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GENETIC DIVERSITY OF CHLOROPHYLL FLUORESCENCE GERMPLASMS EFFECTS ON DRY MATTER OF CASSAVA

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SUMMARY

Physiological traits can help explain cassava's (*Manihot esculenta* Crantz) health and identify superior genotypes for breeding programs. The study objective was to evaluate the performances of various cassava genotypes based on chlorophyll fluorescence, total crop dry weight, and storage root dry weight. The 100 cassava genotypes grown under field conditions ensued from May 2020 to May 2021 (2020–2021) and from May 2021 to May 2022 (2021–2022) at the Field Crop Research Station of Khon Kaen University, Thailand. The chlorophyll fluorescence measurements commenced 3, 6, 9, and 12 months after planting (MAP). Recording of storage root and total crop dry weights occurred at 12 MAP. The results revealed that the appropriate time to observe chlorophyll fluorescence was at 6 and 9 MAP, relating to cassava's dry weight at the final harvest. Huay Bong 90 proved a superior genotype for storage root and total crop dry weights at 12 MAP and chlorophyll fluorescence at 6 and 9 MAP for both growing season years. A genotype CMR 38-125-77 also performed well in chlorophyll fluorescence for both growing seasons, and it was a distinct top genotype for the 2020–2021 growing season and ranked third for the 2021–2022 growing season based on total crop dry weight at 12 MAP. These genotypes could benefit as an alternative germplasm for cultivation and future breeding programs.

Keywords: Breeding, cassava (*Manihot esculenta* Crantz), dry weight, physiology, selection, storage root

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Key findings: The appropriate growth stages to evaluate chlorophyll fluorescence that relate to dry weight at the final harvest of cassava (*M. esculenta* Crantz) germplasm were 6 MAP for F_v'/F_m' and 6 and 9 MAP for F_v/F_m. Cassava germplasm classification for this study depended on F_v'/F_m', F_v/F_m, total crop dry weight, and storage root dry weight. The desirable cassava genotypes for both growing seasons were Huay Bong 90 and CMR 38-125-77.

INTRODUCTION

Cassava (*Manihot esculenta* Crantz) is a recognized essential source of carbohydrates (Balagopalan, 2002). It can serve as food for humans, animal feed, and raw material for several products (Burns *et al.,* 2010; Rosenthal and Ort, 2011). With an increasing world population, the demand for cassava also rises. Several approaches to improve cassava productivity comprise choosing high-yielding cultivars and using appropriate crop management practices.

Cassava breeding for high yield is a strategy to improve productivity sustainably. Selecting suitable parents for crossing is the first critical step for a successful cassava-breeding program. In Thailand, the criteria for choosing the parental clones relied typically on morphology, total crop biomass, and yield. These crop traits usually had low heritability, with some crop characteristics involving destructive samples (Barandica *et al.*, 2016). For a better understanding of the physiology of crop behavior to make proper decision-making for selection, measuring other physiological characteristics is also necessary (Kawano, 1990; Okogbenin *et al.*, 2013). Identifying appropriate cassava genotypes based on physiological features with a practical approach and without destructive samples requires implementation.

Chlorophyll fluorescence is a physiological trait that can help explain plant health and photosynthetic efficiency, and it involves the maximum efficiency of photosystem II (PSII) photochemistry in the light (F_v'/F_m') and the maximum quantum efficiency of PSII photochemistry (F_v/F_m) (Murchie and Lawson, 2013; Santanoo *et al.*, 2019). This physiological trait can be notable by non-destructive samples with simple and continuous measurements. Researchers have widely observed chlorophyll fluorescence to determine the response of crops to various growing conditions. Reports also stated chlorophyll fluorescence for some cassava genotypes growing under nitrogen deficiency (Cruz *et al.*, 2003), rainfed condition (Sawatraksa *et al.*, 2018), and irrigated condition (Santanoo *et al.*, 2019).

However, research on the appropriate growth period to determine the F_v'/F_m' and F_v/F_m that could relate to total crop dry weight and storage root yield for various cassava genotypes is insufficient. Therefore, the study objective was to evaluate the performances of different cassava genotypes based on F_v'/F_m', F_v/F_m, total crop dry weight, and storage root dry weight. This work can provide parental material for future cassava breeding programs, and the information obtained here would help design the appropriate measurement of F_v'/F_m' and F_v/F_m for cassava breeding initiatives.

