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Variation in Tuber Dry Matter Content and Starch Pasting Properties of White Guinea Yam (*Dioscorea rotundata*) Genotypes Grown in Three Agroecologies of NIGERIA

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Abstract: The primary objective of this study was to assess the effects of genotype (G), location (L), and G × L interaction on tuber quality traits (dry matter content and starch pasting parameters) in white Guinea yam (*Dioscorea rotundata* Poir.). Variability in tuber dry matter and starch pasting properties was examined using 18 advanced breeding lines and two dominant landrace cultivars of white Guinea yam grown in three different agroecological zones (forest-savanna transition, southern Guinea savanna, and rainforest) in Nigeria. The starch pasting properties were evaluated using a Rapid Visco Analyser. Our results show that the G × L interaction effect was low compared to the genotype and growing location effects on the variability of key starch properties. In addition, the repeatability of trait performance across locations was high and relatively uniform for key traits, suggesting that any of the three locations used in this study can be employed for their evaluation. Furthermore, TDr1100873 had a higher dry matter content than the dominant landrace cultivars (Amula and Meccakusa) but was similar to them in starch pasting properties. Hence, TDr1100873 is considered a suitable variety for future breeding activities.

Keywords: yam; starch pasting property; dry matter content; tuber quality; genotype × location interaction effect; stability; extracted starch

1. Introduction

Yam (*Dioscorea* spp.) is a major starchy food source in several countries across the humid and sub-humid tropics and a significant source of calories for over 300 million people in the tropics and subtropics [1]. Over 90% of global yam production comes from West Africa, with Nigeria being the leading producer [2]. The yam crop plays a crucial role in social and cultural events in this sub-region, and it is the food of choice at ceremonies and festivals [3]. Indeed, yam production in West Africa increased from 14.5 million tons in 1988 to 66.8 million tons in 2018 [2]. These dramatic increases are associated with crop area expansion into the savannas. However, yam yield has decreased from 9.4 t ha^{-1} in 1988 to 8.4 t ha^{-1} in 2018 [2]. This trend could be catastrophic for the region unless steps are taken to change the situation [4]. Currently, landraces with low productivity are frequently used for yam cultivation in West Africa [5,6]. To meet the growing demand for yam as populations grow and to maintain food security for people in West Africa, it is important to develop and disseminate new and improved yam varieties with appropriate agricultural traits and that satisfy consumer preferences. The breeding and selection of yam have been carried out by the International Institute of Tropical Agriculture (IITA) since the 1970s with a focus on white Guinea yam (*D. rotundata*), the most important species in West African countries [7,8]. The one of the important yam breeding targets include the development of improved varieties with appropriate tuber quality (dry matter content, texture, taste, rate of oxidation) [9]. In terms of yam consumption, the tuber is usually boiled, fried, or processed into flour for other food products. The yam flour can be reconstituted with hot water to form a paste called "Amala" in Nigeria. Pounded yam is a highly preferred food among the various traditional food products prepared from yams in Nigeria. It is prepared by boiling and pounding tuber pieces in a mortar with a pestle to produce a sticky elastic dough, which is often eaten with vegetable or meat sauce [10]. Starch is the main component of yam tubers and accounts for approximately 70-80% of the dry matter content [11]. Starch properties determine the physicochemical, rheological, and textural characteristics of food products derived from yam. Flavor and physical properties, such as texture and appearance, are important attributes of food products and are used by consumers to evaluate the acceptability of the product [12].

The Rapid Visco Analyser (RVA) is a tool that has been widely used to assess the pasting properties of sorghum [13], rice [14,15], wheat [16], potato [17], and cassava [18]. In the case of yams, the RVA has been used as a simple and rapid evaluation method that can mimic the yam flour/starch cooking process, and results have been reported to be highly correlated with the quality of the final product [10,19,20]. It was reported that starch from *D. alata*, *D. rotundata*, and *D. cayenensis* tends to have lower peak viscosity than potato starch and higher final viscosity than potato and cassava starch [21]. Moreover, considering that the starch of *D. alata* and *D. cayanensis-rotundata* has a very high viscosity after baking and good resistance to high-temperature treatments, it can be used as a substitute for chemically modified starches in ultraheat treatment foods and canned baby foods to develop natural products [22]. In addition, a wide variety of starch pasting properties analyzed by RVA have been observed among various yam species [10,11,19,20,23], and within the same yam species [19,24]. The wide and heritable variation in starch pasting properties in yam germplasm suggests the possibility for further genetic improvement of the starch quality and cooking attributes of yam tubers through breeding.

Genotype by location interaction (G × L interaction) refers to differential responses of genotypes or cultivars across a range of environments [25–27]. The G × L interactions in breeding programs reduce the correlations between phenotypic and genotypic traits, resulting in invalid or biased conclusions regarding genetic variance [26]. In cereal crops, starch pasting properties vary in different climates and locations and across seasons [13,28,29]. In the case of yam, the G × L interaction significantly affects fresh tuber yields [30,31]. In Ghana, TDr8902665 was selected for high and stable yields amongst breeding lines cultivated under 13 different environmental conditions and was registered as a new variety [31]. While the effect of the G × L interaction on yam productivity has been defined and the selection of excellent improved lines based on its effect has been promoted, it remains unclear how the G × L interaction affects the tuber quality traits of yam. Hence, rigorous analysis of the G × L interaction on starch pasting properties will facilitate the development of yam varieties with stable starch pasting properties that determine pounding behavior over a range of production and consumption systems. Therefore, it is important to clarify the effects of the G × L interaction on tuber quality traits when considering an effective breeding strategy for yam. Moreover, an improved understanding regarding the extent of the effects imposed by environmental conditions on starch pasting properties will provide an impetus for yam breeding to determine when and how to select specific starch properties during the breeding process.

