineral nutrient content was moderate ranging between 10 and 20% for all mineral nutrients (Table 3). Table 4 shows the mean values of the accessions for each mineral element at each site and their ranking. Genotype Umbu9 accumulated the highest Ca in Roodeplaat but was ranked outside of the top 10 genotypes with the highest Ca concentration in Umbumbulu. Umbu9 was ranked fifth after Amad7_2, Umbu8, Amad101 and Amad6_8 in terms of Ca content across the two sites. Overall, genotypes Amad7_2, Umbu8 and Amad6_8 were consistently ranked high among the top ten genotypes for all the mineral elements.

3.2. Bivariate correlations of mineral element variables

The traits exhibited variable bivariate associations from moderate to strong amongst each other (Table 5). At Umbumbulu, significant correlations were found between Ca and Mg (r = 0.73; p < 0.001) and between Na and P (r = 0.57; p < 0.043) (Table 5, *italicized*). At Roodeplaat, the Zn and Mn exhibited the strongest correlation (r = 0.80; p < 0.001), while Fe and P (r = 0.59, p < 0.025) and Na and K (r = 0.56, p < 0.014) were moderately correlated (Table 5, *unitalicised*). The strongest correlations were observed between K and P (r = 0.89, p < 0.001), as well as Ca and P (r = -0.71, p < 0.001) across the two locations. Ca also exhibited a negative correlation with K (r = -0.67, p < 0.001) and Zn (r = -0.30, p < 0.01). Other significant negative correlations existed among Fe, K and Mg and P.

3.3. Multivariate analysis

The first three principal components (PC) were significant and accounted for 69.28% of the variation among taro accessions evaluated at Umbumbulu (Table 6). The elements Ca, Na and Mg contributed above 15.50% each to the variation explained by the first PC (PC1). The other traits, except Mn, had below 10.15% contribution each to PC1. Elements Fe, Zn and Mn had more than 20.95% contribution each to the second PC (PC2) at Umbumbulu. The third PC (PC3) was dominated by contributions from Mg, Ca, Na and Zn, which contributed 26.05, 19.65, 15.50 and 14.97%, respectively. In comparison, only the first two PCs were significant at Roodeplaat and accounted for a total of 66.35% (Table 6). The first PC explained 34.84% of the variation and was largely associated with P, K and Fe, which contributed 22.55, 21.52 and 18.94%, respectively. The highest contributions to PC2 were from Zn, Mn and Na concentrations with 21.10%, 21.05%, and 20.94%, respectively. Overall, 76.72% of the variation in mineral nutrient content among the accessions was explained by the first three principal components (PC) with Eigen values of more than a unit (Table 6). The first PC accounted for 33.72%, while the second explained 63.41%. Among the mineral nutrient variables, Zn and P were the highest contributors to PC1 with each contributing 32.70% and 29.15% of the variation to the first PC, respectively, while the other mineral elements contributed less than 10% each. To the second PC, Na, Mg and Ca contributed 29.61, 28.86 and 24.61%, respectively. K contributed 12.81% to PC2. Furthermore,

Table 2. Summary statistics of mineral elements measured in 14 taro accessions.

Statistic	Ca	Fe	K	Mg	Mn	Na	P	Zn
	mg kg^{-1}							
Minimum	285.0	21.6	1080.0	199.0	1.3	86.9	218.6	1.5
1st Quartile	314.3	28.2	1334.0	228.7	1.9	106.1	281.8	2.7
Median	351.6	31.6	1454.0	239.9	3.9	127.3	318.1	5.1
Mean	358.6	32.5	1451.0	245.7	3.9	132.1	314.0	6.9
3rd Quartile	402.7	36.1	1615.0	253.4	5.4	156.9	342.7	8.1
Maximum	462.7	45.4	1761.0	320.2	7.3	206.0	424.7	21.6

Ca = calcium, Fe = iron, K = potassium, Mg = magnesium, Mn = manganese, Na = sodium, P = phosphorous, Zn = zinc; mg = milligram; mg kg^{-1} = milligram per kilogram.

Table 3. Mean squares and significance tests for 14 taro accessions evaluated across locations.

Source of variation	d.f.	Ca	Fe	K	Mg	Mn	Na	P	Zn
Block in E	4	4897	4	19551	842	1.8	1326	2215	1.1
Environment (E)	1	1097022**	5120.86**	34120226***	35052**	32***	5188***	25861098***	347***
Genotype (G)	13	21167***	255**	236267***	5371***	28***	7463***	15867***	143***
G × E	13	29468**	321.14***	310839***	2578**	40***	6212***	14321***	173****
Residual	54	2133	18	20746	965	0.5	672	1738	0.5
LSD		5.8	5.8	167.8	43.04	1.0	35.92	57.76	1.01
CV%		12.8	12.8	10.0	12.5	19.1	19.6	13.2	12.2
SE		45.9	4.2	145.0	30.7	0.8	25.9	41.5	0.8

E = Environment, d.f. = degree of freedom; Ca = calcium; Fe = iron; K = potassium; Mg = magnesium; Mn = manganese; Na = sodium; P = phosphorous; Zn = zinc; G x E = genotype by environment interaction; LSD = least significant difference; CV = coefficient of variation; SE = standard error; ** and *** significant at 0.01 and 0.001 probability level, respectively.

Mn contributed the highest variation, which accounted 63.63% in the third PC followed by Fe with the contribution of 12.78% variation among the mineral nutrients. The first PC was strongly correlated with Zn (r = 0.94, p = 0.000) and P (r = 0.89, p = 0.000), while the second PC was associated with Na (r = 0.83, p = 0.000), Mg (r = 0.76, p = 0.000) and K (r = 0.55, p = 0.040).

