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RESEARCH ARTICLE

Evaluation of cassava genotypes for hilly areas under rainfed conditions

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Abstract

In Tamil Nadu, India, cassava (*Manihot esculenta* Crantz) is cultivated under both rainfed and irrigated conditions, primarily for industrial and culinary purposes. Drought poses a significant constraint for cassava cultivation, especially in hilly terrains where water retention is limited. Water scarcity adversely affects cassava growth, leading to reduced leaf area, stunted root development and ultimately loweryields. Studies have shown that under drought conditions, cassava experiences reductions in leaf water potential, osmotic potential, photosynthesis and stomatal conductance, all of which contribute to decreased productivity. To address these challenges, high-yielding, high-starch, drought tolerance cassava genotypes (characterized by high relative water content and greater chlorophyll stability index) as well aspest and disease resistant varieties, must be evaluated for their suitability in hilly regions with poor and marginal soils and limited rainfall. The natural resilience of cassava to harsh conditions makes it an essential crop for resources-limited farmers in marginal locations. In Tamil Nadu, the Salem district hosts approximately 800 small-scale sago and starch production facilities. Salem is surrounded by hills where cassava is the primary crop. Farmers face several challenges, such as poor rainfall, low-yielding varieties, pest and disease incidence and low market prices. Hence, it is very important to evaluate and identify suitable genotypes that can tolerate water deficits, resist disease, yield high and produce greater starch content. Yield and quality traits have direct impact on economic returns for farmers and determine cassava suitability for various industrial applications. Additionally, plant architecture plays a critical role in enabling cassava to withstand environmental stresses common in hilly areas, such as strong winds and heavy rainfall. This study systematically evaluates these traits, aiming to identify and promote suitable cassava genotypes that can enhance the livelihoods of tribal farmers in hilly regions.

Keywords: cassava varieties; chlorophyll stability index; rainfed; relative water content

Introduction

Cassava, a major tuber crop in India, plays a crucial role in rural livelihoods due to its high productivity, year-round availability and adaptability to various farming systems (1). Cassava being a hardy crop thrives in diverse climates, even in marginal soils with limited agricultural resources, making it a vital source of income and food security for smallholder farmers. Farmers market their produce as fresh roots, dried chips, or processed products like flour and starch for local and industrial markets. Tamil Nadu, in particular, has a well-established tapioca starch industry. Industries use starch for textiles, paper, adhesives and pharmaceuticals, thereby creating significant demand and income opportunities. The crops' resilience to drought and poor soils reduces the cost of cultivation, enabling even resource-constrained farmers to cultivate it successfully. Additionally, cassava processing into starch, chips, or flour generates employment opportunities in rural areas, particularly benefiting women and marginalized communities. It is cultivated across 13 states, with Kerala, Tamil Nadu and Andhra Pradesh being the most productive, accounting for 43.33 % of the total cultivation area (2). Tamil Nadu leads in both cassava production and cultivated area, with the highest global productivity. It is cultivated under both irrigated and rainfed conditions, with 60 % grown in Salem, Erode, Dharmapuri and Namakkal districts and remaining 40 % is grown in hilly regions (3, 4). The Salem district alone hosts approximately 800 small-scale sago and starch production facilities. In recent years, cassava cultivation has expanded into challenging environments, particularly hilly areas, where topographical and climatic conditions pose unique challenges (5, 6). However, cassava production in these areas remains constrained by soil erosion, poor soil fertility and water stress, necessitating the identification of suitable genotypes with enhanced performance in marginal environments (7).

A key trait essential for cassava cultivation in hilly terrains is root yield stability, as these regions experience fluctuations in water availability that impact tuber development (8). Additionally, root quality, including starch content and tuber dry matter accumulation, is critical for both food security and industrial applications (9).

Furthermore, resistance to pests and diseases, such as cassava mosaic disease (CMD) and cassava brown streak disease (CBSD), is crucial in these areas, as stressed environments tend to have a higher incidence of disease outbreaks (10). Identifying and selecting varieties with superior performance varieties across these key traits can significantly enhance cassava production in challenging environments, contributing to food security and sustainable agricultural development

Among abiotic stresses, drought poses the greatest challenge to cassava productivity in hilly regions, particularly on marginal lands with poor soils and limited water resources (11, 12). Water scarcity negatively affects cassava growth, leading to reduced leaf area, stunted root development and lower yields. Studies have shown that under drought conditions, cassava exhibits reduced leaf water potential, osmotic potential, photosynthetic efficiency and stomatal conductance, all of which contribute to decreased productivity (13). Approximately 50 % of the total cassava cultivation area in Tamil Nadu is planted with high-yielding genotypes such as H-226 and MVD-1 in Salem and CO 1, CO 2 and CO 3 in other parts of Tamil Nadu. Despite their low-yielding and highly susceptibility to cassava mosaic disease, traditional genotypes such as Burma and Malabar are still cultivated due to their favorable starch content, which meets industry and broker expectation.

Consequently, farmers are reluctant to adopt new varieties without evidence of their performance in hilly regions. Given this scenario, it is imperative to evaluate and identify cassava varieties that exhibit better adaptability, higher yield and improved starch content for cultivation in hilly regions. Particularly in hilly areas such as the Kalvarayan Hills, Pachamalai Hills and Arnoothumalai Hills, outdated genotypes continue to be cultivated, leading to poor yields and low farmer incomes (14). Drought-tolerant varieties have been shown to maintain growth and yield stability under water-limited conditions (14, 15). Therefore, this study aims to evaluate promising cassava genotypes best suited for hilly regions, with the objective of enhancing productivity, improving farmer livelihoods and increasing economic returns.

Materials and Methods

The experiments were conducted with seventeen cassava genotypes, including H 165 as a control, during 2017-18, 2018-19 and 2019-20 at Kaikan Valavu village in the Kalvarayan hills, located in Attur taluk, Pethanaickenpalayam block, Salem district, 52 km east of Salem town, at an altitude of 2600 ft. above sea level. The geographical coordinates of the study site are 11.85 °N latitude and 78.64 °E longitude. The climate of the region is tropical cool, with an average temperature of 23 °C and annual rainfall of 860 mm, predominantly received during the North-east monsoon season (October to December). The soil type varies from red loam to black clay.

Seventeen genotypes were planted during the July-August season in a randomized complete block design (RBCD) with three replications. The recommended dose of fertilizers, as per the crop production guide 2015 (FYM at 12.5 t/ha along with 50 kg N, 65 kg P and 125 kg K/ha), was applied as a basal dose during field preparation. Since the crop was grown under rainfed conditions, no additional amendments were applied.