The genetic improvement of any breeding population mainly depends upon the amount of genetic variability present [32,33]. The genetic characters are governed mainly by polygenes which are highly influenced by the environment. The heritability of a genetic trait is important in determining the response to selection. Similarly, high genetic advance coupled with high heritability offers the most effective condition for selecting a specific character [34]. Hence, the primary objective of the present study was to assess the effects of genotype (G), location (L), genotype by location interaction (G × L interaction), and genetic variability on important tuber quality traits, such as dry matter content and starch pasting properties, in white Guinea yam.

2. Materials and Methods

2.1. Plant Materials and Trial Management

This study was conducted during the 2017/2018 cropping season at three locations representing the major yam production ecologies in Nigeria: Ibadan, Abuja, and Ubiaja (Table 1). The rainfall in the three locations was assessed over the experimental period using data obtained from the Geographical Information System (GIS) unit of IITA (Table 1, Figure 1). These experimental field stations were established by the IITA and are being used for evaluation and selection trials by IITA for a yam breeding program as they represent conditions in the major yam agroecological zones. The Ubiaja station represents the rainforest zone (RF), Ibadan represents the forest–savanna transition zone (FST), and Abuja represents the southern Guinea savanna zone (SGS). The trial sites varied in altitude, soil attributes, amount of rainfall, and temperature (Table 1). Soil samples were collected in April 2017 at depths of 0–20 cm from thirty randomly selected experimental plots in each cultivation location. Samples were air dried before sifting (using a 2 mm sieve) at IITA, Ibadan. Soil pH was determined by initially suspending the soil in water (at a 1:1 soil/water ratio). An available phosphorus extracted according to the Bray-1 procedure [35]. Phosphorus was assayed colorimetrically using Genesys 10S UVVis (Thermo Scientific, Waltham, MA, USA). Organic carbon was determined by chromic acid digestion with a spectrophotometric procedure using the Genesys 10S UV-Vis [36]. Total nitrogen was determined using the Kjeldahl method for digestion and colorimetric determination on a Technicon AAII Autoanalyzer (Seal Analytical, Mequon, WI, USA) [37]. The soil pH in FST site was 5.35, which was the lowest value among the three locations. The nitrogen content in the soil was 0.02% in SGS site, 0.01% in FST site, and 0.004% in RF site. SGS soil had the highest phosphate content and the lowest organic carbon content among the three locations. The potassium content was highest in FST site. The rainfall stopped in SGS and FST sites from November to harvesting time, while rainfall continued in RF site until December (Figure 1).

Table 1. Environmental conditions of the three different experimental sites in Nigeria during 2017.

Attribute	Location		
	Abuja	**Ibadan**	**Ubiaja**
Coordinates			
Latitude	9°09′39.2″ N	7°29.294″ N	6°39.975″ N
Longitude	7°20′48.3″ E	3°53.129″ E	6°20.638″ E
Elevation (m)	431	227	330
Agroecological zone	Southern Guinea savanna	Forest–savanna transition	Rainforest
Weather and climate attributes			
Rainfall (mm)	1268.98	1475.90	1837.20
Temperature (min–max) (°C)	14.5–40.4	16.0–37.0	16.6–34.4
Relative humidity (min–max) (%)	16.6–93.5	24.5–95.5	45.6–94.6
Soil attributes			
pH (H_2O) (1:1)	5.35	6.30	5.49
Organic carbon (%)	0.19	0.51	0.52
Nitrogen (%)	0.02	0.01	0.00
Bray phosphorus (ppm)	3.80	3.62	2.91
Potassium (Cmol [+] kg^{-1})	0.14	0.61	0.11

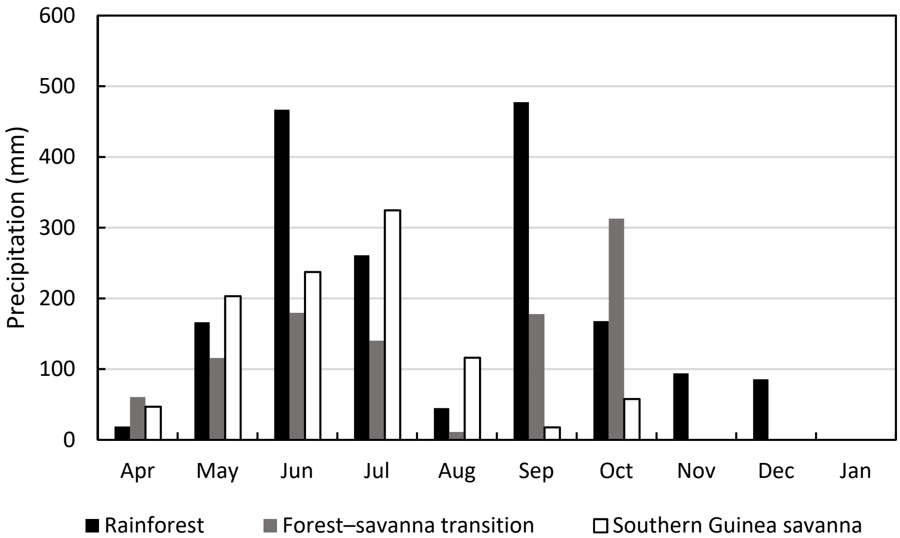

Figure 1. Rainfall (mm per month) over three different locations in Nigeria from April 2017 to January 2018.

Among the dominant cultivated yam species in West Africa, white Guinea yam (*D. rotundata*), which is preferred because of its desirable food quality traits, was used for the current study. Eighteen advanced white Guinea yam breeding lines derived from IITA's yam breeding program, along with the two dominant farmer landrace cultivars (Amula and Meccakusa), were used for this study. The field experiments were laid out in a 4 × 5 lattice design with three replications and 10 plants per replication. Healthy tubers of each genotype were cut into sets of 200 g each as the seed tubers. These seed tubers were treated in a mixture of 70 g Mancozeb (fungicide) and 75 mL Chlorpyrifos (insecticide) in a 10 L volume of tap water for 5 min, then dried for 20 h in shade before planting. The treated seed tubers were planted on ridges that were 1 m apart with 1 m spacing between plants on a ridge for a planting density of 10,000 plants per hectare, in the middle of April 2017. The trial plots were hoed and hand weeded. Harvesting was performed at physiological maturity when the above-ground structure (vines and leaves) showed complete senescence near the middle of January 2018. After harvesting, fresh tuber weights were recorded, and tuber yields (tha^{-1}) in each cultivation location were calculated. One representative and healthy-looking tuber (approximately 1 kg) was selected from each replication at different growing locations for each genotype. One hundred and eighty tubers (20 genotypes × 3 replications × 3 locations) were collected and used for the determination of tuber dry matter content and starch extraction.