3.4. Genotype-trait associations

The multi-variate relationships among accessions and traits were depicted in Figures 2, 3, and 4. The proximity of a genotype to a vector for a particular trait indicates the associations of the genotype-trait, while the genotype vector predicts the performance of a

Table 4. Mean concentration (mg kg^{-1}) of mineral elements in 14 taro accessions evaluated at two sites.

Ca				Fe				K				Mg			
Genotype	RPT	Umb	Mean	Genotype	RPT	Umb	Mean	Genotype	RPT	Umb	Mean	Genotype	RPT	Umb	Mean
Amad7_2	311.5	613.9	463[a]	Umbu9	35.9	54.9	45[a]	Amad6_8	2694.0	829.0	1761[a]	Amad7_2	283	358	320[a]
Umbu8	252.8	637.5	445[a]	Amad101	18.7	66.3	43[ab]	Aamd2053	2733.0	674.0	1704[a]	Umbu8	256	299	278[b]
Amad101	338.5	525.0	432[a]	Amad7_2	30.7	47.2	39[cb]	Amad47	2554.0	820.0	1687[a]	Amad6_8	289	260	274b[c]
Amad6_8	362.8	460.8	412[ab]	Amad2914	23.7	50.4	37[cd]	Amad2919	1788.0	1522.0	1655[ab]	Amad47	184	323	254[bcd]
Umbu9	404.4	346.4	375[cb]	Amad2919	32.4	33.6	33[de]	Amad7_2	2060.0	928.0	1494[bc]	Amad2914	240	266	253[bcd]
Umbu7	351.1	379.4	365[bcd]	3053/5118	17.3	47.8	33[def]	3053/5118	2200.0	728.0	1464[c]	Amad3053	241	255	248[bcd]
Aamd2053	301.7	412.7	357[cd]	Umbu8	23.2	41.3	32[ef]	Umbu8	2082.0	846.0	1464[c]	Aamd2053	234	249	242[cd]
Amad56	184.8	507.3	346[cde]	Amad6_8	35.0	27.1	31[efg]	Amad2914	2217.0	669.0	1443[c]	Amad56	216	260	238[d]
Amad47	145.3	492.7	319[def]	Umbu5	23.7	35.8	30[efg]	Amad101	1948.0	787.0	1367[c]	Umbu7	236	223	230[de]
Amad2914	145.3	490.8	318[def]	Amad3053	18.7	39.5	29[efg]	Amad3053	2017.0	678.0	1347[cd]	Amad101	199	259	229[de]
Umbu5	112.6	513.3	313[def]	Amad47	26.9	28.8	28[fg]	Umbu7	1737.0	921.0	1329[cd]	Umbu9	214	243	229[de]
Amad3053	162.8	441.4	302[ef]	Aamd2053	26.3	28.1	27[g]	Umbu5	1880.0	777.0	1328[cd]	Amad2919	205	250	228[de]
3053/5118	190.4	385.8	288[f]	Umbu7	13.8	39.5	27[g]	Umbu9	1763.0	621.0	1192[de]	3053/5118	198	240	219[de]
Amad2919	156.7	413.3	285[f]	Amad56	19.3	23.9	22[h]	Amad56	1566.0	594.0	1080[e]	Umbu5	157	241	199[e]
LSD	79.5	75.4	53.2		3.5	9.3	4.8		285.1	188.6	167.80		57.6	45.9	35.48
Mn				**Na**				**P**				**Zn**			
Umbu8	5.9	8.8	7.0[a]	Amad6_8	253.1	158.9	206.0[a]	Amad47	701.9	147.4	425[a]	Amad47	35.4	3.6	22.0[a]
Umbu5	0.0	7.2	7.0[a]	Amad101	172.0	170.0	171.0[b]	Amad6_8	570.0	158.1	364[b]	Amad2914	18.5	0.0	19.0[b]
Amad47	8.9	2.8	6.0[b]	Amad7_2	222.8	113.7	168.0[b]	Umbu9	558.9	151.1	355[b]	Amad6_8	8.9	0.0	9.0[c]
Amad101	0.9	10.8	6.0[bc]	Aamd2053	196.2	130.2	163[bc]	Umbu8	530.9	163.1	347[bc]	Umbu8	8.7	7.7	8.0[cd]
3053/5118	0.0	10.1	5.0[cd]	Amad2919	110.2	166.2	138.0[cd]	Amad7_2	524.8	134.8	330[bcd]	3053/5118	2.1	14.7	8.0[d]
Amad2914	6.3	1.5	4.0[de]	3053/5118	126.7	143.1	135.0[cd]	Aamd2053	508.3	140.0	324[bcde]	Umbu7	7.1	3.9	6.0[efg]
Amad6_8	3.5	4.6	4.0[de]	Umbu8	98.6	158.8	129.0[de]	Amad2919	490.6	148.0	319[bcde]	Umbu5	0.0	5.6	6.0[efg]
Umbu7	2.5	5.2	4.0[e]	Amad47	102.9	149.1	126.0[de]	3053/5118	509.7	123.8	317[bcde]	Amad7_2	7.6	0.7	5.0[fg]
Umbu9	6.1	1.2	4.0[e]	Amad56	78.0	170.6	124.0[de]	Amad56	436.2	173.2	305[bcdef]	Amad3053	4.6	0.0	5.0[g]
Amad7_2	1.4	4.0	3.0[f]	Amad3053	170.4	76.0	123.0[de]	Amad3053	508.1	70.6	289[def]	Amad56	0.8	5.2	3.0[h]
Aamd2053Ex	1.6	0.0	2.0[fg]	Umbu9	123.2	77.6	100.0[ef]	Umbu5	444.1	114.6	279[ef]	Umbu9	3.7	1.2	3.0[hi]
Amad2919	1.6	0.0	2.0[fg]	Amad2914	97.4	83.7	91.0[f]	Amad2914	387.5	145.3	266[fg]	Amad2919	2.0	0.0	2.0[hij]
Amad3053Ex	1.5	0.0	2.0[fg]	Umbu7	93.5	83.4	88.0[f]	Amad101	379.1	135.8	257[fg]	Amad101	1.3	2.2	2.0[ij]
Amad56	0.0	1.3	1.0[g]	Umbu5	115.0	58.7	87.0[f]	Umbu7	302.9	134.3	219[g]	Aamd2053	1.9	0.9	2.0[j]
lsd	0.6	1.6	0.9		56.5	24.4	29.9		93.6	32.0	48.0		1.3	1.1	0.9