To study morphological traits, three superior plants from each line were chosen and tagged. Drought tolerance and soil fertility adaptation are particularly important in ensuring cassavas' ability to perform well under unpredictable climatic conditions. Root yield and quality are vital for both food security and the economic value of the crop, while disease resistance ensures the longevity and stability of cassava cultivation. Additionally, plant architecture also contributes to overall crop resilience, reducing the risk of damage due to adverse environmental factors (16).

Data on morphological traits, such as number of days taken for sprouting, sprouting percentage, number of roots and length of the roots, were recorded during plant establishment. Growth parameters, such as plant height, number of leaves and stem girth, were measured at 2, 4, 6 and 8 months after planting and at harvest. Yield attributes, such as the number of tubers per plant, tuber yield (kg/plant) and starch content (%), as along with the CMD grade, were recorded during the 3rd and 6th months after planting and at harvest from the tagged plants.

The starch content of the tubers was quantified using the specific gravity method (17), wherein specific gravity was determined by weighing samples in air and water. Five plants were randomly selected and tagged to score disease severity, using a grading scale from 1 (no symptoms) to 5 (very severe symptoms) for CMD (18) (Fig. 1). The CMD incidence was calculated as the percentage of symptomatic plants in relation to the total number of plants assessed.

Drought tolerance parameters, such as relative water content (RWC) and the chlorophyll stability index (CSI) were estimated. RWC provides a straightforward, easy-to-measure estimate of plant hydration status, while CSI indicates the plants' ability to maintain cell membrane stability under drought, which is crucial for preventing cellular damage and loss of function due to dehydration. The RWC was measured by soaking fresh leaf samples in deionized water for 24 hr, followed by calculating the turgor weight (TW) was then drying the samples at 80 °C to a constant dry weight (DW). The RWC (19) was measured by using equation:

$$\text{Leaf RWC (\%)} = (FW-DW)/(TW-DW) \times 100 \quad (7) \qquad \text{(Eq. 1)}$$

where FW is fresh weight, TW is turgor weight and DW is dry weight.

CSI was periodically calculated using the formula (20):

$$\text{(CSI\%)} = (\text{Total Chlorophyll under stress/Total Chlorophyll irrigated condition as control}) \times 100. \qquad \text{(Eq . 2)}$$

This formula is commonly used in studies evaluating the effects of stress (such as drought) on chlorophyll content and it is based on the general principle that stress-induced chlorophyll degradation can be used as an indicator of plant health.

Analysis of variance (ANOVA) was performed for all measured traits, following the RCBD model (21). Statistical analyses were conducted using SPSS 16.0 (SPSS Inc., Chicago, USA) (22). The data were tabulated with means from three replicates, along with standard errors.

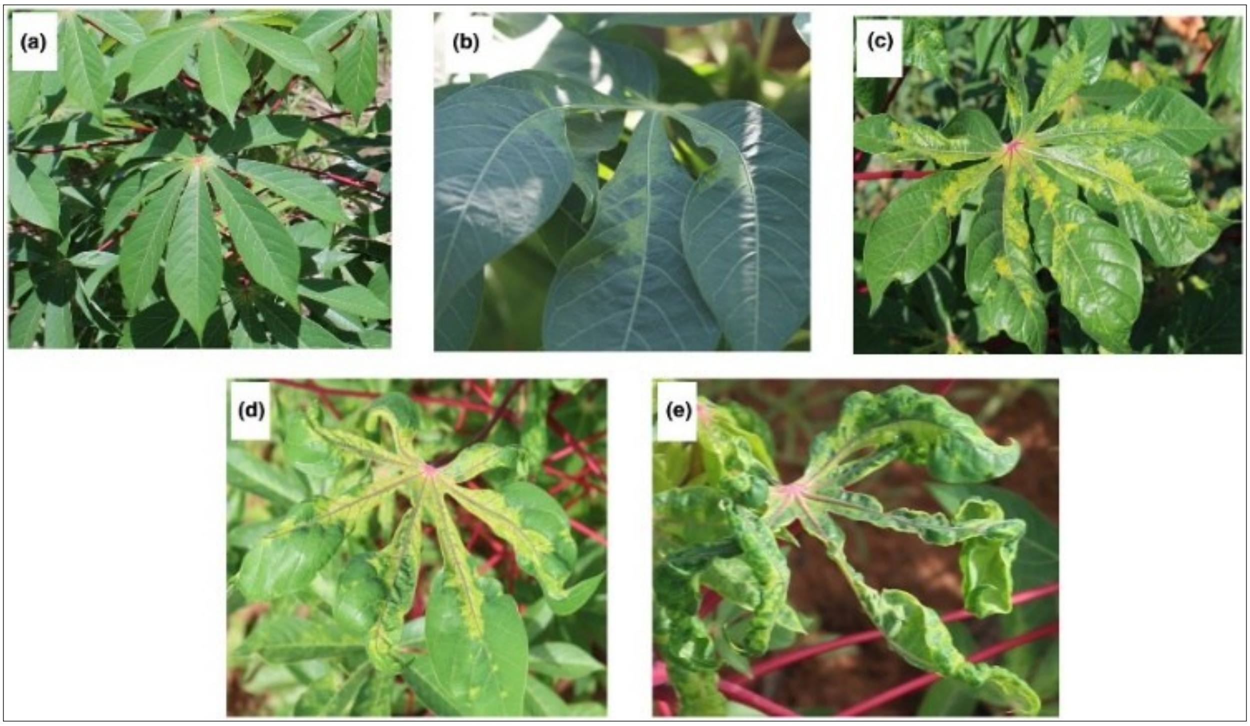

Fig. 1. Symptoms of cassava mosaic disease observed on infected cassava plants during the surveys, using a scale from 1 (no symptoms) to 5 (very severe symptoms). (a) = 1, (b) = 2, (c) = 3, (d) = 4, (e) = 5 as referred (18).

Results and Discussion

Cassava, with its ability to thrive in poor soils with minimal rainfall and low fertility, serves as a vital staple food for resource-constrained populations in marginal regions (23). Although cassava is widely recognized as a drought-tolerant crop, its root yield is highly susceptible to water stress, particularly under extreme conditions. The adverse effects of drought on plant growth and productivity have become a major concern (24).