2.2. Tuber Dry Matter Content Measurement and Starch Extraction

Tuber dry matter content measurement and starch extraction process were conducted at IITA Ibadan. Tuber dry matter content measurement and starch extraction were conducted following the protocol described by Matsumoto et al. [38]. Only the middle portion of the tuber was extracted and used as the test material after washing and peeling. The sampled tubers were peeled, cut, and chipped using a hand-held crusher to produce small pieces (5 cm long and 0.5 mm thick). Approximately 250 g of chipped tuber was obtained for starch extraction and tuber dry matter content measurements. A sub-sample of approximately 100 g was dried in a forced-air oven at 105 °C for 16 h (i.e., until constant weight) for tuber dry matter content determination.

The fresh complete tuber is majorly used for pounded yam preparation in the traditional food system. That is why the current study targeted the completed tuber instead of yam flour. Starch was extracted using an approximately 100 g sub-sample of fresh material that was macerated in a blender (Iwatani Mirusa IFM-800, Iwatani, Tokyo, Japan) with 200 mL of tap water for 90 s and passed through a 125-μm sieve. Tap water was then added until a volume of 3 L was reached. The slurry was left at room temperature (25–30 °C) for 3 h to settle. The supernatant was decanted after 3 h. The starch slurry was re-suspended in distilled water to remove heavy molecule components such as protein, fiber, and inorganic materials in tap water (Table S1). The distilled water was prepared by Direct-Q® 3 UV Water Purification System (Certified Genetool Inc., Pleasanton, CA, United States). The obtained starch was dried at room temperature overnight and in a forced-air oven at 35–40 °C for 24 h, and then ground in a blender for 60 s. After grinding, the quantity of obtained starch in each sample was recorded. The starch samples were stored at room temperature in sealed polyethylene bags with silica gel.

2.3. Starch Pasting Properties

Experiments were performed using an RVA (RVA-TecMaster, Perten Instruments, Australia) with modified protocol for white Guinea yam starch based on the method for Perten Instruments [39]. A 1.7 g portion of starch was mixed with 25 mL of distilled water in the RVA sample container after correction for the original starch moisture content. The RVA was conducted using Thermocline for Windows software (Version 3.15.3.347, Perten Instruments, Australia). The time–temperature profile used with a heating and cooling cycle was set at (1) holding at 50 °C for 1 min, (2) heating to 95 °C in 3 min 42 s, (3) holding at 95 °C for 3 min 30 s, (4) cooling to 50 °C in 3 min 48 s, and (5) holding at 50 °C for 5 min. The RVA paddle speed was 960 rpm for the first 10 s of each test and was subsequently maintained at 160 rpm. The results of RVA are displayed as viscosity in centipoise (cP). The RVA was conducted for each of the 180 extracted starch samples. Each starch sample was subjected to two replications using the RVA.

Three original parameters (peak viscosity, trough viscosity, and final viscosity) were obtained from the pasting curve. In addition, breakdown (peak viscosity–trough viscosity) and setback (final viscosity–trough viscosity) were derived from the three original parameters, and peak time and pasting temperature were recorded (Figure 2). The value of peak viscosity can explain the water-holding capacity of the starch or mixture. Trough viscosity is the ability of the starch granules to remain undisrupted when the yam paste is subjected to a hold period of constant high temperature and mechanical shear stress. Final viscosity is the ability of the material to form a viscous paste after cooking and cooling. RVA analysis used as the lowest temperature 50 °C, in this temperature starch only can exist as a paste. During the cooling phase, an increase in viscosity implies that all constituents present in the hot paste are re-associated with the reduction in temperature. Starch breakdown indicates the resistance of the starch paste to heat and shear. Meanwhile, setback refers to the tendency of starch pastes to recrystallize and is an index of starch retrogradation or gelling ability [40]. The setback viscosity is the recovery of the viscosity during cooling of the heated starch suspension and is related to the retrogradation and reordering of starch molecules, i.e., low setback values indicate a low rate of starch retrogradation and syneresis. The pasting temperature is measured at the onset of a rise in viscosity and may indicate the gelatinization temperature of the starch, thereby indicating the minimum temperature at which the starch should be cooked.