Different letters in the same column indicate significant differences at 0.05 probability level; LSD = least significant differences; RPT = Roodeplaat (Gauteng Province); Umb = Umbumbulu (KwaZulu-Natal Province); Ca = calcium; Fe = iron; K = potassium; Mg = magnesium; Mn = manganese; Na = sodium; P = phosphorous; Zn = zinc.

Table 5. Pearson correlation coefficients for mineral elements among 14 taro accessions evaluated at Umbumbulu (*italicized*), Roodeplaat and across locations (bold).

	Ca	Fe	K	Mg	Mn	Na	P	Zn
Ca								
Fe	*0.04*							
	0.26							
	0.51*							
K	*0.00*	*-0.12*						
	0.06	0.29						
	-0.67*	**-0.54***						
Mg	*0.73***	*-0.01*	*0.08*					
	0.49*	0.26	0.29					
	0.61*	**0.29***	**-0.30**	**-0.15**				
Mn	*0.20*	*0.38*	*0.38*	*-0.11*				
	-0.16	0.31	0.19	**0.13**				
	0.26	**0.41***	**-0.11**	*0.24*				
Na	*0.26*	*-0.20*	*0.30*	*0.57*	*0.29*			
	0.48	0.40	0.56*	**0.24***	-0.44			
	0.14	**-0.06**	**0.31**		**-0.02**			
P	*0.19*	*-0.20*	*0.10*	*0.18*	*-0.47*	*0.57**		
	-0.08	0.59*	053*	0.04	0.45	0.24		
	-0.71*	**-0.49***	**0.89***	**-0.37***	**-0.06**	**0.26***		
Zn	*-0.07*	*-0.03*	*-0.06*	*-0.25*	*0.52*	*0.22*	*-0.16*	
	-0.36	0.13	0.44	-0.12	0.80***	-0.20	0.48*	
	-0.30	**-0.11**	**0.37***	**-0.13**	**0.56***	**-0.02**	**0.41***	

*, ** and *** indicate significance at 0.05, highly significant at 0.01 and 0.001 probability levels, respectively; Ca = calcium; Fe = iron; K = potassium; Mg = magnesium; Mn = manganese; Na = sodium; P = phosphorous; Zn = zinc.

Table 6. Eigen values and variance for principal components for 14 taro accessions evaluated in two locations.

	Umbumbulu			Roodeplaat		Overall		
	PC1	PC2	PC3	PC1	PC2	PC1	PC2	PC3
Eigen values	2.24	1.90	1.40	2.79	2.52	2.70	2.38	1.07
Variance (%)	28.04	23.74	17.51	34.84	31.51	33.72	29.68	13.32
Cumulative variance (%)	28.04	51.77	69.28	34.84	66.35	33.72	63.41	76.72
Ca	26.25	0.04	19.65	2.03	18.58	9.57	24.61	0.14
Fe	0.02	20.95	8.70	18.94	0.39	7.39	3.98	12.78
K	1.74	9.01	2.57	21.52	0.06	9.57	12.81	9.40
Mg	19.59	2.94	26.05	6.93	14.49	0.72	28.86	8.34
Mn	10.15	34.05	0.93	7.29	21.05	6.05	0.02	63.63
Na	23.58	2.47	15.50	11.16	20.94	4.84	29.61	0.01
P	15.01	5.83	11.63	22.55	3.38	29.15	0.11	5.19
Zn	3.67	24.72	14.97	9.59	21.10	32.70	0.00	0.53

Ca = calcium; Fe = iron; K = potassium; Mg = magnesium; Mn = manganese; Na = sodium; P = phosphorous; Zn = zinc.