Therefore, it is crucial to assess cassava accessions for hilly regions, focusing on growth parameters and drought tolerance indices such as the CSI and RWC. Water shortage leads to a decline in RWC, a crucial determinant of plant drought resistance, with the magnitude of reduction varying among different genotypes (11). The performance of the cassava varieties evaluated over the three-year. The study period is presented below:

First year (2017-18)

Among the 17 varieties evaluated for plant establishment, 100 percent sprouting was found in all the accessions except Sree Swarna, TCMS 8, TCa 12-4 and TCMS 6 (Table 1). A significant difference in sprouting percentage was noted among the accessions, with Sree Swarna recording 64.29 %, while TCMS 6 had the lowest sprouting rate of 28.57 %. Although drought tolerance in cassava has not been precisely quantified, it appears to be more closely related to plant survival (3). The critical period of irrigation in cassava is the initial 3-4 months after planting (25, 26).

The number of days taken for sprouting was found to be the lowest for Sree Vijaya (13 days), which was statistically at par with H 165, Thailand white, TCMS 3 and TCa 12-5. In contrast, the longest time to sprouting (16 days) was observed in Sree Athulya and Rasi 20.

Regarding growth parameters, H 226 exhibited significantly greater plant height and a higher number of leaves per plant, followed by Sree Athulya for plant height and Sree Jaya for number of leaves and stem girth (Fig 2. a & b).

Table 1. Performance of cassava genotypes on plant establishment under hilly tract of Kalrayan hills (2017-18)

S.No.	Genotypes	No. of days taken for sprouting	Sproutin (%)	Length of roots (cm)
1	H 165	14	100.0	25.1
2	Sree Jaya	16	100.0	20.4
3	Sree Vijaya	11	100.0	23.0
4	Sree Athulya	18	100.0	22.8
5	Sree Pavithra	15	100.0	19.6
6	Sree Swarna	15	64.29	21.9
7	Sree Raksha	17	100.0	18.0
8	H 226	15	100.0	24.0
9	YTP 1	16	100.0	35.9
10	Rasi 20	18	100.0	22.0
11	YTP 2	15	100.0	20.6
12	TCMS 3	12	100.0	18.1
13	TCMS 6	16	28.57	16.4
14	TCMS 8	15	42.86	22.9
15	TCa 12-4	17	42.86	19.9
16	TCa 12-5	12	100.0	23.4
17	Thailand white	14	100.0	25.9
	SEd	1.81	1.21	2.53
	CD (0.05)	3.77	2.53	5.28
	CV	14.6	1.53	13.7

Regarding the yield parameters (Table 2), H 165 produced the highest number of tubers per plant (9.37), statistically comparable to YTP 1, Sree Vijaya, YTP 2, Sree Jaya, Sree Athulya and Sree Swarna. This was followed by TCMS 8, with yielded 7.17 kg/ plant, on par with Sree Pavithra, Rasi 20, Sree Raksha, H226, TCa 12-4, Thailand white, TCMS 3, TCa 12-5 and TCMS 6.

However, in terms of tuber yield per plant, both H 226 and Sree Swarna recorded 3.84 kg per plant, which was comparable to YTP 2, H 165, Sree Raksha, YTP 1, Thailand white, Sree Jaya, Sree Pavithra and Rasi 20. These were followed by

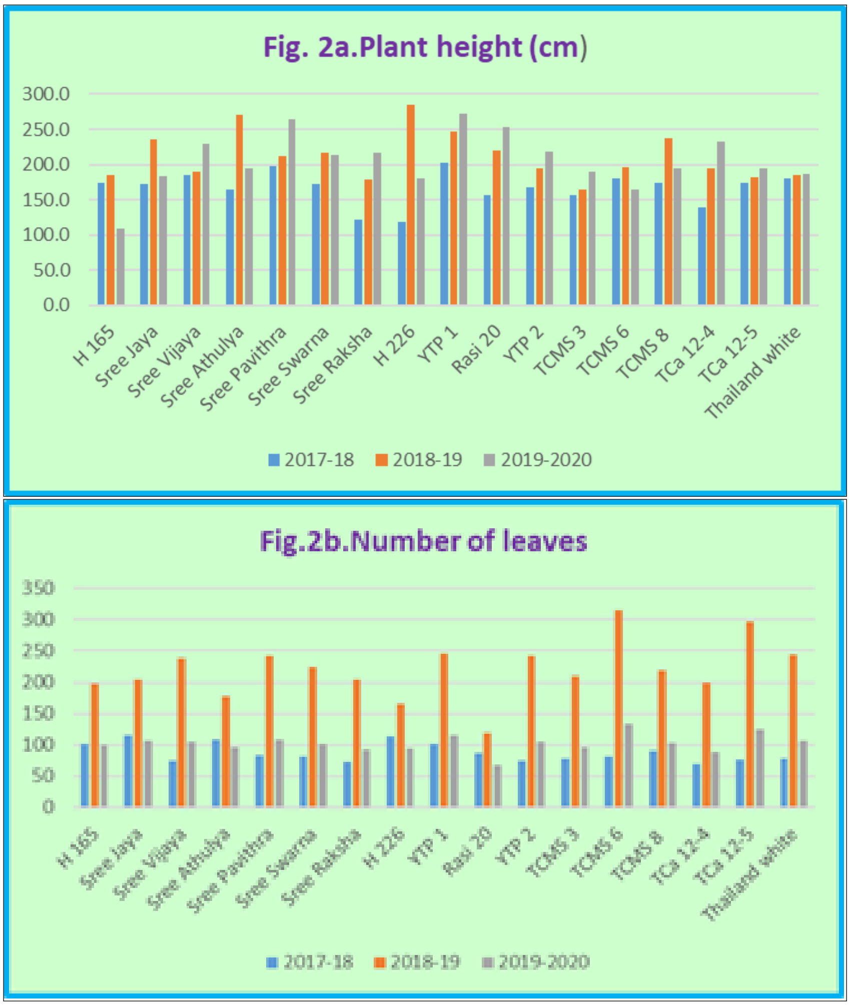

Fig. 2. Comparison of growth parameters (Plant height and number of leaves) of cassava genotypes over three years.