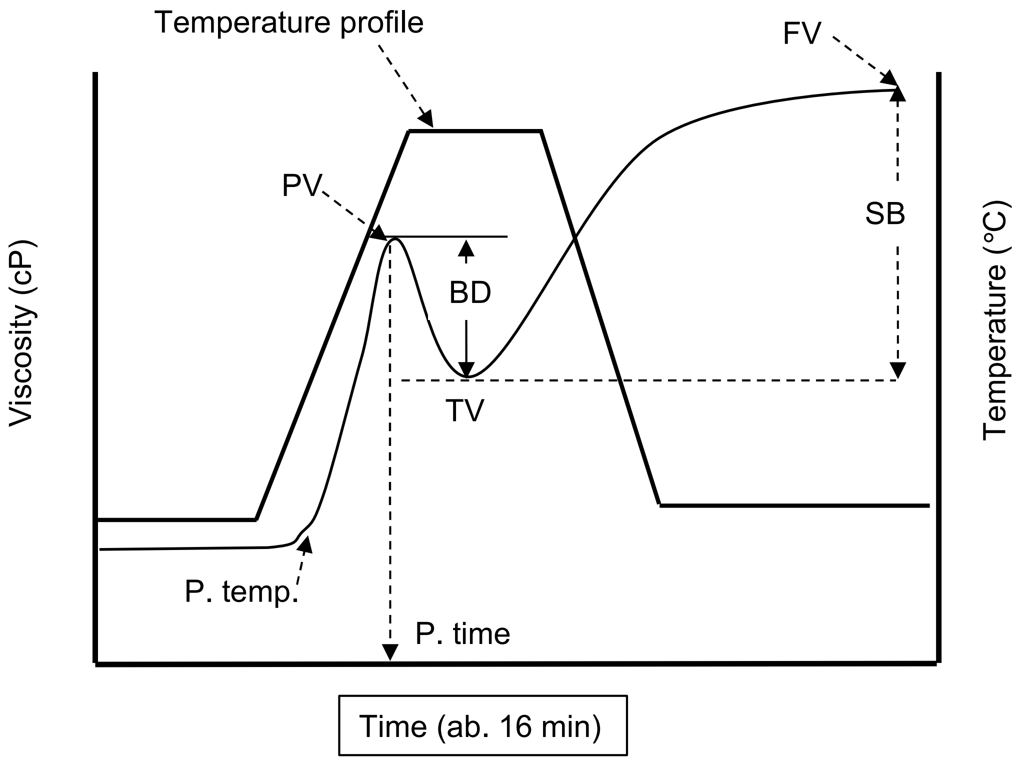

Figure 2. Pasting profile of *Dioscorea rotundata* starch using a Rapid Visco Analyser (RVA). P. temp., pasting temperature; P. time, peak time; PV, peak viscosity; TV, trough viscosity; BD, breakdown; FV, final viscosity; SB, setback.

2.4. Data Analysis

Data were recorded for tuber quality traits (tuber dry matter content and starch pasting properties) for each genotype across locations and replications. The data were fit to a mixed model analysis using ASReml-R version 4 software [41]. Genetic parameters, such as phenotypic coefficient of variation (PCV), genotypic coefficient of variation (GCV), and repeatability, were estimated to identify variability among genotypes and determine genetic and environmental effects on different traits. The variance components were estimated for each trait by fitting the data into a mixed model where location and replication were considered as fixed terms and genotype, genotype × location interaction, block nested within replication, and location as random effect terms. Phenotypic coefficient of variation (PCV) and genotypic coefficient of variation (GCV) were calculated by standard formulae [42]. Heritability (broad sense) was calculated as σ^2G/σ^2P, where σ^2G is genetic variance and σ^2P represents phenotypic variance. The repeatability of a trait performance across locations, which is the average correlation between locations, was determined as the ratio of genotypic variance (σ^2G) over the sum of variances of genotypic and genotype × location interaction ($\sigma^2G\times L$). Repeatability values close to zero indicated that a genotype's rank in one location differed significantly from its rank in another location (i.e., low stability), while a value close to 1 indicated that a single location ranking could be used across locations without loss of information (i.e., high stability). The multiple comparison analysis using Tukey's HSD test were performed to detect any statistically significant differences in dry matter content and starch pasting properties among cultivation site using R software version 4.0.3 using the package agricolae [43]. The average genetic values of genotypes across all locations (BLUP = best linear unbiased prediction) were also calculated for the traits measured in the trial. Correlation analyses among tested different parameters were determined with Pearson correlation coefficients. The least significant difference was calculated to determine significant differences in dry matter content and starch properties among genotypes using R package agricolae. A cluster analysis of starch pasting properties was performed using the Mahalanobis generalized distance and a dendrogram was constructed using the packages ecodist [44] and ape [45] in R environment [46].

Data were recorded for tuber yield and crude starch yield for each genotype across locations and replications. The effects of environment, genotype, and G × L interaction on tuber yield and crude starch yield were analyzed using an additive main effect and multiplicative interaction (AMMI) model [47]. To select genotypes with higher yield stability over the environments, the AMMI stability value (ASV) and yield stability index (YSI) were calculated according to Oliveira et al. [48]. Multiple comparisons testing was performed for clusters of genotypes on starch pasting properties for tuber yielding potential and crude starch content using a plotting package ggplot2 in R environment.

3. Results

3.1. Genetic and Non-Genetic Effects on Dry Matter Content and Starch Pasting Properties

Estimates of the variance components and genetic parameters for tuber dry matter content and starch pasting properties of tested white Guinea yam genotypes grown at the three locations are presented in Table 2. The genotypic variance was high relative to the G × L interaction variance for all traits. The G × L interaction was significant for the setback viscosity and peak time. The random residual effect contributed more variability and exceeded that of both the genotype and the G × L interaction with higher values at the FST site for all traits except tuber dry matter content, trough viscosity, and peak time. Tuber dry matter content had the highest residual variance at RF site, while trough viscosity and peak time exhibited the highest residual variance at the SGS site. The residual variance exceeded both the genotype and G × L interaction variances for trough viscosity at SGS and RF sites, and for breakdown viscosity, final viscosity, setback, and pasting temperature at all test sites.

The PCV ranged from 1.70% to 58.91%, while the GCV ranged from 0.98% to 31.30%. Among starch pasting properties, the breakdown showed the highest GCV (31.30%) and PCV (58.91%) values, whereas pasting temperature showed the lowest GCV and PCV values of 0.98% and 1.70%, respectively (Table 2). Trait repeatability (average correlation between the experimental sites) for the expression of traits varied from 0.99 to 0.62. The repeatability was high and approached unity (more than 0.80) for tuber dry matter content, peak viscosity, trough viscosity, final viscosity, peak time, and pasting temperature, but low (below 0.65) for breakdown and setback. Heritability (broad sense) ranged from 0.28 (peak viscosity and breakdown) to 0.59 (peak time).