MATERIALS AND METHODS

Plant materials and experimental design

The experiment on cassava (*Manihot esculenta* Crantz) commenced under field conditions from May 2020 to May 2021, and its repetition ensued from May 2021 to May 2022 at the Field Crop Research Station of Khon Kaen University, Khon Kaen Province, Thailand (latitude 16°47′ N, longitude 102°80′ E, 195 masl). The soil type for this experimental site is Yasothon Series (Yt: Oxic Paleustults, fine-loamy, siliceous). The experimental design was a randomized complete block design with three replications. The 100 cassava genotypes' arrangement as treatments had a plot size of 3 m × 6 m with plant spacing of 100 cm × 80 cm.

Crop management

For land preparation, breaking the hardpan employed a chisel plow at 30–60 cm depth. Sunn hemp (*Crotalaria juncea*) treatment as green manure occurred during planting, with cow dung applied at 6250 kg ha^{-1}. Standard plowing provided uniform soil for the experiment. Healthy stems of cassava were options as planting sources, with their stem cuttings of 20 cm (stick) used for cultivation. The cuttings' immersion into water containing thiamethoxam (3-[2-chlorothiazol-5-ylmethyl]-5-methyl-[1,3,5]-oxadiazinan-4-ylidene-N-nitroamine 25% water dispersible granules) had a rate of 4 g 20 L^{-1} water for 20 min. Their incubation in a gunny sack followed at ambient temperature for three days.

Inserting the sticks into the soil on the soil ridges had a 100 cm × 80 cm spacing. The sets of tensiometer placement comprised a 40 cm depth for each replication to monitor soil water tension. Supplementary irrigation to avoid crop water stress included an overhead sprinkler system when water tension was below -30 kPa, and irrigation stopped when the water tension was between -20 and -10 kPa (Richards and Weaver, 1944).

Weed control continued manually throughout the cropping season. For 30 days after planting, fertilizer application depended on soil properties earlier determined before planting and the nutrient requirements for cassava, as proposed by Howeler (2002). Applying the fertilizers carbonic diamide CH_4N_2O and potassium chloride (KCl) had rates of 46.9 and 56.25 kg ha^{-1}, respectively. In addition, the treatment of compound fertilizer of N-P_2O_5-K_2O formula 15-7-18 used 312.5 kg ha^{-1} two months after planting (MAP) (Department of Agriculture, 2008).

Data collection

Soil samples before planting came from three points at depths of 0–15 and 15–30 cm. Consideration of the physical and chemical properties of soil has progressed (Table 1). The chlorophyll fluorescence measurements followed 3, 6, 9, and 12 MAP with matured leaves (5th position from the top) for four plants in each experimental plot using Mini Pam II (Heinz WalzGmbH, Effeltrich, Germany) under natural light conditions (starting from 9:00 and 10:00 a.m.) to measure the maximum efficiency of PSII photochemistry under natural light (F_v'/F_m') conditions. Minimal fluorescence yield of the dark-adapted state (F_0) measurement happened in complete darkness before sunrise (4:30 a.m.). Maximal fluorescence of the dark-adapted state (F_m) employed a saturating pulse of 400 µmol $m^{-2}s^{-1}$ lasting 0.8 s. The maximal quantum yield of PSII photochemistry (F_v/F_m) calculation followed the equation below:

$$F_v/F_m = (F_m - F_0)/F_m \quad (1)$$

Table 1. Soil properties before planting for 2020–2021 and 2021–2022 growing seasons.