genotype for a particular trait. Genotypes with long vector and in close proximity to a vector for a particular trait exhibit high performance on that trait. The threshold contribution is determined as the average contribution if all variables were to contribute uniformly to the PCs based on model specific algorithms. Variables that contribute less than the average are regarded to be less important for consideration and are not included in the biplot. At Umbumbulu, genotype Amad101 was positively associated with Zn and Ca, while Umbu8 had significant correlation with high Ca content (Figure 2). Elements Na, Mg and P were correlated to genotypes Amad56, Amad7_2, Amad6_8 and Amad47. There were some genotypes such as Umbu9, Umbu7 and Amad3053 Ex that did not have associations with most elements but exhibited very weak correlation with Fe as they were clustered in the same quadrant. The element Mn contributed less than the threshold contribution of 10% and was not included in the biplot. At Roodeplaat, genotypes Amad7_2, Amad6_8 and Amad2053 Ex were

positively associated with elements Mg and Na (Figure 3). Genotypes Umbu8 and Amad47 exhibited positive relationship with Mn, Zn and P. The other genotypes such as Umbu7, Umbu 5 and Amad56 were not particularly associated with any of the elements. Fe and Ca had insignificant contribution to the two PCs and were not included in the biplot. At both locations, genotypes Umbu8 and Umbu9 were highly associated with Fe, Zn, P and Ca (Figure 4). Genotypes Amad6_8, Amad101 and Amad7_2 excelled in their associations with Na, Mg and Ca. Genotypes including Amad2919, Amda56 and 3053/5118 had generally below average mineral nutrient content or did not show excellence in any particular mineral nutrient (Figure 4). Genotypes that consistently ranked low for most traits are located further away from the vectors for the mineral nutrient in the negative third quadrant (Figure 4). The element Mn contributed less than 4% threshold to the total variation explained by the two PCs, and is not shown in the biplot.
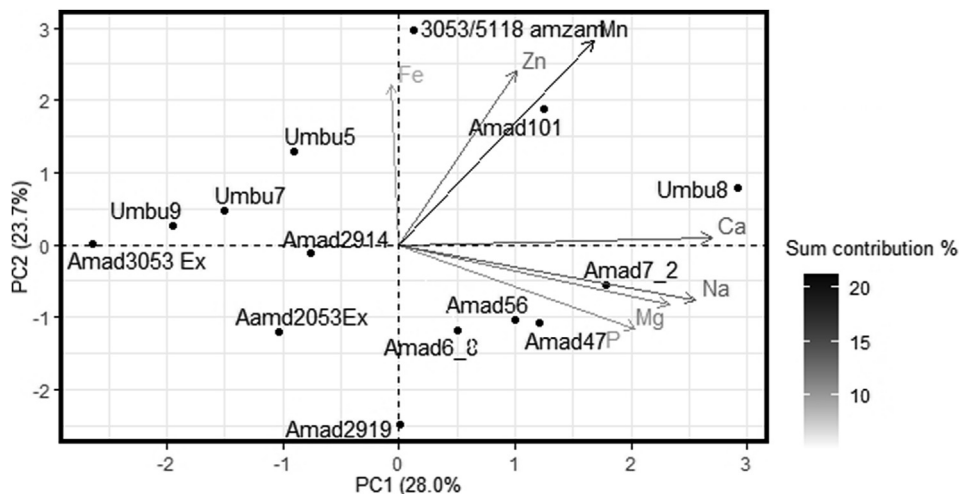
Figure 2. Genotype-trait associations and contributions to PCs among the mineral elements measured in 14 taro accessions at Umbumbulu
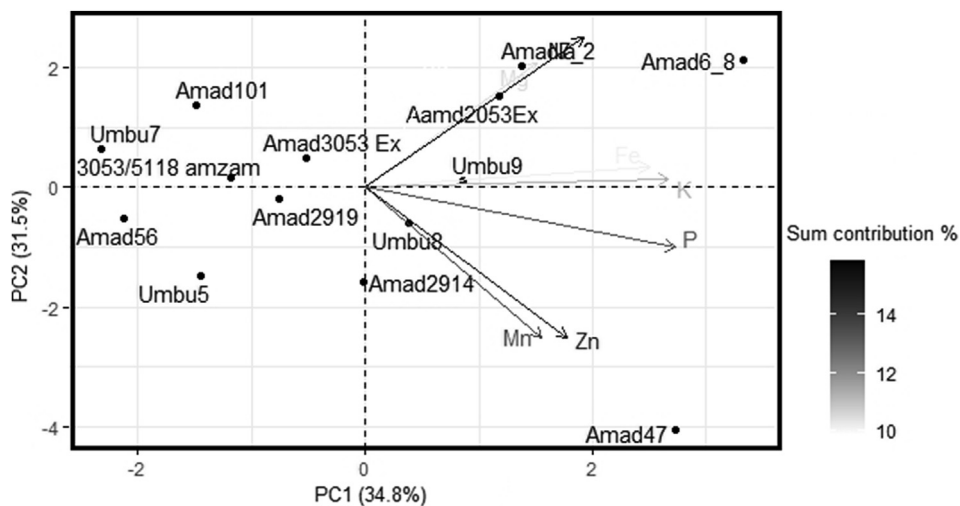

Figure 3. Genotype-trait associations and contributions to PCs among the mineral elements measured in 14 taro accessions at Roodeplaat
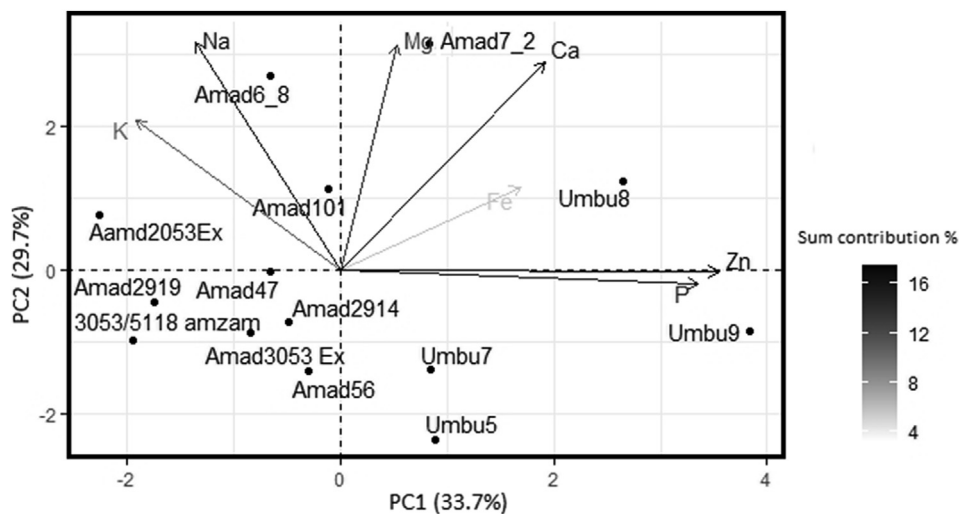