Table 2. Performance of cassava genotypes on yield attributes under hilly tract of Kalrayan hills (2017-18)

S.No.	Genotypes	No. of tubers per plant	Tuber yield (kg per plant)	Starch content (%)	CMD Score at harvest
1	H 165	9.37	3.72	30.13	4.2
2	Sree Jaya	8.23	3.26	25.92	4.6
3	Sree Vijaya	8.80	2.89	25.37	4.2
4	Sree Athulya	8.17	2.88	27.35	3.0
5	Sree Pavithra	6.70	3.08	27.06	2.2
6	Sree Swarna	8.07	3.84	30.12	1.8
7	Sree Raksha	6.53	3.62	27.47	0.0
8	H 226	6.53	3.84	29.64	4.6
9	YTP 1	8.93	3.45	27.12	3.8
10	Rasi 20	6.57	3.01	22.97	2.4
11	YTP 2	8.27	3.77	30.20	0.0
12	TCMS 3	6.10	2.90	25.60	0.0
13	TCMS 6	5.17	2.60	26.02	0.0
14	TCMS 8	7.17	2.32	23.14	1.8
15	TCa 12-4	6.33	2.50	23.71	0.0
16	TCa 12-5	5.53	2.71	26.83	0.0
17	Thailand white	6.20	3.35	29.26	4.8
	SEd	0.98	0.43	1.05	-
	CD (0.05)	2.04	0.90	2.20	-
	CV	15.5	15.7	4.71	-

TCMS 3 (2.90 kg per plant), which was statistically similar to Sree Vijaya, Sree Athulya, TCMS 6, TCa 12-5, TCa 12-4 and TCMS 8, the latter recording the lowest yield (2.32 kg per plant).

The observed water deficit stress conditions negatively impacted plant growth and development, as evidenced by the reduction in the plant height, number of leaves, number of tubers and tuber yield.

Starch content was found to be significantly higher in YTP 2 (30.20 %), which was on par with H 165, Sree Swarna, H 226 and Thailand white. The lowest starch content was recorded in Rasi 20 (22.97 %) (Table 2).

The CMD incidence was observed in all the entries except Sree Raksha, YTP 2, TCMS 3, TCMS 6, TC a 12-4 and TCa 12-5. The highest CMD severity score was high (4.8) was recorded in Thailand, followed by H 226, Sree Jaya, H 165 and Sree Vijaya.

Second year (2018-19)

Nearly 100 percent sprouting was observed across all accessions, except Sree Swarna, TCMS 8, TCa 12-4 and TCMS 6 (Table 3). The accessions Sree vijaya, H 165, Thailand white, TCMS 3 and TCa 12-5 exhibited earlier sprouting compared to the others.

The highest number of roots per plant was recorded in YTP 1 (12.5) followed closely by TCMS 6 (12.4), Sree Jaya (12.2), H 165 (11.8), Sree Raksha (11.6) and Thailand white (11.5). The length of the roots was found to be more in YTP 1 followed by Thailand white, H 165, H 226 and YTP 2.

Significant differences were observed in plant height and number of leaves at 2 MAP, 4 MAP, 6 MAP, 8 MAP and at harvest (Fig 2.a & b). The accession YTP 1 exhibited the highest plant height (201.7 cm), while TCMS 6 recorded the highest number of leaves per plant (315.2).

However, with regard to tuber yield per plant, YTP 1 (8.54 kg/ plant), Sree raksha (8.20 kg /plant) and TCa 12-4 (8.15kg/

Table 3. Performance of cassava genotypes on plant establishment under hilly tract of Kalrayan hills

S.No.	Genotypes	No. of days taken for sprouting	Sprouting (%)	Number of roots	Length of roots (cm)
1	H 165	12.00	100.00	11.8	28.50
2	Sree Jaya	14.00	100.00	12.2	22.50
3	Sree Vijaya	11.00	100.00	10.5	25.60
4	Sree Athulya	16.00	100.00	12.0	23.80
5	Sree Pavithra	13.00	100.00	11.0	21.30
6	Sree Swarna	14.00	68.97	10.0	23.40
7	Sree Raksha	16.00	100.00	11.6	20.50
8	H 226	12.00	100.00	15.0	27.70
9	YTP 1	13.00	100.00	12.5	36.60
10	Rasi 20	17.00	100.00	10.4	25.30
11	YTP 2	12.62	100.00	9.5	27.50
12	TCMS 3	11.07	100.00	10.8	23.70
13	TCMS 6	15.35	31.57	12.4	22.80
14	TCMS 8	14.72	41.53	10.6	24.20
15	TCa 12-4	17.26	44.93	11.5	21.90
16	TCa 12-5	12.04	100.00	11.2	24.10
17	Thailand white	11.51	100.00	11.5	30.40
	SEd	1.241	0.693	1.239	2.887
	CD (0.05)	2.592	1.447	2.589	6.031
	CV	11.11	0.87	13.26	13.85

plant) were on par, followed by Rasi 20 (8.01 kg/plant) and TCMS 6 (7.72 kg/plant). TCMS 8 exhibited a yield comparable to TCa 12 -5 and Sree Athulya, while Sree vijaya recorded the least yield (5.64 kg per plant) (Table 4).

Starch content was found to be significantly higher in H 165 (30.0 %), which was on par with YTP 2 (29.6 %), Rasi 20 (29.0 %), Thailand white (28.93 %) and H 226 (28.33 %). The lowest starch content was recorded in Sree Swarna (25.00 %).

The CMD incidence was observed in all the entries except Sree Raksha, YTP 2, TCMS 3, TCMS 6, TCa 12-4 and TCa 12-5. The highest CMD severity score (4.6) was recorded in Thailand white, Sree Jaya and H 226 followed by H 165 (4.4), Sree Vijaya and YTP 1(4.0).

Drought is one of the major constraints limiting cassava growth and productivity, particularly during the first three months after planting. Understanding the mechanisms underlying cassavas' drought tolerance at the seedling stage is crucial (27). Hence, drought-related parameters such as RWC and CSI were analyzed in comparison with H 165 (Table 8).

Among the 17 accessions evaluated for RWC, H 226 recorded the highest RWC (92.50 %), indicating strong drought tolerance and was statistically comparable to H 165, YTP 2, YTP 1 and Sree Vijaya. Thailand White exhibited moderate drought tolerance, on par with Sree Swarna, Sree Raksha, Sree Jaya, TCMS 6 and TCMS 3. TCMS 8 and Sree Pavithra showed mild drought tolerance. In contrast, TCa 12-4, Sree Athulya, TCa 12-5 and Rasi 20 recorded RWC levels below 70 %, indicating high susceptibility to drought. RWC is a widely used indicator of plant water status, often employed to assess drought tolerance. Under drought stress conditions, RWC declines as water loss surpasses uptake. A higher RWC typically correlates with better drought resilience, as it reflects the plants' ability to retain water despite unfavorable conditions. With regard to chlorophyll stability index, YTP 1 (90.16 %) was statistically significant and was on par with H 226, YTP 2 H 165 and Thailand white. Sree Raksha, Sree Pavithra, Sree jaya, Sree vijaya, TCMS 6 and TCMS 3 were moderately tolerant to drought, as indicated by their CSI values. In contrast, the accessions Sree Athulya, Sree Swarna, Rasi 20, TCMS 8, TCa 12-4 and TCa 12-5 exhibited CSI values below 70 %, classifying them as drought-susceptible (Table 8).