3.2. Variation in Tuber Dry Matter Content and Starch Pasting Properties among Locations

The differences in the means and ranges of locations for dry matter content and pasting properties are shown in Table 3. Tuber dry matter content differed significantly across locations: 36.7% for SGS, 34.9% for FST, and 36.9% for RF. The average peak viscosity across genotypes was lowest in RF (2290.2 cP) and highest in FST (2495.7 cP). The average trough viscosity was similar in different locations. The breakdown of different locations ranged from 311.2 cP in RF to 447.6 cP in FST (Table 3). Unlike peak viscosity, a significant difference in final viscosity among the locations was not detected. Average setback differed significantly across locations: 1106.8 cP for SGS, 932.5 cP for FST, and 1201.2 cP for RF. The average peak time was lowest in FST (5.1 min) and highest in RF (5.3 min). In terms of the pasting temperature, the highest value was observed in RF (82.2 °C; Table 3).

3.3. Variation in Tuber Dry Matter Content and Starch Pasting Properties among Genotypes

The best linear unbiased prediction (BLUP) values of the nine traits are presented in Table 4. A broad range of tuber dry matter content and pasting properties were observed in the 20 genotypes, with an average of 36.2% tuber dry matter content, 2344.9 cP peak viscosity, 1971.7 cP trough viscosity, 383.8 cP breakdown, 3030.7 cP final viscosity, 1062.8 cP setback, 5.2 min peak time, and 81.3 °C peak temperature (Table 4).

Table 2. Variation due to random effect and genetic parameter estimates of tuber dry matter content and starch pasting properties in twenty *Dioscorea rotundata* genotypes grown in three different locations in Nigeria.

Variance and Genetic Paremeters	Dry Matter Content		Peak Viscosity		Trough Viscosity		Breakdown		Final Viscosity		Setback		Peak Time		Pasting Temp.	
Variance component																
Genotype	5.27	*	40,181.48	*	51,455.75	*	14,429.07	*	123,274.50	*	54,769.15	*	0.11	*	0.64	*
Genotype: Location	1.33		849.74		373.77		8989.99		31,239.04		32,034.98	*	0.02	*	0.10	
Loc: Rep: Block	0.82		0.01		0.01		0.01		0.06		0.00		0.00		0.13	
Error variance (SGS)	4.61	**	109,165.90	**	87,993.32	**	24,825.70	**	145,470.30	**	61,587.15	**	0.07	**	0.75	*
Error variance (FST)	3.72	**	128,866.20	**	47,365.28	**	40,080.76	**	104,636.70	**	74,931.97	**	0.04	**	1.04	**
Error variance (RF)	7.04	**	73,139.90	**	69,574.90	**	18,247.77	**	122,843.60	**	57,839.27	**	0.05	*	1.30	**
Genetic parameters																
Phenotypic Coefficient of variation (PCV)%	9.79		16.22		17.58		58.91		17.42		36.63		8.40		1.70	
Genetic Coefficient of variation (GCV)%	6.35		8.55		11.50		31.30		11.58		22.02		6.47		0.98	
Repeatability	0.80		0.97		0.99		0.62		0.80		0.63		0.85		0.86	
(average correlation b/n locations)	(0.12)		(0.22)		(0.11)		(0.18)		(0.12)		(0.16)		(0.08)		(0.15)	
Heritability	0.45		0.28		0.42		0.28		0.44		0.36		0.59		0.33	
(broad-sense)	(0.10)		(0.09)		(0.10)		(0.10)		(0.11)		(0.12)		(0.10)		(0.15)	

Note: Values in bracket standard error. *, ** indicate significance at $p < 0.01$ and $p < 0.001$ levels, respectively. SGS mean Southern Guinea Savanna. FST mean Forest-Savanna Transition. RF mean rainforest.

Table 3. Mean (and range) of dry matter content and pasting properties at different locations.

Location	Dry Matter Content (%)	Peak Viscosity (cP)	Trough Viscosity (cP)	Breakdown (cP)	Final Viscosity (cP)	Setback (cP)	Peak Time (min)	Pasting Temp. (°C)
South Guinea Savanna	36.7 b (30.8–42.7)	2294.9 a (1801.0–2972.7)	1918.1 a (1384.7–2297)	376.8 ab (77.0–915.3)	3024.9 a (2296.0–3958.0)	1106.8 ab (514.0–1902.0)	5.2 ab (4.6–6.3)	80.8 a (79.4–83)
Forest Savanna transition	34.9 a (29.1–39.3)	2495.7 b (1818.7–3311.0)	2018.0 a (1425.7–2464.7)	477.6 b (50.0–1043.3)	2950.5 a (2142.0–4869.7)	932.5 a (396.0–2711.0)	5.1 a (4.6–5.7)	80.9 a (79.6–82.9)
Frainforest	36.9 b (31.8–43.2)	2290.2 a (1933.0–2905.3)	1979.0 a (1593–2462.3)	311.2 a (106.7–527.7)	3180.2a (2399.3–3780.0)	1201.2 b (770.0–1644.7)	5.3 b (4.8–6.4)	82.2 b (79.9–84.8)

Different letters in the same column indicate significant differences at $p < 0.05$ as determined by Tukey's HSD test.

Table 4. Best linear unbiased prediction values of tuber dry matter content and starch pasting properties in twenty *Dioscorea rotundata* genotypes grown in three different locations in Nigeria.