Soil properties	Soil depth (cm)			
	0-15		15-30	
	2020–2021	2021–2022	2020–2021	2021–2022
Physical properties				
Sand (%)	77.3	71.5	75.6	68.3
Silt (%)	17.5	19.7	18.9	19.2
Clay (%)	5.2	8.8	5.6	12.4
Soil texture	Sandy loam	Sandy loam	Sandy loam	Sandy loam
Chemical properties				
pH (1:1 H_2O)	6.6	6.6	6.5	6.7
Electrical conductivity (1:5) (mS cm^{-1})	0.05	0.03	0.05	0.03
Organic matter (%)	0.50	0.50	0.51	0.30
Total Nitrogen (%)	0.04	0.03	0.03	0.03
Available Phosphorus (mg kg^{-1})	163.8	75.0	148.1	50.3
Exchangeable Potassium (mg kg^{-1})	89.3	35.8	83.0	32.3
Cation exchange capacity (cmol kg^{-1})	5.0	3.6	4.8	4.1

Storage root and total crop dry weights came from four plants in the middle rows of each plot at 12 MAP. The plants reached separation into storage roots and other plant organs. Plant parts became subsamples (about 10% of the total fresh weight of each organ). The subsamples of the plant received oven drying at 80 °C to achieve a constant dry weight. Then, the total crop and storage root dry weights calculation followed.

Statistical analysis

A stepwise regression analysis helped examine the relationship between the chlorophyll fluorescence, total crop dry weight, and storage root dry weight. The analysis of variance continued for each growing season, followed by the combined analysis for both growing seasons. The statistical analysis used the Statistix 10 program (Statistix, 2013) and the MSTAT–C Version 4.2 (Freed and Nissen, 1992) following the procedure described by Gomez and Gomez (1984).

RESULTS

Combined analysis

In Cassava (*M. esculenta* Crantz), the combined analysis of variance for 2020–2021 and 2021–2022 growing seasons showed that genotype (G) shared the maximum proportion of variation for total crop dry weight (49.79%), storage root dry weight (62.02%), F_v'/F_m' at 6 MAP (66.04%), F_v/F_m at 6 MAP (49.47%), and F_v/F_m at 9 MAP (71.40%). These revealed highly significant differences ($P < 0.01$) (Table 2), indicating the diversity of the tested genotypes based on these crop traits. The contribution of year (Y) seemed better for total crop and storage root dry weights, with a variation value of 37.35% and 23.89%, respectively. The difference in the growing environment, such as soil properties before planting (Table 1) and weather conditions (Figure 1), may account for the variation between the two growing seasons. The interaction between genotype and year (G × Y) was evident for total crop and storage root dry weights, F_v'/F_m' and F_v/F_m at *6* and 9 MAP, implying different responses of the cassava genotypes in the separate years.

Stepwise regression analysis

The stepwise analysis ensued to investigate the relationship between dry matter at 12 MAP and chlorophyll fluorescence at 3, 6, 9, and 12 MAP. The results from Table 3 demonstrated that chlorophyll fluorescence (F_v'/F_m' and F_v/F_m at 6 MAP and F_v/F_m at 9 MAP) linked to the total crop dry weight for both growing seasons. The coefficient of determination values also indicated that the total crop dry weight could be due to F_v'/F_m' and F_v/F_m at 6 MAP and F_v/F_m at 9 MAP, with levels of 89% for the 2020–2021 growing season and 84% for the 2021–2022 growing season. For storage root dry weight, it showed association with F_v'/F_m' at 6 MAP and F_v/F_m at 9 MAP with the coefficient of determination values of 74% and 80% for the 2020–2021 and the 2021–2022 growing seasons, respectively.

Promising genotypes

The results indicated significant differences statistically ($P < 0.01$) among the tested genotypes for chlorophyll fluorescence and dry matter. Total crop dry weight for the 2020–2021 and 2021–2022 growing seasons varied from 0.47–3.53 and 0.19–2.30 kg plant^{-1}, respectively. For storage root dry weight, the results ranged from 0.27–2.75 to 0.10–1.78 kg plant^{-1} for the 2020–2021 and 2021–2022 growing seasons, respectively. Since there are too many cassava genotypes in this study, the data focused more on the favorable genotypes for better understanding.

The mean comparison for the 2020–2021 growing season (Table 4) indicated that the top genotypes for total crop dry weight at 12 MAP were Huay Bong 90, Huay Bong 80, Kasetsart 50, Rayong 1, CMR 38-125-77, CMR 36-30-329, and HP2 (CM305-13). These genotypes also had the highest values for F_v'/F_m' at 6 MAP, F_v/F_m at 6 MAP, and F_v/F_m at 9 MAP. Table 4 also shows the classification of Huay Bong 90 as the top genotype for storage root dry weight at 12 MAP.