Table 4. Performance of cassava genotypes on yield attributes under hilly tract of Kalrayann hills (2018-19)

S.No.	Genotypes	No. of tubers per plant	Tuber yield (kg per plant)	Starch content (%)	CMD Score at harvest
1	H 165	6.93	6.61	30.00	4.4
2	Sree Jaya	6.62	6.00	26.00	4.6
3	Sree Vijaya	6.22	5.64	27.00	4.0
4	Sree Athulya	5.60	7.43	28.00	3.0
5	Sree Pavithra	5.78	6.78	26.00	2.0
6	Sree Swarna	5.60	6.68	25.00	2.0
7	Sree Raksha	5.78	8.20	27.00	**0.0**
8	H 226	6.62	6.67	28.33	4.6
9	YTP 1	7.24	8.54	27.00	4.0
10	Rasi 20	6.62	8.01	29.00	2.5
11	YTP 2	6.36	7.13	29.60	**0.0**
12	TCMS 3	6.18	6.81	27.17	**0.0**
13	TCMS 6	6.49	7.72	25.58	**0.0**
14	TCMS 8	6.49	7.63	27.00	2.0
15	TCa 12-4	6.79	8.15	29.13	**0.0**
16	TCa 12-5	6.19	7.58	25.08	**0.0**
17	Thailand white	6.19	7.06	28.93	4.6
	SEd	0.2849	0.515	1.875	-
	CD (0.05)	0.5951	1.075	3.917	-
	CV	5.51	8.95	8.35	-

Third year (2019-20)

During the third year (2019-2020), 100 percent sprouting was observed in all accessions, except for Sree Swarna, TCMS 6, TCMS 8 and TCa 12-4 (Table 5). The accessions Sree vijaya, H 165, Thailand white, TCMS 3 and TCa 12-5 exhibited early sprouted, occurring in less than 11 days, compared to other accessions.

Enhancing cassava root yield and quality requires a comprehensive understanding of storage root initiation and development (28). This can be achieved by assessing key root traits, such as root number, root width and root length, which are directly correlated with storage root yield (29, 30).

In this study, the number of roots per plant was highest in H226 (13.0) followed by TCMS 6 (11.6), Sree Jaya (11.5), YTP 1 (11.2), H 165 (11.0) and Sree Athulya (11.0). The longest roots were observed in H 226 (24.8cm), followed by YTP 2(24.1cm), YTP 1 (23.8cm), H 165 (23.6cm) and Sree Vijaya (23.4cm).

Among all accessions, Sree Athulya exhibited a significantly higher number of tubers per plant (9.44) which was statistically on par with H 165 (9.11), YTP 1 (9.11), YTP 2 (8.67), Sree Vijaya (8.44), Sree Jaya (8.33), Sree Swarna and TCMS 3.

However, with regard to tuber yield per plant (Table 6), Sree Swarna (3.87 kg /plant), H 226 (3.81 kg/plant), YTP 2 (3.78 kg/plant), H 165 (3.66 kg/plant), Sree Raksha (3.64 kg /plant), TCa 12-5 (3.40 kg/ plant), YTP 1 (3.38 kg/plant) and Sree Jaya (3.26 kg/plant) were on par, followed by Sree Pavithra (3.06 kg/plant), Rasi 20 (3.02 kg/plant) and TCMS 6 (7.72 kg/plant).

Starch content was found to be significantly high in Sree Swarna (29.96 %), H 165 (29.78 %), YTP 2 (29.60 %) Thailand white (28.89 %) and H 226 (28.24 %), which was on par with Sree Raksha (27.56 %), Sree Athulya (27.11 %) and TCa 12-5 (27.11 %). The lowest starch content was recorded in TCMS 8 (22.78 %) (Fig. 2).

CMD incidence was observed in all the accessions except for Sree Raksha, YTP 2, TCMS 3, TCMS 6, TCa 12-4 and TCa 12-5. The highest CMD severity score (3.3) was recorded in Thailand white, followed by Sree Jaya, H 165 (4.4) and Sree Vijaya and H 226 (3.0). Similar findings were reported for the YTP 2 variety (31).

The drought parameters (Table 8), including RWC and CSI, were analyzed in comparison with H 165.

Table 5. Performance of cassava genotypes on plant establishment under hilly tract of Kalrayan hills (2019-20)

S.No.	Genotypes	No. of days taken for sprouting	Sprouting (%)	Number of roots	Length of roots (cm)
1	H 165	11.3	100.00	11.0	23.60
2	Sree Jaya	13.0	100.00	11.5	20.20
3	Sree Vijaya	10.4	100.00	10.0	23.40
4	Sree Athulya	14.3	100.00	11.0	21.60
5	Sree Pavithra	11.6	100.00	10.0	18.90
6	Sree Swarna	13.0	71.50	8.0	21.20
7	Sree Raksha	14.0	100.00	10.0	18.50
8	H 226	11.3	100.00	13.0	24.80
9	YTP 1	12.3	100.00	11.2	23.80
10	Rasi 20	15.3	100.00	9.0	22.90
11	YTP 2	11.3	100.00	10.0	24.10
12	TCMS 3	10.1	100.00	8.5	20.20
13	TCMS 6	13.3	32.33	11.6	19.70
14	TCMS 8	13.0	43.67	8.0	21.30
15	TCa 12-4	15.7	49.33	10.0	18.40
16	TCa 12-5	10.7	100.00	9.5	20.40
17	Thailand white	10.3	100.00	8.8	22.50
	SEd	0.54	0.26	1.23	2.55
	CD (0.05)	1.12	0.55	2.57	5.33
	CV	5.31	0.33	14.91	14.24

Table 6 Performance of cassava genotypes on yield attributes under hilly tract of Kalrayan hills (2019-20)