	Dry Matter Content (%)	Peak Viscosity (cP)	Trough Viscosity (cP)	Breakdown (cP)	Final Viscosity (cP)	Setback (cP)	Peak Time (min)	Pasting Temp. (°C)
Meccakusa	34.4	2565.8	1922.8	607.5	2629.5	671.6	5.0	80.9
Amula	36.2	2606.3	2363.2	394.4	3403.3	1036.6	5.1	81.1
TDr1100163	35.6	2341.6	1990.5	362.3	3086.8	1092.6	5.1	82.8
TDr1100421	33.3	2527.7	2270.5	305.7	3534.7	1238.9	5.2	81.2
TDr1100034	33.5	2395.7	2243.3	190.4	3409.6	1190.6	5.7	81.5
TDr1100873	39.8	2417.5	2081.7	348.9	2840.0	752.7	5.4	81.3
TDr1100835	36.6	2262.8	1828.8	304.5	3022.9	1185.6	5.1	80.5
TDr0900082	37.1	2107.7	1613.3	483.8	2422.9	828.9	4.7	80.9
TDr1100101	36.4	2219.4	1793.5	424.9	2621.0	831.1	5.0	81.8
TDr1100492	38.5	2468.5	1906.4	547.3	2758.7	846.5	4.9	80.1
TDr1100497	37.8	2376.4	1841.9	542.4	2731.8	902.7	4.9	80.6
TDr0900002	38.2	1985.0	1530.6	379.8	2484.0	961.9	4.9	82.3
TDr0500491	38.7	2274.7	1802.4	509.0	2762.1	995.2	4.9	81.6
TDr8902665	39.6	2536.0	2195.8	509.8	3209.0	1031.5	5.2	80.6
TDr8902157	39.3	2651.0	2212.7	467.0	3256.1	1048.5	5.1	80.4
TDr0900058	36.3	2145.1	1792.9	345.0	2872.6	1096.9	5.1	81.3
TDr1100585	31.7	2352.2	2091.6	264.0	3288.2	1165.8	5.3	81.0
TDr1100582	32.2	2171.3	1905.6	281.2	3157.6	1271.4	5.4	81.7
TDr1100278	34.0	2206.6	2058.8	145.2	3684.8	1401.5	6.1	82.6
TDr1100396	34.1	2287.8	1988.2	263.6	3438.9	1705.5	5.5	81.1
Average	36.2	2344.9	1971.7	383.8	3030.7	1062.8	5.2	81.3
Least significant difference	3.0	335.7	242.1	220.7	462.4	400.8	0.3	1.1

The dry matter content of tubers from different genotypes ranged from 31.7% in TDr1100585 to 39.8% in TDr1100873 with a mean and standard deviation of 36.2 and 2.4, respectively. TDr0500491, TDr0900002, TDr1100492, and TDr1100873 expressed higher tuber dry matter content than the landrace cultivars, Amula and Meccakusa. Trough viscosity varied from 1530.6 cP (TDr0900002) to 2363.2 cP (Amula). Final viscosity in the genotypes ranged from 2422.9 cP to 3684.8 cP, with the lowest for TDr0900082 and the highest for TDr1100278. The lowest breakdown was found in TDr1100278 (145.2 cP) and the highest was in Meccakusa (607.5 cP), while Meccakusa had the lowest setback (671.6 cP) and TDr1100396 had the highest setback (1705.5 cP). TDr0900082 showed the lowest peak time (4.7 min) and TDr1100034 showed the highest peak time (5.7 min). Less variation in pasting temperature (80.1–81.3 °C) was observed in tested genotypes.

3.4. Correlation Analyses among Tested Parameters (Dry Matter Content and Starch Pasting Properties)

The Pearson correlation coefficients for the relationship between dry matter content and starch properties are shown in Table 5. The dry matter content of tubers showed a positive correlation with breakdown and a negative correlation with final viscosity, setback, and peak time. Peak viscosity exhibited positive correlations with trough viscosity and negative correlations with peak temperature. Trough viscosity showed significant and positive correlations with final viscosity and peak time. Breakdown had negative correlations with final viscosity, setback, peak time, and pasting temperature. Final viscosity was positively correlated with setback and peak time. Setback had a positive correlation with peak time.

Table 5. Correlation Analysis of dry matter content and starch pasting properties by using Best linear unbiased prediction (BLUP) value in twenty *Dioscorea rotundata* genotypes grown at three different locations in Nigeria.

Parameter	Dry Mater Content	Peak Viscosity	Trough Viscosity	Breakdown	Final Viscosity	Setback	Peak Time
Peak viscosity	0.12						
Trough viscosity	−0.21	0.80 ***					
Breakdown	0.61 **	0.32	−0.27				
Final viscosity	−0.50 *	0.38	0.80 ***	−0.67 **			
Setback	−0.54 *	−0.16	0.28	−0.74 **	0.76 ***		
Peak time	−0.48 *	0.02	0.51 *	−0.80 ***	0.78 ***	0.65 **	
Pasting temperature	−0.31	−0.50 *	−0.14	−0.50 *	0.13	0.24	0.38

*, **, *** indicate significant different at $p < 0.05$, 0.01 and 0.001 level, respectively.

3.5. Differentiation and Grouping of Genotypes Based on Starch Pasting Properties

Data on starch pasting properties was used to estimate the Mahalanobis generalized distance between the yam genotypes, and a dendrogram was constructed using the predicted BLUP value for each trait (Figure 3). The analysis divided the 20 genotypes into three clusters. Two genotypes were clustered together into cluster I, eleven genotypes were clustered together into cluster II, and seven genotypes, including the two landrace cultivars, clustered into cluster III (Figure 3).

3.6. AMMI Model Analysis on Tuber Yield and Crude Starch Yield

The average tuber yield and crude starch yield were estimated through AMMI model analysis. In addition, AMMI stability values (ASV), yield stability index (YSI), and the ranking orders on tuber yield and crude starch yield were calculated and indicated in Table S2. Among the genotypes, a higher mean tuber yield was observed for TDr0900058, and genotypes with a stable tuber yield over the environments, represented by a lower AMMI stability value (ASV), was observed for TDr1100873 (Table S2). In crude starch content, the highest crude starch content was observed for TDr1100873, and TDr1100492 showed the lowest ASV among the tested genotypes. However, the post-hoc testing for mean fresh tuber yield (tha^{-1}) and crude starch content (%) showed no significant differences between the clusters of white yam genotypes based on starch pasting properties (Figure 4).