Figure 4. Genotype-trait associations and contributions to PCs among the mineral elements measured in 14 taro accessions across two locations.

3.5. Genotype hierarchical clustering

The UPGMA dendrograms revealed different clustering at each of the two locations and combined locations (Figures 5, 6, and 7). The largest cluster at Umbumbulu contained 10 genotypes that were highly correlated with K and Ca and moderate correlations with Mn and Zn (Figure 5). The second and third clusters had two genotypes each. The cluster containing Amad2919 and Amad3053Ex was characterized by very weak associations with Mn and Zn. The other cluster was characterized by very low Zn content but moderate Mn. At Roodeplaat, the UPGMA revealed three clusters with four, eight and two genotypes each, respectively (Figure 6). The cluster with four genotypes 3053/5118 amzam, Aamd2053Ex, Amad2919 and Amad101 exhibited strong correlations with K, Ca and Mg and very weak correlations with Mn and Zn. The largest cluster also had strong association with K, Ca and Mg and moderate correlations with Mn and Zn. The remaining cluster containing Umbu5 and Amad56 had the weakest correlation to Mn and Zn. Overall, across both locations, the largest cluster comprised of 6 genotypes, while the second and third clusters contained 4 genotypes each (Figure 7). High K, Mg, Ca, P and Zn content, with respective means of 1451.0, 245.7, 358.6, 314.0 and 6.9 mg kg^{-1} (Table 2), respectively, characterized genotypes in the largest cluster. For cluster 2, there was a tendency to group genotypes that had the lowest means for mineral elements, while the third cluster had intermediate means.

4. Discussion

4.1. Genotype and environmental impact on mineral element content

The mineral element concentration among the accessions varied widely (Table 2). Potassium was the most important nutrient element by concentration with a mean of 1451.0 mg kg^{-1}, while the means for Ca, Zn and Mn were 358.6, 6.9 and 3.9 mg kg^{-1}, respectively. This observation is in agreement with reports indicating that K was by far the most abundant mineral element in taro corms (Mulugeta and Tebeka, 2017; Alcantara et al., 2013). The high content of K and other essential elements such as Ca, Mg and Zn makes this population of taro important for addressing hidden hunger in South African communities, especially the poor and rural communities with limited access to balanced diet. For instance, Zn deficiency is recognized as a global public health challenge and the promotion of taro utilization can combat this challenge (Hambridge, 2000; Stein, 2010). The mean Fe content (Table 2) in the tested accessions was comparable to the mean Fe content reported in taro of Tanzania origin (Ndabikunze et al., 2011). Boampong et al. (2019) reported significant genetic variations in mineral nutrients among the taro test genotypes in Ghana while highlighting the competitiveness of taro with other root and tuber crops. Furthermore, Kobayashi et al. (2011) observed significant variations in mineral element composition of taro based on their geographic origin.

The significant genotype × environment co-action effects on mineral nutrient content (Table 3) showed that the difference in mineral element concentration of the genotypes could be partitioned to genetic and environmental impact and their interaction. There were differential responses of each genotype to different environmental conditions during mineral element accumulation. Genetic differences and environmental conditions such as soil fertility, ambient conditions and radiation affect plant physiology. Mineral composition and biomass allocation in plant tissues exhibit environmental plasticity to plant, soil and climatic factors (Pittelkow et al., 2015; Sánchez et al., 2014). Mbuma et al. (2020) similarly reported significant effects of genotype, environment, and their interaction on mineral element content of cowpea, another economically important underutilized crop.

The genetic constitution dictates biochemical synthesis in plant tissues, which has direct impact on nutrient composition. The different genotypes were differentially constituted genetically, which partly contributed to the variation in their mineral element content. The soils in

the different agro-ecological locations exerted different edaphic constraints and conditions that contributed to differences in mineral composition in the soils as well as differences in the uptake of these mineral elements by different taro plants in their systems. Soil conditions affect moisture and nutrient availability to plants and this has significant implications on plant physiology, particularly biosynthesis and assimilate partitioning. Mwenye et al. (2011) also attributed variation in mineral element composition of taro to soil properties. The soil is particularly important for taro, which is a tuber crop. For instance, moisture and nutrient scarcity in the soil are known to promote translocation of assimilates to below ground biomass. Therefore, the different soil conditions in the two study locations contributed to the observed variation in mineral element content among the genotypes. The ambient conditions such as air temperature and radiation are also instrumental in influencing growth and biosynthesis of compounds in plants, which can be reflected in mineral element content. Elements such as Fe are photochemically active and their accumulation can be influenced by radiation and temperature, which affect reactivity (Husson, 2013). High temperature and solar radiation exacerbate other stresses leading to changes in the biosynthesis of compounds in the plant. The production of biochemical compounds such as abscisic acid (ABA) and cytokinins is known to respond to environmental stresses such as temperature and moisture deficit (Gujjar and Supaibulwatana, 2019). These phytohormones can affect the accumulation and transport of primary elements such as Fe, Mg and Na in plant tissues in response to environmental conditions. Ultimately, the environmental conditions caused cross-over ranking of genotypes in terms of mineral content. The differences in environmental conditions between the two locations and variation in genetic constitution of the genotypes contributed to the observed variation in mineral content. However, the contribution of each component to the variance must be quantified for devising effective breeding strategies.