S.No.	Genotypes	No. of tubers per plant	Tuber yield (kg per plant)	Starch content (%)	CMD Score at harvest
1	H 165	9.11	3.66	29.78	3.0
2	Sree Jaya	8.33	3.26	25.44	3.0
3	Sree Vijaya	8.44	2.89	24.89	3.0
4	Sree Athulya	9.44	2.88	27.11	1.9
5	Sree Pavithra	6.67	3.06	26.78	1.3
6	Sree Swarna	7.89	3.87	29.96	1.1
7	Sree Raksha	6.78	3.64	27.56	1.0
8	H 226	6.67	3.81	28.24	3.0
9	YTP 1	9.11	3.38	25.82	2.3
10	Rasi 20	6.78	3.02	22.83	2.0
11	YTP 2	8.67	3.78	29.60	1.0
12	TCMS 3	7.67	2.91	25.32	1.0
13	TCMS 6	5.22	2.64	24.89	1.0
14	TCMS 8	7.11	2.38	22.78	1.8
15	TCa 12-4	6.33	2.36	23.33	1.0
16	TCa 12-5	5.44	3.40	27.11	1.0
17	Thailand white	5.89	2.99	28.89	3.3
	SEd	1.14	0.42	0.84	-
	CD (0.05)	2.38	0.87	1.76	-
	CV	17.54	15.32	3.81	-

Out of all the 17 accessions evaluated for RWC, H 226 exhibited the highest value (91.93 %), indicating strong drought tolerance and was on par with H 165, YTP 2, YTP 1 and Sree Vijaya. Thailand White was found to be moderately tolerant, on par with Sree Suwarna, Sree Raksha, Sree jaya, TCMS 6 and TCMS 3. TCMS 8 and Sree Pavithra exhibited mild drought tolerance. In contrast, TCa12-4, Sree Athulya, Tca 12-5 and Rasi 20 had RWC values below 70 percent, indicating high susceptibility to drought.

With regard to CSI, YTP 1 (89.93 %) was statistically significant and was on par with H 165 and H 226, followed by YTP 2 and Thailand white, indicating high drought tolerant. Sree Raksha, Sree Pavithra, Sree jaya, Sree vijaya, TCMS 6 and TCMS 3 exhibited moderate tolerance, as reflected in their CSI values. In contrast, Sree Athulya, Sree Suvarna, Rasi 20, TCMS 8, TCa 12-4 and TCa 12-5 recorded CSI values below 70 %, categorizing them as drought-susceptible (Table 8).

Pooled analysis

Pooled data from three years (2017-18, 2018-19 and 2019-20) for yield attributes, including tuber yield per plant (kg) and starch content (%), were analyzed (Table 7 & 8 & Fig. 2 a & b). Among the 17 genotypes evaluated in the Kalrayan Hills, Sree Raksha recorded the highest per-plant tuber yield of 5.15 kg, which was stastistically on par with YTP 1 (5.12 kg), YTP 2 (4.89 kg), Sree Swarna (4.80 kg) and H 226 (4.77 kg), followed by Rasi 20 (4.68 kg). All other genotypes exhibited lower yields than the check variety H 165 (4.66 kg).

In terms of starch content, H 165 recorded the highest value of 29.97 % , which was statistically on par with YTP 2 (29.80 %), Thailand White (29.03 %), H 226 (28.74 %) and Sree Swarna (28.36 %). All other accessions had starch content below 28 %. Notably, YTP 2 consistently performed on par with H 165 across all three years, maintaining starch content above 28% while also exhibiting high yield (27).

CMD incidence was absent in Sree Raksha, YTP 2, TCMS 3, TCMS 6, TCa 12-4 and TCa 12-5 (Table 7).

Pooled data for drought parameters, specifically RWC and CSI, were analyzed for two years (2018-19 and 2019-20) in comparison with H 165 (Table 8). Among the 17 genotypes evaluated for RWC, H 226 exhibited the highest value (92.22 %), indicating significant drought tolerance and was on par with H 165 and YTP 2. Thailand white showed moderate drought tolerance, comparable to YTP 1. Sree Vijaya, Sree Swarna, Sree Jaya, Sree Raksha and Thailand White exhibited slight drought tolerance. In contrast, TCa 12-4, Sree Athulya, TCa 12-5, TCa 12-4 and Rasi 20 recorded RWC values below 70 %, indicating susceptibility to drought.

Regarding the CSI, YTP 1 (90.05 %) was significant and

Table 7. Pooled data analysis for yield attributes in cassava genotypes

S.No.	Genotypes	Tuber yield (kg /pt)				Starch content (%)			
		2017-18	2018-19	2019-20	Pooled mean	2017-18	2018-19	2019-20	Pooled mean
1	H 165	3.72	6.61	3.66	4.66	30.13	30.00	29.78	29.97
2	Sree Jaya	3.26	6.00	3.26	4.17	25.92	26.00	25.44	25.79
3	Sree Vijaya	2.89	5.64	2.89	3.81	25.37	27.00	24.89	25.75
4	Sree Athulya	2.88	7.43	2.88	4.40	27.35	28.00	27.11	27.49
5	Sree Pavithra	3.08	6.78	3.06	4.31	27.06	26.00	26.78	26.61
6	Sree Swarna	3.84	6.68	3.87	4.80	30.12	25.00	29.96	28.36
7	Sree Raksha	3.62	8.20	3.64	5.15	27.47	27.00	27.56	27.34
8	H 226	3.84	6.67	3.81	4.77	29.64	28.33	28.24	28.74
9	YTP 1	3.45	8.54	3.38	5.12	27.12	27.00	25.82	26.65
10	Rasi 20	3.01	8.01	3.02	4.68	22.97	29.00	22.83	24.94
11	YTP 2	3.77	7.13	3.78	4.89	30.20	29.60	29.60	29.80
12	TCMS 3	2.90	6.81	2.91	4.21	25.60	27.17	25.32	26.03
13	TCMS 6	2.60	7.72	2.64	4.32	26.02	25.58	24.89	25.50
14	TCMS 8	2.32	7.63	2.38	4.11	23.14	27.00	22.78	24.31
15	TCa 12-4	2.50	8.15	2.36	4.34	23.71	29.13	23.33	25.39
16	TCa 12-5	2.71	7.58	3.40	4.56	26.83	25.08	27.11	26.34
17	Thailand white	3.35	7.06	2.99	4.47	29.26	28.93	28.89	29.03
	SEd	0.431	0.515	0.42	0.89	1.0549	1.875	0.84	1.01
	CD (0.05)	0.901	1.075	0.87	1.86	2.2037	3.917	1.76	2.10
	CV	15.74	8.95	15.32	23.87	4.710	8.35	3.81	4.51