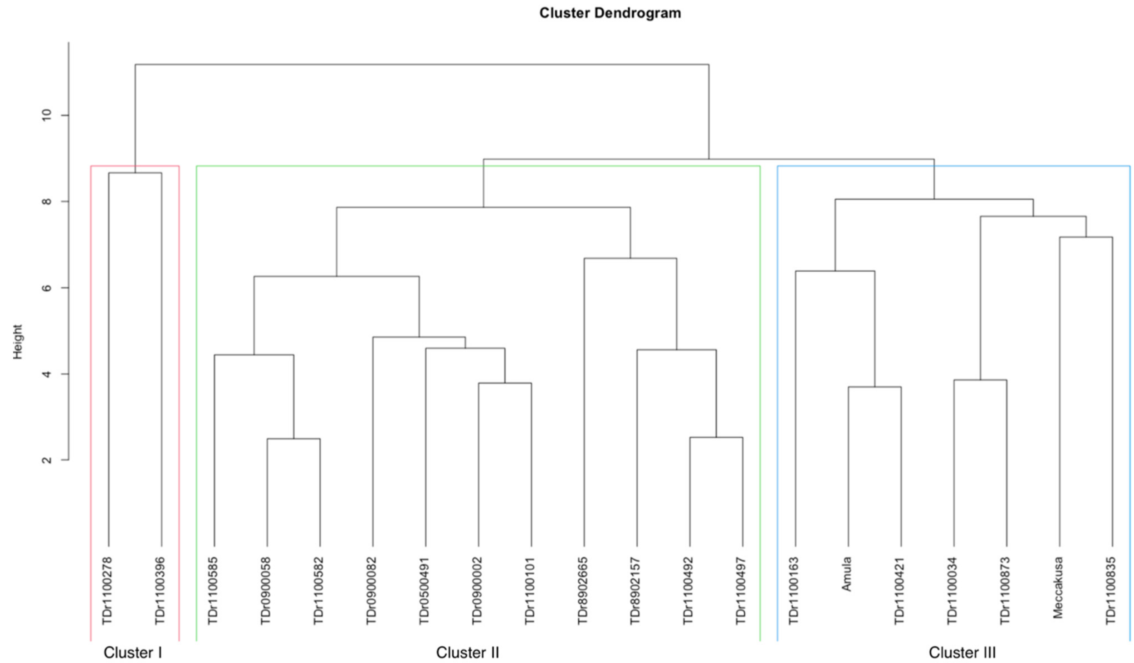

Figure 3. Cluster analysis of predicted best linear unbiased prediction (BLUP) values of starch pasting properties between genotypes.

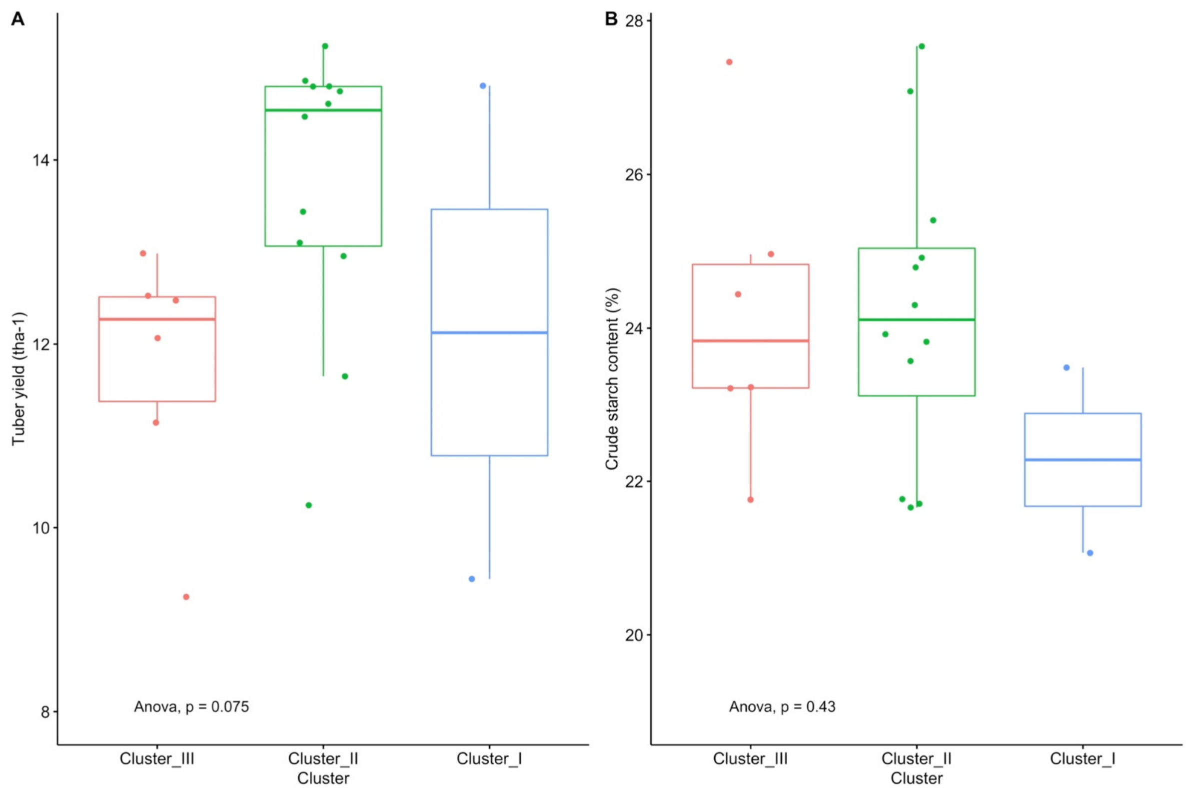

Figure 4. Multiple comparisons test of cluster means of white yam genotypes based on starch pasting properties for tuber yielding potential and crude starch content estimated by AMMI model analysis. (**A**) = cluster mean comparisons test for tuber yielding potential and (**B**) = cluster mean comparisons test for crude starch content.