The moderate variation, ranging between 10 and 20% for all mineral nutrients, indicates that there is a need to introduce more accessions into the germplasm to increase and broaden genetic variation for effective breeding. Crop improvement hinges on the extent of genetic variation in germplasm and introductions, and recombination and mutation can be deployed to widen the genetic pool (Griffiths et al., 2000). The accessions that ranked highest for a particular trait in each location must be selected for developing breeding populations to increase genetic diversity and improve the particular trait. The crossover ranking allows the identification of specific and broadly adapted genotypes. Genotypes such as Amad7_2, Umbu8, Umbu9 and Amad101, which consistently showed high mineral element content should be selected for advancement as parental lines in a breeding program to improve mineral content in taro. Genotypes such as Amad6_8 (K and Na), Amad47 (P and Zn) that showed high accumulation of specific mineral elements in specific locations can be selected for breeding in the respective locations and for the target elements. These can be crossed to genotypes with broad adaptation to improve the specific element content. For instance, Amad6_8 can be crossed with Amad7_2, Umbu8, Umbu9 and Amad101 to improve their K and Na content. Similarly, Amad47 can be used as donor for high P and Zn genes.

4.2. Associations among genotypes and mineral elements

The variable bivariate associations amongst the traits (Table 5) presents both opportunities and challenges for simultaneous selection and improvement. Positive correlations allow for simultaneous and direct selection, while negative correlations can present challenges for simultaneous selection of desirable traits. The differences in correlations exhibited by the traits at different locations shows the impact of environmental conditions. The changes in the associations among the mineral elements at Umbumbulu and Roodeplaat are expected because trait associations are dynamic and vary with environmental factors. Although specific correlations at each site must be taken into cognizance when devising breeding strategies, it may be expensive and overall correlations
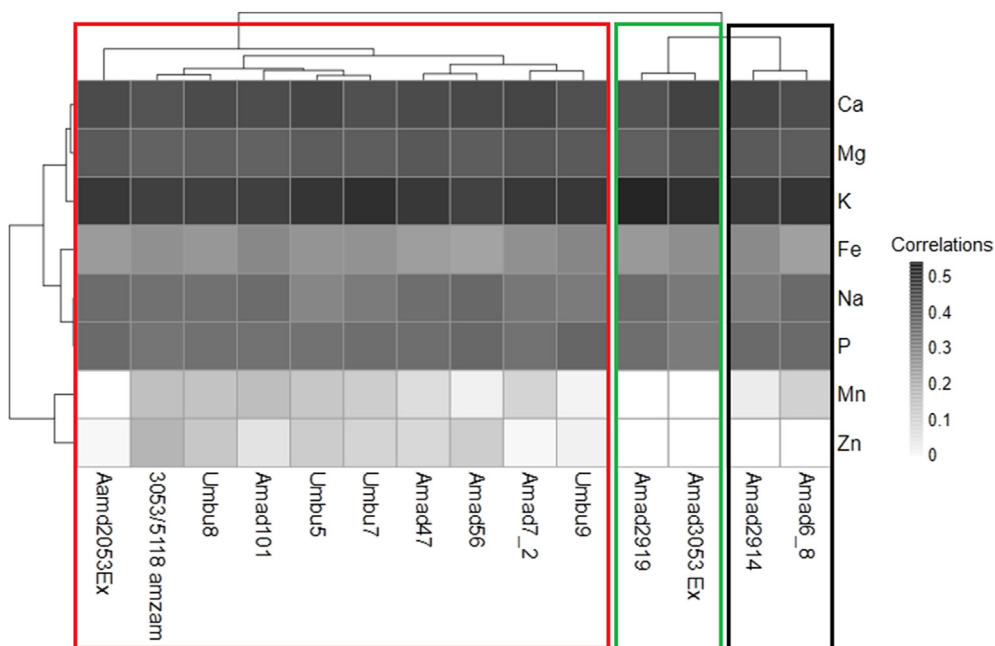
Figure 5. Dendrogram depicting the interrelatedness of 14 taro accessions based on the concentration of mineral element at Umbumbulu
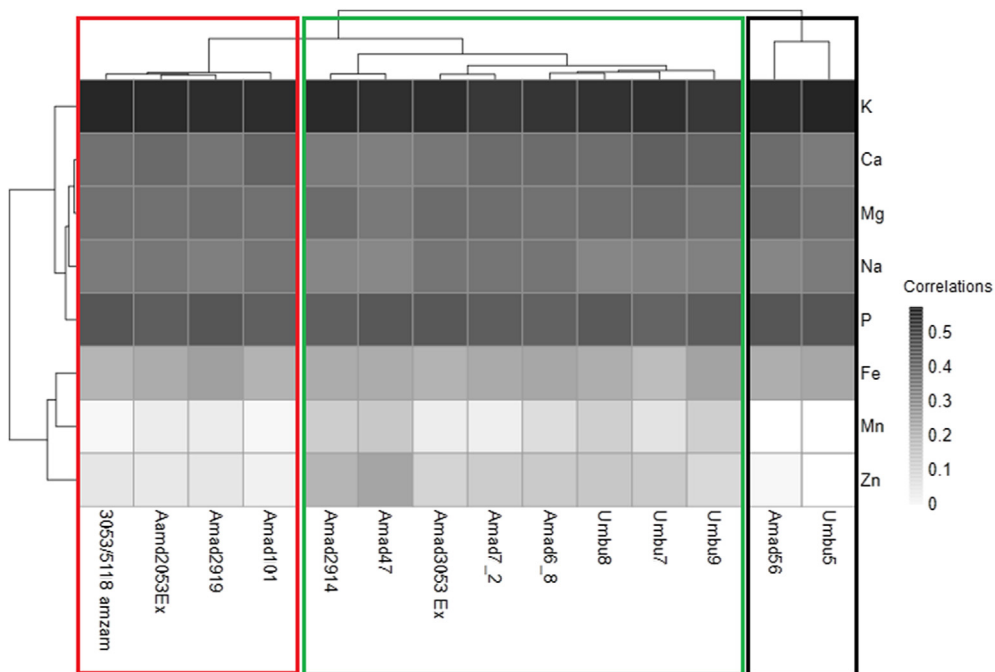

