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Assessment of Yellow and White Fleshed Cassava Tuberous Root Cultivars Reveals Different Responses to Post-harvest Physiological Deterioration

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Abstract

Identification of post-harvest physiological deterioration (PPD) tolerance in cassava is crucial, as PPD significantly hampers the cassava tuberous root industry by shortening storage periods post-harvest and diminishing product quality. Characteristics linked to PPD tolerance encompass high carotenoid levels and low dry matter content (DMC). This study aimed to evaluate the PPD responses of six yellow-fleshed and ten white-fleshed cassava tuberous roots and determine the source of PPD tolerance. PPD and DMC assessments were conducted using standard methods at three storage periods: 2, 5, and 10 days after harvest (DAH). The k-means clustering analysis revealed six clusters, each corresponding to distinct PPD symptom patterns and tolerance statuses. Cluster 1, comprising three yellow-fleshed and three white-fleshed cassava cultivars, demonstrated PPD tolerance with minimal symptoms up to 5 DAH. Clusters 2 and 3 exhibited a moderate PPD response with elevated symptoms at 5 DAH, comprising three yellow-fleshed and three white-fleshed cassava cultivars. Clusters 4 to 6 displayed a sensitive response to PPD, showcasing a significant increase in symptoms at 5 and 10 DAH, with four white-fleshed cassava cultivars identified within this cluster. These findings underscored the presence of PPD tolerance in both yellow-fleshed and white-fleshed cassava tuberous roots. The correlation between PPD and DMC was significant only at 2 DAH, displaying a moderate positive correlation. Consequently, this study identified three cultivars, “Carvita-25”, “Manggu”, and ““Ubi Kuning””, with high DMC and low PPD incidence at 5 DAH, suggesting their suitability for further breeding programs.

Keywords: carotenoid, germplasm characterization, dry matter content, root damages, shelf-life

Introduction

Cassava (*Manihot esculenta* Crantz) is one of the most essential carbohydrate crops worldwide, consumed by millions of populations in Africa, Asia, and Latin America (Parmar et al.., 2017). Indonesia is the fifth largest cassava producer after Nigeria, the Republic Congo, Thailand, and Ghana. Moreover, Indonesia has the highest productivity compared to other cassava-producer countries, reaching 26.09 tons.ha^{-1} in 2020 (FAO, 2021). Cassava production in Indonesia supplied 7.04% of the global demand (Indonesian Ministry of Agriculture, 2020), reaching 18.3 million tons of annual production in 2020 (FAO, 2021). Those data indicate that Indonesia has great potential in the world cassava supply chain. In addition, the utilization of cassava also continues to expand globally, including for fresh consumption and industrial raw materials (Parmar et al., 2017).

The storability of cassava tuberous roots is a crucial trait for cassava processing because it can only be stored for less than two or three days after harvest (Bechoff et al., 2016; Prempeh et al., 2017; Udogu et al., 2021). The short shelf-life of cassava tuberous roots is caused by post-harvest physiological deterioration (PPD), resulting in blue, black, or brown root discoloration (Hu et al., 2016). PPD is initiated when cassava tuberous roots are cut from the mother plant, leading to oxidative stresses and complex biochemical processes (Hu et al., 2016; Djabou et al., 2017). PPD hamper many disadvantages in the cassava market trade, including loss yield, degraded quality of fresh root and derived products, shortened processing time and distribution distance, and diminished economic value (Sanchez et al., 2013; Naziri et al., 2014; Prempeh et al., 2017; Aondoaver et al., 2021; Praise et al., 2021). Thus, PPD tolerance is one of the main priority traits for cassava breeding

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in many cassava-producer countries (Bechoff et al., 2016; Zainuddin et al., 2018).

Developing PPD-tolerant cassava cultivars is a long-term and cost-effective approach to prolonging tuberous root shelf-life (Moyib et al., 2015; Bechoff et al., 2016). PPD-tolerant cultivars could be achieved by developing yellow-fleshed cassava tuberous roots (Beyene et al., 2018; Nduwumuremyi et al., 2018; Udogu et al., 2021). Yellow-fleshed cassava tuberous roots contain a high carotenoid content that enhances reactive oxygen species scavenging capacity and results in longer shelf-life than white-fleshed (Uarrota et al., 2014; Beyene et al., 2018; Udogu et al., 2021). Additionally, a low dry matter content (DMC) could also be used to address PPD-tolerant cultivars because both traits have a positive correlation (Nduwumuremyi et al., 2018; Beyene et al., 2022; Udogu et al., 2021; Lebot et al., 2023). Therefore, exploration of germplasm sources of PPD tolerance and additional desirable traits is necessary for starting breeding purposes (Moyib et al., 2015; Zainuddin et al., 2023).