Table 8. Pooled data analysis for drought parameters in cassava genotypes

S.No.	Genotypes	RWC (%)			CSI (%)		
		2018-19	2019-20	Pooled mean	2018-19	2019-20	Pooled mean
1	H 165	90.60	89.60	90.10	88.88	89.83	89.36
2	Sree Jaya	82.56	83.47	83.01	86.26	85.57	85.92
3	Sree Vijaya	85.73	86.13	85.93	78.28	76.70	77.49
4	Sree Athulya	67.50	69.40	68.45	74.51	75.63	75.07
5	Sree Pavithra	77.94	77.47	77.70	80.31	79.10	79.71
6	Sree Swarna	84.32	84.10	84.21	70.52	69.86	70.19
7	Sree Raksha	84.92	82.57	83.74	81.30	80.57	80.93
8	H 226	92.50	91.93	92.22	85.91	87.70	86.80
9	YTP 1	87.36	86.33	86.85	90.16	89.93	90.05
10	Rasi 20	61.24	60.63	60.94	60.11	61.40	60.75
11	YTP 2	88.96	89.90	89.43	82.08	82.17	82.13
12	TCMS 3	81.57	80.40	80.99	76.10	75.97	76.03
13	TCMS 6	82.88	81.73	82.31	78.57	77.90	78.24
14	TCMS 8	77.61	74.60	76.10	58.33	56.23	57.28
15	TCa 12-4	68.61	66.30	67.46	55.89	57.07	56.48
16	TCa 12-5	66.68	63.37	65.02	48.15	50.23	49.19
17	Thailand white	85.31	87.17	86.24	81.64	82.37	82.01
	SEd	3.43	3.14	1.092	3.816	3.08	0.858
	CD (0.05)	7.16	6.56	2.283	7.972	6.44	1.792
	CV	5.11	4.70	1.36	5.88	4.75	1.14

was on par with H 165, followed by H 226, YTP 2 and Thailand white, all of which demonstrated high drought tolerance. Sree Raksha, Sree Pavithra, Sree jaya, Sree vijaya, TCMS 6 and TCMS 3 exhibited moderate drought tolerance. However, Sree Athulya, Sree Swarna, Rasi 20, TCMS 8, TCa 12-4and TCa 12-5 recorded CSI values below 70%, classifying them as drought susceptible.

Sprouting was observed in all genotypes except Sree Swarna, TCMS 8, TCa 12-4 and TCMS 6 (Fig. 3). The genotypes Sree vijaya, Thailand white, TCMS 3 and TCa 12-5 exhibited early sprouting compared to others. Root length was highest in H 226, followed by YTP 2, YTP 1, H 165, Sree Vijaya, Rasi 20 and Thailand white. The highest number of roots per pant was recorded in H226, TCMS 6, Sree Jaya, YTP 1, H 165 and Sree Athulya. The highest number of tubers per plant was observed in Sree Athulya, YTP 1, H 165 and YTP 2, while tuber yield per plant was highest in Sree swarna, H 226, YTP 2, H 165 and Sree Raksha.

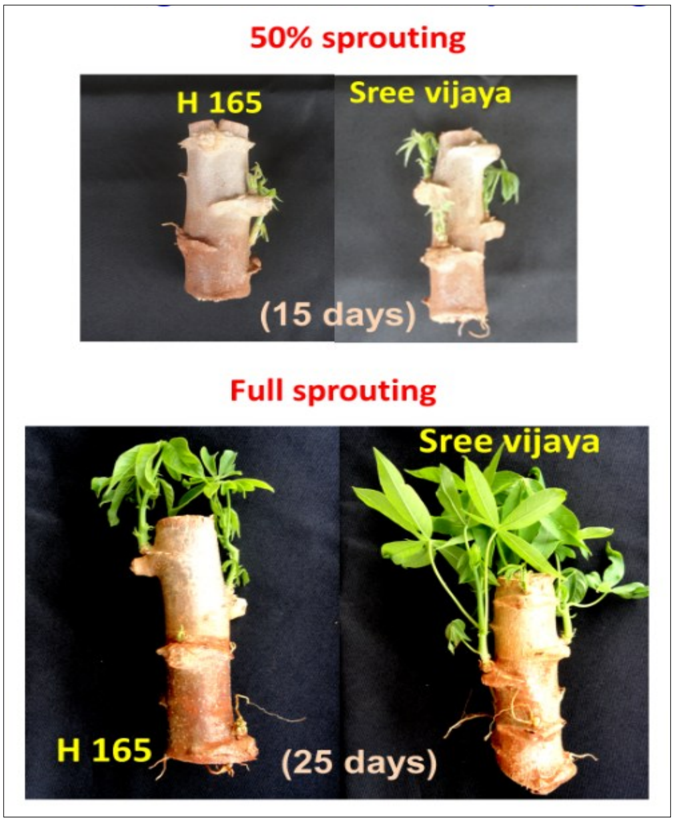

Fig. 3. Variation in sprouting.

Drought-tolerant plants often exhibit deeper or more extensive root systems, enabling them to access water from deeper soil layers. A separate root architecture analysis (e.g., root depth, length and density), was conducted specifically for the YTP 2 variety during its release. YTP 2 exhibited a greater number of long and deep roots, enhancing its drought tolerance. Additionally, this variety is characterized by a branching growth habit, profuse leaves and a short stature, which enhances its resistance to strong winds in hilly regions

Starch content was highest in Sree swarna, followed by H 165, YTP 2 and Thailand white. CMD incidence was absent in Sree Raksha, YTP 2, TCMS 3, TCMS 6, TCa 12-4 and TCa 12-5. H 226, H 165, YTP 2, YTP 1 and Sree Vijaya demonstrated drought tolerance, with high RWC and CSI values (18,19).

The results clearly indicate that YTP 2 exhibited peak drought tolerance parameters (Fig. 4) as well as superior tuber yield and starch content (Fig. 5). In this study, conducted in a hilly area, YTP 2 (Fig. 6) recorded a high yield and starch content with no incidence of CMD. This variety maintained higher mean RWC and CSI throughout its growth period, allowing it to withstand drought conditions in hilly areas.

The performance of YTP 2 was consistent across all the three years. Further, the variety was officially released in 2021 by the state variety release committee after extensive performance assessments in various regions and farmers' field. The introduction of a high-yielding, starch-rich and drought-tolerant cassava variety represents a significant advancement for cassava growers in hilly areas. This popularity of this variety has expanded to both plains and hill regions, with planting materials being produced and distributed to farmers by the Tapioca Research Station, Yethapur. The findings of this study align with other morphological parameters, including plant height, leaf count, tuber count and tuber yield, under water-deficit stress conditions (3, 23).