Table 2. Percentage of sum squares (%SS) based on the combined analysis of variance for the 2020–21 and the 2021–22 growing seasons for total crop dry weight and storage root dry weight at 12 months after planting (MAP) and for chlorophyll fluorescence at 3, 6, 9, and 12 MAP.

Crop traits		Source of variation				
		Years (Y)	Replications within year	Genotypes (G)	G × Y	Pool error
Total crop dry weight		37.35**	0.33	49.79**	8.81**	3.71
Storage root dry weight		23.89**	0.19	62.02**	9.16**	4.71
F_v'/F_m'	3 MAP	0.00^{ns}	4.00	39.13**	0.00^{ns}	56.87
	6 MAP	1.95*	0.64	66.04**	14.12**	17.25
	9 MAP	1.95*	0.95	18.85^{ns}	19.19**	59.06
	12 MAP	0.03^{ns}	10.66	15.14^{ns}	12.45^{ns}	61.72
F_v/F_m	3 MAP	0.00^{ns}	5.23	29.54**	0.00^{ns}	65.23
	6 MAP	0.00^{ns}	7.84	49.47**	12.71**	29.98
	9 MAP	0.00^{ns}	0.54	71.40**	18.15**	9.90
	12 MAP	0.85^{ns}	3.79	18.10^{ns}	16.11^{ns}	61.14

F_v'/F_m' is the maximum efficiency of photosystem II (PSII) photochemistry in the light. F_v/F_m is the maximum quantum efficiency of PSII photochemistry. ** = significant at P < 0.01, * = significant at P < 0.05, ns = nonsignificant.