The BRIN's genetic engineering research center currently has cassava germplasm consisting of white-fleshed and yellow-fleshed tuberous roots that can potentially be used to explore PPD-tolerant sources. Therefore, this study aimed to assess the PPD responses of six yellow-fleshed and ten white-fleshed cassava tuberous roots and find the source of PPD tolerance.

Cassava (Manihot esculenta Crantz) stands as one of the most vital carbohydrate crops globally, serving as a staple for millions across Africa, Asia, and Latin America (Parmar et al., 2017). Indonesia, ranked fifth in cassava production after Nigeria, the Republic of Congo, Thailand, and Ghana, boasts the highest productivity among cassava-producing nations, achieving 26.09 tons per hectare in 2020 (FAO, 2021). With Indonesia supplying 7.04% of the global demand (Indonesian Ministry of Agriculture, 2020), its cassava production hit 18.3 million tons annually in 2020 (FAO, 2021), signalling its significant role in the global cassava supply chain. Furthermore, the utilization of cassava continues to broaden worldwide, encompassing both fresh consumption and industrial applications (Parmar et al., 2017).

The storability of cassava tuberous roots is a critical factor in cassava processing, as they can only be stored for a short period of two to three days post-harvest (Bechoff et al., 2016; Prempeh et al., 2017; Udogu et al., 2021). This limited shelf-life stems from post-harvest physiological deterioration (PPD), which manifests as blue, black, or brown discoloration of the roots (Hu et al., 2016). PPD onset occurs upon cutting cassava tuberous roots from the mother plant, triggering oxidative stress and complex biochemical processes (Hu et al., 2016; Djabou et al., 2017). PPD poses numerous challenges in the cassava market, including yield loss, decreased quality of fresh roots and derived products, shortened processing time and distribution distance, and reduced economic value (Sanchez et al., 2013; Naziri et al., 2014; Prempeh et al., 2017; Aondoaver et al., 2021; Praise et al., 2021). Consequently, PPD tolerance ranks among the top priority traits for cassava breeding in many producer countries (Bechoff et al., 2016; Zainuddin et al., 2018).

Developing PPD-tolerant cassava cultivars offers a long-term and cost-effective strategy for extending tuberous root shelf-life (Moyib et al., 2015; Bechoff et al., 2016). Yellow-fleshed cassava tuberous roots, known for their high carotenoid content, exhibit enhanced reactive oxygen species scavenging capacity, resulting in prolonged shelf-life compared to their white-fleshed counterparts (Uarrota et al., 2014; Beyene et al., 2018; Udogu et al., 2021). Additionally, low dry matter content (DMC) has emerged as another trait conducive to PPD tolerance, given its positive correlation with carotenoid content (Nduwumuremyi et al., 2018; Beyene et al., 2022; Udogu et al., 2021; Lebot et al., 2023). Hence, exploring germplasm sources for PPD tolerance and other desirable traits serves as a crucial step in breeding efforts (Moyib et al., 2015; Zainuddin et al., 2023).

The genetic engineering research center at BRIN currently houses cassava germplasm comprising both white-fleshed and yellow-fleshed tuberous roots, offering potential resources for investigating PPD-tolerant sources. Consequently, this study aims to evaluate the PPD responses of six yellow-fleshed and ten white-fleshed cassava tuberous roots, with the goal of identifying sources of PPD tolerance.

Material and Methods

Plant Materials and Experimental Design

Sixteen cassava cultivars were planted at the BB Biogen Experimental Farm in Depok, Indonesia, in December 2020, with the support of the Indonesian Cassava Society (MSI) to cultivate the evaluated cassava tuberous roots. For each of the sixteen cassava cultivars (refer to Table 1), three stem cuttings were planted and maintained until harvesting. The planting distance between stem cuttings was set at 0.8 x 0.8 square meters. One month after planting, the cassava plants were fertilized with NPK at a rate

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of 200 kg per hectare. Standard cultivation practices, including weed and pest control, were subsequently implemented.