Figure 6. Dendrogram depicting the interrelatedness of 14 taro accessions based on the concentration of mineral element at Roodeplaat

may provide a general guide. The overall strong correlations between K and P (r = 0.89, p < 0.001) will allow for selection to improve both K and P using suitable parental lines (Table 5). Possible challenges will be encountered during selection due to the negative correlation observed between Ca on one hand and P, K and Zn on the other hand. Similarly, the negative correlations between Fe and K, and Mg and P, which are traits that exhibit undesirable correlations, would be difficult to improve using conventional selection methods. Molecular or mutation breeding methods would present better opportunities to break unfavorable linkages or induce mutations to create mutants with increased concentration of the particular traits. Similarly, previous reports have indicated variable correlations among the mineral elements (Mwenye et al., 2011).

Competition in absorption of minerals in plant nutrition have been recorded previously, for instance high concentration of Ca and P can inhibit the absorption of Mn (Soetan et al., 2010). The differences between correlations reported in other studies (Mwenye et al., 2011; Alcantara et al., 2013) from those reported in this study could emanate from differences in germplasm and attendant environmental conditions.

The first three PCs accounted for at least 66% of the variation in mineral nutrient content among the accessions at Umbumbulu, Roodeplaat and the combination of both locations (Table 6), indicating that the traits and genotypes that were associated with these components were important in explaining the variation. Similarly, Hair et al. (1998) reported that eigen values greater than one are considered to be significant
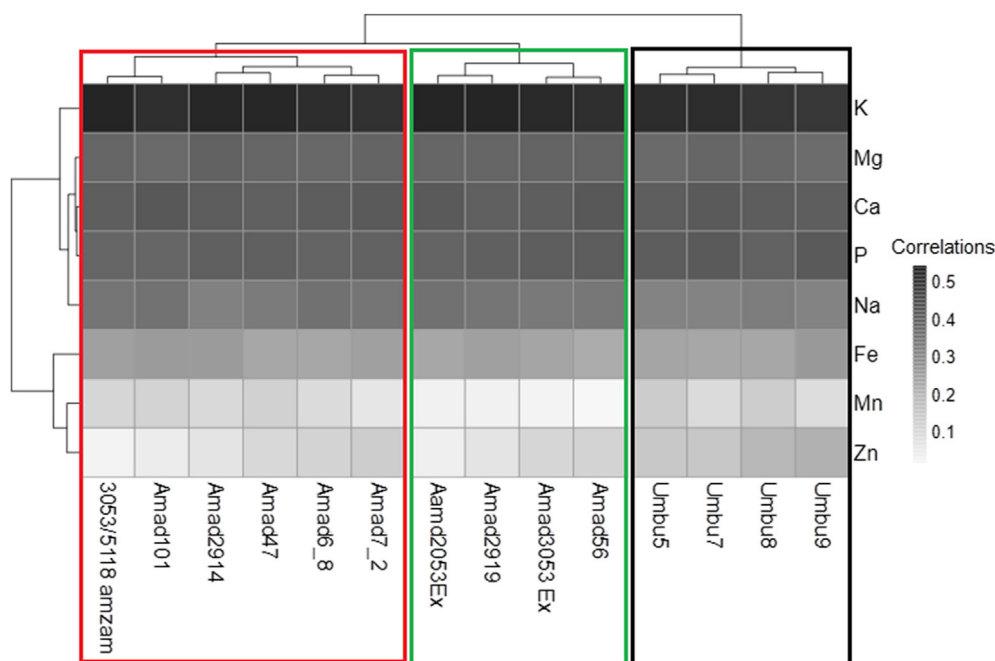
Figure 7. Dendrogram depicting the interrelatedness of 14 taro accessions based on the concentration of mineral element across two locations.