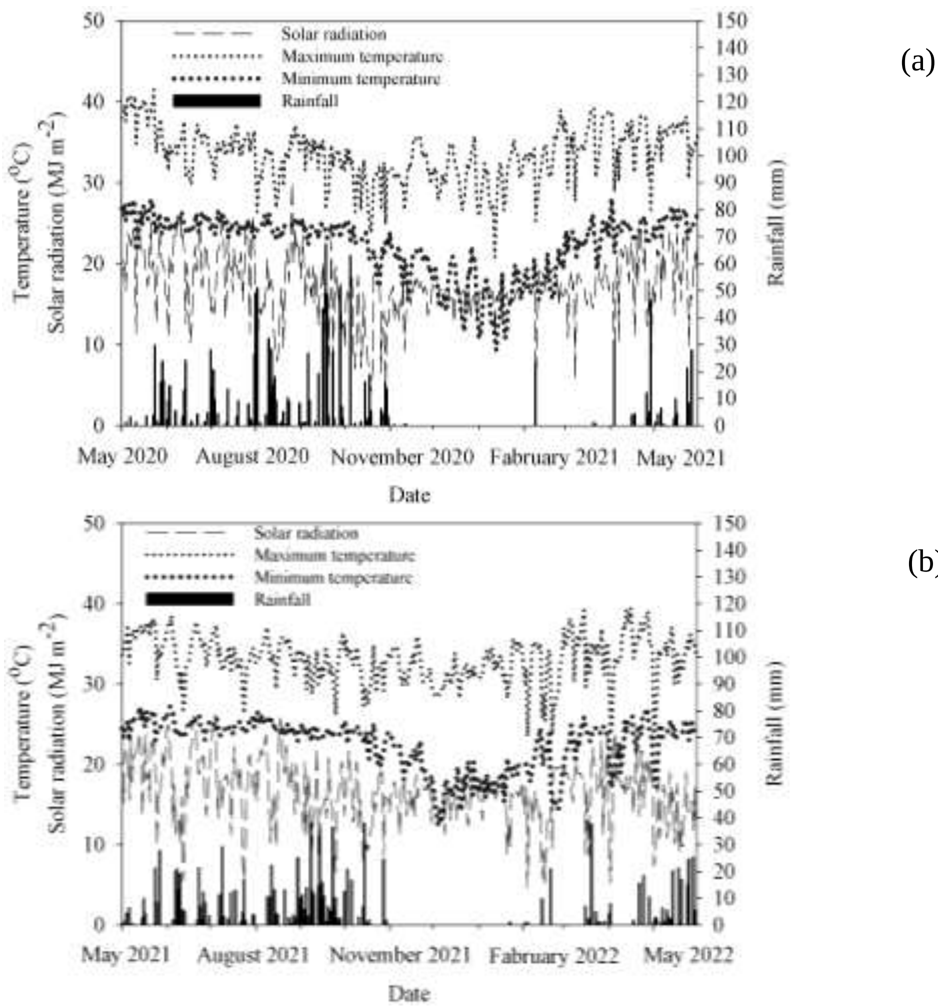

Figure 1. Rainfall (mm), maximum temperature (°C), minimum temperature (°C), and solar radiation (MJ m^{-2}) from May 2020 to May 2021 (a) and May 2021 to May 2022 (b) at the Field Crop Research Station, Khon Kaen University, Thailand.

Table 3. Stepwise regression analysis for the total crop and storage root dry weights at 12 months after planting (MAP) and chlorophyll fluorescence for the tested cassava genotypes for the 2020–21 and the 2021–22 growing seasons.

Years	Variables	Coefficient	t	Determination coefficient (R^2)
2020–21	Total crop dry weight			
	Constant	-16.34	-32.10**	0.89
	F_v'/F_m' at 6 MAP	1.63	3.49**	
	F_v/F_m at 6 MAP	2.96	3.88**	
	F_v/F_m at 9 MAP	18.30	22.10**	
	Storage root dry weight			
	Constant	-10.39	-17.22**	0.74
	F_v'/F_m' at 6 MAP	2.67	4.82**	
	F_v/F_m at 6 MAP	1.89	2.10*	
	F_v/F_m at 9 MAP	10.56	10.76**	
2021–22	Total crop dry weight			
	Constant	-7.24	-17.67**	0.84
	F_v'/F_m' at 6 MAP	4.41	11.72**	
	F_v/F_m at 6 MAP	1.19	1.98*	
	F_v/F_m at 9 MAP	6.21	9.27**	
	Storage root dry weight			
	Constant	-5.02	-16.25**	0.80
	F_v'/F_m' at 6 MAP	3.78	11.60**	
	F_v/F_m at 9 MAP	4.60	8.78**	

F_v'/F_m' is the maximum efficiency of photosystem II (PSII) photochemistry in the light. F_v/F_m is the maximum quantum efficiency of PSII photochemistry. ** = statistical significance at $P < 0.01$, * = statistical significance at $P < 0.05$.

Table 4. Mean comparison for the top genotypes based on total crop dry weight (kg plant^{-1}) and storage root dry weight (kg plant^{-1}) at 12 months after planting (MAP) and their chlorophyll fluorescence (F_v'/F_m' and F_v/F_m) at 6 and 9 MAP for the 2020–21 growing season.