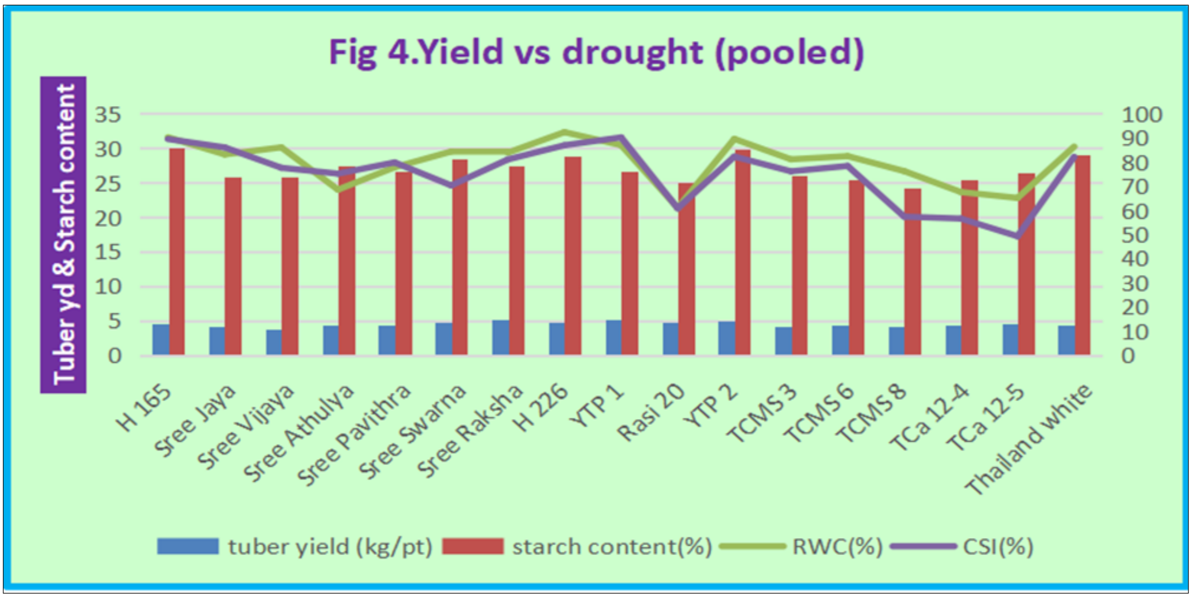

Fig. 4. Evaluation of varieties based on yield, starch content and drought parameters.

Fig. 5. Variation in tuber characters of different cassava genotypes.

Fig. 6. Cassava genotype (YTP 2) suitable for hilly tracts.

Conclusion

High root yield is essential for maximizing production in any environment. In hilly regions, varieties that maintain good yields despite topographical challenges are particularly preferred. Additionally, tuber quality traits such as starch content and dry matter percentage directly influence marketability and processing potential (9, 32). Resistance to diseases like CMD and CBSD is a vital trait in ensuring sustainable cassava production in hilly areas, where disease pressure can be higher due to environmental stress (10). Varieties with improved disease resistance help reduce yield losses and ensure crop stability.

A compact, upright plant structure can help reduce the impact of strong winds and soil erosion in hilly environments while facilitating easier harvesting. RWC provides a straightforward, easy-to-measure estimate of plant hydration status, whereas the CSI reflects a plant's ability to maintain cell membrane stability under drought conditions. This is crucial for preventing cellular damage and maintaining physiological function during periods of water scarcity.

Drought-tolerant plants often exhibit deeper or more extensive root systems that allow them to access water from deeper soil layers (33). An analysis of root architecture (e.g., root depth, length and density) was conducted specifically for the YTP 2 variety at the time of its release. YTP 2 exhibited a higher number of long and deep roots, contributing to its drought tolerance. Additionally, this variety has a branching growth habit with profuse leaves,and a short stature, making it resistant to strong winds in hilly regions. Due to its branching nature and low hydrogen cyanide content in leaves, farmers can use the leaves as cattle fodder (34). Farmers can use cassava leftovers, such as cassava peels, as livestock feed, lowering feed costs and increasing profitability.

The YTP 2 cassava variety, released from Tamil Nadu Agricultural University, has been found to perform well in hilly areas, yielding 4.89 kg per plant with a starch content of 29.80%. Additionally, it has shown no incidence of cassava mosaic disease incidence. The high yield and starch content are inherent genetic attributes of this variety.

The other unique traits include its branching growth habit, with profuse leaves and short stature, which allows the plant to withstand heavy winds. Also it is easy to pull the plant during harvest with the tubers held tight to main stem without breaking.

The absence of CMD in YTP 2 has been consistently observed across different environmental conditions and over years. The variety was given to nearly 155 trials in 20 locations in Tamil Nadu, Kerala, Andhra Pradesh, Maharashtra and Meghalaya, where all centres confirmed its yield potential, starch content and absence of CMD. Its suitability for industrial applications has been acknowledged by sago factories due to its starch content exceeding 28 %. Furthermore, its low HCN content makes it suitable for culinary use. The reduced HCN levels in its leaves also make it an excellent feed option for cattle. Under the All India Coordinated Research Project, YTP 2 has gained widespread popularity and its adoption rate is significantly high. It is currently being promoted in other hilly regions such as Pachamalai and Javadhu Hills by state agricultural departments. The Tapioca Research Station in Yethapur is actively producing and distributing planting materials to facilitate large-scale cultivation.

There is substantial evidence supporting the efficacy of cassava leaf protein in addressing malnutrition by fortifying protein-rich cassava leaves with common food items (35). This remains an important area for further exploration. In addition to traditional breeding techniques, advanced genome editing tools such as CRISPR/Cas9 (36) hold promise for enhancing cassavas' drought tolerance and improving its future potential. Further research should focus on developing value-added cassava products to promote its adoption in hilly regions, thereby ensuring greater economic benefits for farmers and contributing to food security.

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Authors' contributions

PSK and RN carried out the field trials and drafted the manuscript. MKK performed the analysis of drought parameters, reviewing and editing. MV participated in the design of the study and editing of manuscript. SRV performed the final drafting and statistical analysis. AS participated in the disease screening of varieties in lab and field and. All authors read and approved the final manuscript.

Compliance with Ethical Standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

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