4. Discussion

The current study was carried out to aid yam breeders in developing breeding strategies for improved tuber quality (dry matter content and starch pasting properties). The study assessed the effects of genotype, growing location, and their interaction on the dry matter content and starch pasting properties of white Guinea yam in three different agroecological zones of Nigeria (Table 2). Although the effect of genotype by growing environment on starch pasting properties has been reported for rice [14,15], wheat [16], and potato [17], the present study is the first to report the effects of growing location and G × L interaction on the pasting properties of white Guinea yam starch. In the current study, genotype and growing location contributed most to the variance in tuber dry matter content and starch pasting properties. However, the G × L interaction effect was lower than the genotype and growing location effects. In addition, high repeatability of the data was observed in tuber dry matter content, peak viscosity, trough viscosity, final viscosity, peak time, and pasting temperature from the three different locations. Peak viscosity, trough viscosity, and final viscosity of yam flour are reported to positively correlate with food qualities, such as consistency, elasticity, and hardness of water yam (*D. alata*) products (pounded yam) [9]. Therefore, it is suggested that any of the three cultivation locations could be used as an evaluation site for the above traits. Butler et al. [41] suggested that GCV, together with heritability estimates, provides optimal insights into the extent of advancement that can be expected by selection. The high GCV and high heritability observed for the tuber dry matter content, trough viscosity, and peak time in the present study (Table 2) indicate that selection pressure can be applied to encourage desirable traits in the most promising clones. Meanwhile, moderate PCV and GCV were observed for peak viscosity, breakdown, final viscosity, setback, and pasting temperature, implying that their characteristics can be improved by more vigorous selection across multiple environments.

In the current study, results revealed that the growing location influences dry matter content and starch pasting properties, particularly peak viscosity, breakdown, setback, peak time, and pasting temperature (Table 3). In the three different agroecological zones where this study was conducted, the rainfall patterns after November differed (Figure 2), and the soil nutrient conditions were also different (Table 1). Sriroth et al. [18] reported that rainfall had a significant effect on the pasting properties of cassava starch, especially when it occurred prior to harvesting time. It was also reported that variations in soil moisture and nutrient availability and ambient temperature impact rice starch properties such as amylose content, and starch granule size distribution [49]. The current study suggests that the environmental factors in the growing location, such as rainfall, particularly before the harvesting period, and soil nutrients can affect starch pasting properties in white Guinea yam. However, it is necessary to conduct further research to clarify the relationships among dry matter accumulation, starch pasting properties, and environmental factors in growing locations.

Moreover, the results of this study revealed that the dry matter content and characteristics of starch pasting properties differ depending on the genotype (Table 4). The pasting temperature of the starch in the current set of materials was high (over 80 °C), which agrees with previous reports [21,22]. However, narrow diversity of pasting properties was observed compared with those reported by Otebayo et al. [19], who observed highly significant variation in starch pasting properties among 27 white Guinea yam cultivars collected in Nigeria. A mini core collection for white Guinea yam germplasm (106 genotypes) has been developed based on simple sequence repeat markers, which has revealed a wide diversity of agronomic traits [50]. A wide diversity of tuber quality traits in the mini core collection for white Guinea yam is expected. Therefore, the implementation of dry matter content and starch characterization to enhance the breeding process for starch utilization should be further assessed.

Baah et al. [10] reported a positive correlation between final viscosity and eating quality of pounded yam, such as consistency, elasticity, and hardness in *D. alata*. The current study showed that final viscosity has positively correlated with trough viscosity, breakdown, setback, and peak time (Table 5), which agrees with previous results in rice starch pasting properties [14]. The current study suggested that the dry matter content is closely related to the final viscosity associated with the quality of Pounded yam (Table 5). In addition, since the heritability of dry matter weight is relatively high (Table 2), the dry matter content of white guinea yam tuber could be one of the selection indexes for selecting excellent breeding lines based on the quality of pounded yam.

Characterization of starches in terms of their pasting properties was performed by cluster analysis, and three groups were identified (Figure 3). Cluster III contained Amula, which is recognized as an excellent landrace cultivar for making pounded yam in Oyo North, Nigeria [51]. Thus, from the cluster analysis, it was inferred that yam starches in the same cluster group have similar, or closely related, pasting properties to the extracted yam starch. From our studies, TDr1100412 exhibited the most similar starch pasting properties to those of Amula, while TDr1100835 showed the most similar starch pasting properties to Meccakusa, among the tested breeding lines (Figure 3). Among cluster III, the tuber yield of TDr1100873 was the second highest after Amula, and the tuber yield was stable throughout three cultivation locations. The crude starch yield of TDr1100873 was the highest, with stable all cultivation locations in cluster III (Table S2). In addition, TDr1100873 showed similar starch pasting properties and higher dry matter content to the two landrace cultivars (Figure 3 and Table 4). Therefore, they are considered suitable varieties for future breeding activities. The current study findings may contribute to the establishment of a more effective breeding scheme for the improvement of yam tuber quality. Since TDr1100873 has a higher dry matter content than landrace cultivars and exhibits similar starch pasting properties with them, it could be a good candidate to use in breeding and to register as a new improved variety for direct use in cultivation. In addition, the breakdown of starch of TDr1100837 (348.9 cP) was lower than starches from cassava varieties (709.34–1208.30 cP) [52], suggesting that starch from the white yam variety is superior to the cassava varieties as its viscosity not rapidly lowered on heating under shear. Likewise, the high pasting temperature of yam variety starches in our study (~81.3 °C, Table 4) suggested that they did not easily form pastes, and hence were more resistant to heating and shearing than starches of cassava varieties [52]. Therefore, the starch obtained from the TD1100873 can also be used as a hydrocolloid or thickener in foods that will be submitted to heat and mechanical treatment, such as canned foods, dehydrated soups, and foods that need sterilization.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/agronomy11101944/s1. Table S1: Water chemical properties of IITA, Ibadan. Table S2: AMMI stability values (ASV), yield stability index (YSI) and the ranking orders.

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