No.	Genotypes	Total crop dry weight	Storage root dry weight	F_v'/F_m' at 6 MAP	F_v/F_m at 6 MAP	F_v/F_m at 9 MAP
73.	Huay Bong 90	3.527 A	2.750 A	0.757 AB	0.876 A	0.877 A
72.	Huay Bong 80	3.277 AB	2.280 B	0.751 A-D	0.875 AB	0.874 AB
78.	Kasetsart 50 (KU50)	3.193 A-C	2.113 B-D	0.744 A-H	0.874 A-C	0.872 A-D
83.	Rayong 1	3.167 A-D	1.917 B-G	0.734 A-L	0.875 AB	0.873 A-C
69.	CMR 38-125-77	3.113 A-E	2.187 BC	0.746 A-G	0.874 A-C	0.870 A-E
64.	CMR 36-30-329	3.093 A-F	1.830 C-I	0.725 A-Q	0.875 AB	0.869 A-F
74.	HP2 (CM305-13)	2.983 A-G	2.147 BC	0.743 A-I	0.874 A-C	0.868 A-F
35.	CMR 24-89-65	2.970 B-H	2.027 B-E	0.726 A-P	0.874 A-C	0.867 A-F
85.	Rayong 11	2.967 B-H	2.127 BC	0.739 A-J	0.873 A-D	0.868 A-F
90.	SM 937-8	2.940 B-I	1.993 B-F	0.749 A-F	0.874 A-C	0.868 A-F
51.	CMR 31-06-103	2.873 B-J	1.873 B-H	0.758 AB	0.873 A-D	0.867 A-F
100.	Rayong 72	2.837 B-K	2.190 BC	0.740 A-I	0.872 A-E	0.863 A-H
98.	Pirun 2	2.820 B-K	2.040 B-E	0.752 A-C	0.873 A-D	0.865 A-G
61.	CMR 35-23-76	2.707 B-L	1.370 J-U	0.748 A-F	0.871 A-F	0.859 A-I
58.	CMR 35-21-199	2.687 C-M	1.573 F-O	0.749 A-F	0.870 A-G	0.859 A-I
36.	CMR 25-105-1280	2.660 C-N	1.060 P-h	0.734 A-L	0.869 A-G	0.855 A-J
21.	CM 781-2	2.600 D-O	1.423 H-S	0.751 A-D	0.870 A-G	0.854 A-J
1.	1167	2.573 E-P	1.320 J-X	0.762 A	0.869 A-G	0.858 A-I
14.	CM 3299-14	2.523 F-Q	1.413 I-T	0.740 A-I	0.868 A-H	0.851 A-M
71.	Huay Bong 60	2.517 F-Q	1.757 C-J	0.752 A-C	0.868 A-H	0.852 A-L

F_v'/F_m' is the maximum efficiency of photosystem II (PSII) photochemistry in the light. F_v/F_m is the maximum quantum efficiency of PSII photochemistry. Means in the same column with the same letters are not significantly different according to Duncan's multiple range test (DMRT) at $P < 0.01$.

Table 5. Mean comparison for the top genotypes based on total crop dry weight (kg plant^{-1}) and storage root dry weight (kg plant^{-1}) at 12 months after planting (MAP) and their chlorophyll fluorescence (F_v'/F_m' and F_v/F_m) at 6 and 9 MAP for the 2021–22 growing season.

No.	Genotypes	Total crop dry weight	Storage root dry weight	F_v'/F_m' at 6 MAP	F_v/F_m at 6 MAP	F_v/F_m at 9 MAP
73.	Huay Bong 90	2.296 A	1.778 A	0.792 A	0.820 A-F	0.865 AB
98.	Pirun 2	2.060 B	1.383 C	0.787 AB	0.820 A-F	0.863 A-C
69.	CMR 38-125-77	1.927 C	1.535 B	0.778 A-C	0.819 A-G	0.861 A-E
71.	Huay Bong 60	1.904 CD	1.427 C	0.777 A-C	0.819 A-G	0.860 A-E
72.	Huay Bong 80	1.902 CD	1.429 C	0.774 A-D	0.819 A-G	0.861 A-E
58.	CMR 35-21-199	1.876 CD	1.308 D	0.773 A-E	0.819 A-G	0.861 A-E
74.	HP2 (CM305-13)	1.874 CD	1.274 DE	0.777 A-C	0.819 A-G	0.860 A-E
64.	CMR 36-30-329	1.814 DE	1.182 F	0.769 A-F	0.818 A-H	0.858 A-E
83.	Rayong 1	1.766 E	1.210 EF	0.762 A-H	0.817 A-I	0.856 A-G
78.	Kasetsart 50 (KU50)	1.765 E	1.283 DE	0.763 A-G	0.817 A-I	0.855 A-G

F_v'/F_m' is the maximum efficiency of photosystem II (PSII) photochemistry in the light. F_v/F_m is the maximum quantum efficiency of PSII photochemistry. Means in the same column with the same letters are not significantly different according to Duncan's multiple range test (DMRT) at $P < 0.01$.