in detecting variation. They also explained that the component loadings which are greater than ±0.3 need to be considered as they are meaningful in defining the variances. Therefore, from this current study, only the first three eigen vectors showed eigen values greater than one and cumulatively explained 66.35% of the total variation among the taro accessions at Roodeplaat location, and 69.28% of the total variation observed at Umbumbulu site. At Umbumbulu, elements Ca, Na and Mg were highly correlated with the first PC, while the highest contributors to PC1 at Roodeplaat were P, K and Fe, showing that these elements were the most discriminatory at the respective locations. Overall, the high contribution and strong association of Zn and P with the first PC indicate that these two traits were the most discriminatory traits among the genotypes (Table 6). The Zn and P content varied widely among the genotypes, which provided a basis for discrimination in each environment. The high contribution of these elements to the first PC shows that they must be used as target traits for evaluation in the respective locations and discriminating genotypes for conservation purposes. However, their importance in discriminating the genotypes does not imply that they are more important than the other mineral elements in terms of concentration or dietary requirements. The elements that contributed most to PC2 at Ubumbulu and Roodeplaat included Mn and Zn. Overall, the next most important elements for discriminating the genotypes were Na, Mg, Ca and K, which were highly correlated and contributed significantly to the second PC. These elements also exhibited wide variation. The lack of significant overall contribution by Mn and Fe shows that they were the least discriminatory among the mineral elements and may not be useful for generalized strategies for taro improvement. Mwenye et al. (2011) also found that mineral elements had different contributions to PCs, however, they found K to be the most discriminatory element among their test genotypes. The differences in the importance of traits can be attributed to differences in germplasm and environmental conditions. The third PCs at Umbumbulu included Ca, Mg and Na, which were already identified as important to PC1. This shows that there will be no loss of information by focusing on the important traits in the first and second PCs at Umbumbulu. Overall, Mn and Fe were identified in PC3 showing that they had a discrimination potential among the mineral elements tested in PC3, which contributed 13.32% variance, while Ca, Na and Zn had weak significant effect on this PC.

4.3. Genotype-trait associations for multi-trait selection

The genotype-trait biplot allows selection of genotypes with high performance for multiple traits. Conventional methods of comparing means are weak as they can only compare one trait at a time (Flores et al., 1998). Genotype Amad101 was positively associated with Zn and Ca, while Umbu8 had significant correlation with high Ca content at Umbumbulu (Figure 2) showing that these genotypes accumulated high amounts of these respective elements. Furthermore, genotypes Amad56, Amad7_2 and Amad47 accumulated significantly higher amounts of Na, Mg and P while Umbu9, Umbu7 and Amad3053 Ex genotypes accumulated average or below average amounts for most elements. At Roodeplaat (Figure 3), genotypes Amad7_2, Amad6_8 and Amad2053 Ex accumulated substantial amounts of Mg and Na while genotypes Umbu8 and Amad47 had high Mn, Zn and P contents as exhibited by the significant proximity to the respective vectors of these elements. Genotypes Umbu7, Umbu 5 and Amad56 had below average amounts for most elements. Overall, the proximity of genotypes Umbu8 and Umbu9 with vectors highly associated with Fe, Zn, P and Ca shows that these genotypes had high concentration in these mineral elements (Figure 4). Genotypes Amad6_8, Amad101 and Amad7_2 were associated with vectors for Na, Mg and Ca, while genotypes including Amad2919, Amad56 and 3053/5118 were not associated with a particular vector. The depiction in the biplots corroborated with the analysis of variance and the genotypic mean performance. The genotypes that were not associated with a particular vector had generally below average mineral nutrient content and consistently ranked low for most traits. Genotypes Umbu8 and Umbu9, and Amad6_8, Amad101 and Amad7_2 will be selected for improving Fe, Zn, P and Ca, and Na, Mg and Ca, respectively. The hierarchical clustering consistently grouped 3053/5118 amzam, Aamd2053Ex and Amad101 together due to their similarities in Ca, Fe and Mg accumulation, while Amad2919 and Amad3053 Ex were grouped together with similar Ca, Mn and Na contents at the two locations (Figures 5, 6, and 7). Overall, the genotype-trait association biplot clustered where Umb8 and Umbu9 close together based on their high Na and Ca content, while Amad6_8, Amad101 and Amad7_2 were in close proximity. The rest of the genotypes were clustered together with high Fe content being common. The UPGMA method also clustered these

genotypes in the same clusters consistent with the genotype-trait biplot. Clustering based on phenotypic and biochemical traits has been used widely to identify divergence among genotypes (Kobayashi et al., 2011; Hirai et al., 1989). The selection of genotypes for crossing should focus on divergent genotypes to avoid inbreeding depression. In this study, selection of genotypes for crossing must commence after determining the gene action involved in inheritance of mineral content. For instance, if mineral element content is additively inherited, then the crossing of parental lines could be recommended to improve the mineral element content and enhance its importance in the food and nutritional system in Africa and beyond. However, taro is commonly vegetatively propagated and the use of genotypes with initially high mineral element content is highly recommended.

5. Conclusion

The mineral content of taro varies with genotype and environmental conditions under which the genotypes are grown. Genotypes Umbu8, Umbu9, Amad6_8, Amad101 and Amad7_2 were selected for improving Fe, Zn, P, Na, Mg and Ca requirement in diets. Further investigation on anti-nutrient phytochemicals in the accessions are recommended as these affect the bio-availability of the mineral element. The study further demonstrates the nutritional value of taro and its ability to compliment the microelement needs in human diets.

Declarations

Author contribution statement

Abe Shegro Gerrano: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Isack Mathew, Admire I. T. Shayanowako, Willem Jansen Van Rensburg: Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Stephen Amoo, John Jason Mellem: Contributed reagents, materials, analysis tools or data; performed the experiments; analysed and interpreted the data; Wrote the paper.

Michael Wolday Bairu, Sonja Louise Venter: Performed the experiments; analyzed and interpreted the data; Wrote the paper.

Data availability statement

Data included in article/supplementary material/referenced in article.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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