According to results for the 2021–2022 growing season (Table 5), the genotype Huay Bong 90 gave the highest value for total crop and storage root dry weights at 12 MAP, followed by Pirun 2, CMR 38-125-77, Huay Bong 60, Huay Bong 80, CMR 35-21-199, HP2 (CM305-13), CMR 36-30-329, Rayong 1, and Kasetsart 50. Moreover, these cassava genotypes had high F_v'/F_m' at 6 MAP, F_v/F_m at 6 MAP, and F_v/F_m at 9 MAP.

Considering the overall results for both growing seasons, therefore, a superior cassava genotype based on F_v'/F_m' at 6 MAP, F_v/F_m at 6 MAP, F_v/F_m at 9 MAP, and total crop and storage root dry weights at 12 MAP was Huay Bong 90 (Tables 4 and 5). The genotypes Huay Bong 80, Kasetsart 50, Rayong 1, CMR 38-125-77, CMR 36-30-329, and HP2 (CM305-13) also performed well for F_v'/F_m' at 6 MAP, F_v/F_m at 6 MAP, and F_v/F_m at 9 MAP for both growing seasons. Additionally, the results from Tables 4 and 5 showed that the CMR 38-125-77 genotype had high values of chlorophyll fluorescence for both growing seasons and emerged as a top genotype, ranking third in total crop dry weight for 2020–2021 and 2021–2022, indicating an alternative genetic resource for future cassava breeding programs.

DISCUSSION

This study showed the diversity of the tested genotypes for F_v'/F_m' and F_v/F_m at 6 MAP, F_v/F_m at 9 MAP, and total crop and storage root dry weights, indicating more effect came from the genotype (Table 2). The performance of chlorophyll fluorescence of each cassava genotype involves the metabolic capacity of individual genetic backgrounds, as controlled by the quantitative gene (Makhtoum *et al.*, 2021). The processes for chlorophyll fluorescence expression seemed polygenic, with the quantitative genetic tools vital to determine their genetic variation and inheritance mechanisms (Čepl *et al.*, 2016).

The difference between the two growing seasons for total crop and storage root dry weights was due to the varying environmental conditions between the growing seasons. Soil fertility for the 2020–2021 growing season was more favorable than the 2021–2022 growing season (Table 1). Applying green manure and cow dung before planting began in the 2020–2021 growing season could be the reason. Additionally, a variation between the two growing seasons could refer to weather conditions, such as temperature and solar radiation (Figure 1). The rainfall difference between the two growing seasons was irrelevant to the difference in total crop and storage root dry weights since supplementary irrigation ensued during the dry period. The average daily air temperature for the experimental periods varied from 21.8 °C to 32.9 °C for the 2020–2021 growing season and from 22.1 °C to 32.8 °C for 2021–2022. The daily total solar radiation ranged from 4.08 to 30.30 MJ m^{-2} for 2020–2021 and 5.40 to 26.20 MJ m^{-2} for the 2021–2022 growing season.

In general, study results from both growing seasons revealed that Huay Bong 90 was a preferable genotype based on storage root and total crop dry weights, which also relates to the performance of chlorophyll fluorescence (Tables 4 and 5). For various growing conditions, however, the genotype Huay Bong 90's performance regarding chlorophyll fluorescence and other physiological traits linked to dry matter are still essential to discover. The superior performance of Huay Bong 90 proves it a valuable genetic resource for cultivation and application as a parental source for cassava breeding programs.

Moreover, the genotypes Huay Bong 80, Kasetsart 50, Rayong 1, CMR 38-125-77, CMR 36-30-329, and HP2 (CM305-13) performed well in chlorophyll fluorescence for both 2020–2021 and 2021–2022 growing seasons. Considering the dry weight, however, CMR 38-125-77 appeared as the top genotype for the 2020–2021 growing season, ranking third for 2021–2022 for total crop dry weight at 12 MAP. Therefore, genotype CMR 38-125-77 is also interesting for future breeding programs. Previous studies have also recorded the desirable performance in chlorophyll fluorescence (Sawatraksa *et al.*, 2018), photosynthesis (Ruangyos *et al.*, 2023), growth, and yield (Phoncharoen *et al.*, 2019; Wongnoi *et al.*, 2020) of CMR 38-125-77 genotype grown under different environments.

For the stepwise regression analysis, the results signified F_v/F_m and F_v'/F_m' can benefit as another criterion to support decision-making for varietal selection as they relate to photosynthetic efficiency, which involves dry matter accumulation. Interestingly, total crop and storage root dry weights could have clarity by measuring chlorophyll fluorescence at 6 and 9 MAP (Table 3), suggesting the appropriate time to observe F_v/F_m and F_v'/F_m' from the cassava field. At 6 MAP, cassava reached maximum growth of leaf (source) and canopy size (Alves, 2002). Hence, high chlorophyll fluorescence in this crop age could enhance the photosynthate and produce more cassava dry matter (Santanoo *et al.*, 2019). During 6 to 9 MAP is the period for the photosynthate to high partition from leaf to storage root (sink) (Alves, 2002). Furthermore, high chlorophyll fluorescence in this period might allow more storage of root bulking and dry matter accumulation. However, chlorophyll fluorescence is not only a decision-making criterion to support varietal selection. Other crop parameters relating to cassava dry matter have been reported, such as photosynthesis (De Tafur *et al.*, 1997; El–Sharkawy, 2006), leaf area index (El–Sharkawy, 2006; Phuntupan and Banterng, 2017; Phoncharoen *et al.*, 2019), specific leaf area, growth rate of leaf, storage root, and crop (Phuntupan and Banterng, 2017; Phoncharoen *et al.*, 2019; Sawatraksa *et al.*, 2019), and stem growth and net assimilation rates (Sawatraksa *et al.*, 2019). These can also help in identifying the genotypes with high dry matter (Nimlamai *et al*., 2020; Pratama *et al*., 2023).

Chlorophyll fluorescence determination for cassava genotypes before harvesting provides valuable information to explain crop health and increase varietal selection efficiency. This process could help breeders classify cassava genotypes before harvest, which is especially useful in selecting the superior genotype from massive germplasm collections. F_v/F_m is a widely used parameter to measure the maximum photochemical efficiency of PSII in plants. It reflects the maximum efficiency of light energy conversion into photochemical energy in PSII and thus indicates the overall health and vitality of the plant (Murchie and Lawson, 2013). However, F_v/F_m alone does not provide information on the actual photosynthetic performance of the plant under natural conditions, as it only measures the potential, not the actual photochemical yield.

Therefore, F_v'/F_m' has been introduced as a more comprehensive parameter for assessing the effective quantum yield of PSII under natural conditions. It considers the contribution of non-photochemical quenching (NPQ) processes, which are crucial for plant stress tolerance and overall photosynthetic performance (Santanoo *et al.*, 2019). Reports of the relationship between chlorophyll fluorescence and dry matter accumulation in cassava emerged. Sawatraksa *et al.* (2018) found that F_v/F_m and F_v'/F_m' were associated with storage root and total crop dry weights at 1, 5, and 6 MAP, and they also indicated the possibility of using chlorophyll fluorescence as criteria to improve the efficiency for cassava varietal selection.

Another approach to improve breeding efficiency, the studies to determine the quantitative trait loci (QTL) linked to chlorophyll fluorescence might also be helpful, with the markers for identifying the superior genotypes for specific growing conditions, such as drought tolerance selection in sunflowers (Kiani *et al.*, 2008) and in barley (Guo *et al.*, 2008). The evidence on QTL analysis of chlorophyll fluorescence for various cassava genotypes is also valuable to support future breeding programs.

This study figured out some characteristics of a large cassava population, and the information on the performance of each genotype is beneficial to design the appropriate variety for cultivation and future breeding programs. However, the other physiological and agronomic traits of cassava genotypes grown under different environments are still necessary to explore to achieve better information on crop behavior and adaptability and confirm the potential of the candidate genotype.

CONCLUSIONS

Measurements of chlorophyll fluorescence at 6 and 9 MAP showed a linkage to the dry weight of cassava at 12 MAP. The cassava genotype Huay Bong 90 was desirable for storage root and total crop dry weights at 12 MAP and chlorophyll fluorescence at 6 and 9 MAP. The performances based on chlorophyll fluorescence and total crop dry weight at 12 MAP for the genotype CMR 38-125-77 also indicated superiority. These genotypes are an alternative source for cultivation and future breeding programs.

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