Cassavas were harvested ten months after planting (MAP) in September 2021, with harvesting conducted manually in three stages to accommodate the storage and observation procedures. Tuberous roots harvested at 10 MAP were selected, with roots exceeding 15 cm in length and 5 cm in diameter (as per Luna et al., 2020), utilized for subsequent PPD and DMC experiments. All observations, except field activities, were carried out at the Genetic Engineering Research Center Laboratory, BRIN, located in Cibinong, Bogor, Indonesia.

Table 1. List of 16 cassava cultivars used in this study.

No	Cultivars	Remarks	Tuberous-flesh color
1	“Adira-1”	Indonesian national variety	Yellow
2	“Bokor”	Boyolali local cassava cultivar	Yellow
3	“Carvita-25”	Soma-clonal variant from cv. “Adira-4”	Yellow
4	“Mentega-2”	Tasikmalaya local cassava cultivar	Yellow
5	“Nangka”	Bogor local cassava cultivar	Yellow
6	“Ubi Kuning”	Indonesian local cassava cultivar	Yellow
7	“Adira-4”	Indonesian national variety	White
8	“Adira-4-R”	Gamma irradiation from cv. “Adira-4”	White
9	“Apuy”	Sukabumi local cassava cultivar	White
10	“Iding”	Indonesian local cassava cultivar	White
11	“Iding-R”	Gamma irradiation from cv. “Iding”	White
12	“Kristal-Merah”	Indonesian local cassava cultivar	White
13	“Manggu”	Indonesian national variety	White
14	“Menti”	Bantul local cassava cultivar	White
15	“Revita”	Soma-clonal variant from cv. “Roti”	White
16	“Roti”	Indonesian local cassava cultivar	White

PPD Symptom Assessment

PPD was induced using the Centro International de Agricultura Tropical (CIAT) standard method. The proximal and distal ends of cassava tuberous roots were trimmed, leaving 15-20 cm roots. The distal end of the cut roots was then covered with PVC film (Luna et al., 2020). These root samples were stored for 2, 5, and 10 days after harvest (DAH) under ambient temperature conditions (28 - 34 ºC) and relative humidity levels of 70 - 90%, placed on open racks shielded from direct sunlight and rain.

The assessment of PPD was conducted by slicing the cassava tuberous roots into approximately 0.5 cm thick sections at the proximal, middle, and distal parts (Rahmawati et al., 2022). Subsequently, images of the tuberous root slices were captured using a digital camera (OPPO Reno2 F-48MP). Image processing was carried out using ImageJ to measure the percentage of root discoloration indicative of PPD symptoms (Qin et al., 2017; Rahmawati et al., 2022). For each storage period, one cassava tuberous root per cultivar was utilized for PPD observation, with the process repeated three times.

Dry Matter Content Measurement

Dry matter content (DMC) was measured at each storage period. A total of 40 g of chopped cassava tuberous roots were oven-dried at 105 ºC for 24 hours (Qin et al., 2017; Luna et al., 2020). The dried samples were weighed, and then DMC was obtained as a percentage of dry weight relative to the fresh weight samples (Sanchez et al., 2013). For each storage period, one cassava tuberous root per cultivar was used for the DMC observation, and the observations were repeated three times.

Statistical Analysis

PPD symptom and DMC data were analyzed using ANOVA and Duncan’s Multiple Range Test (DMRT) post hoc test at a 5% significance level. Referring to García et al. (2013), PPD symptom data were previously transformed using the Arcsine square method to minimize experimental errors. K-means clustering analysis of PPD response statuses was performed using the factoextra package in RStudio

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version 4.3.0 (Zainuddin et al., 2023). Correlation analysis was conducted on PPD symptoms and DMC variables using Pearson's method. ANOVA and correlation analysis were conducted using Statistical Tools for Agriculture Research (STAR) software (http://bbi.irri.org/products).

Result and Discussion

PPD Symptom and Tolerance Response of Sixteen Cassava Cultivars

Identifying PPD tolerance sources is essential for developing a prolonged shelf-life of cassava tuberous root cultivars (Moyib et al., 2015; Zainuddin et al., 2023). To explore PPD-tolerant cultivars, PPD symptoms of sixteen Indonesian cassava cultivars were assessed at 2, 5, and 10 DAH. According to Zainuddin et al. (2023), k-means clustering analysis could be used to demonstrate the PPD tolerance pattern. In this study, clustering analysis using PPD symptoms at 2, 5, and 10 DAH distinguished sixteen cassava cultivars into six clusters, corresponding to their PPD response status (Figure 1).

Cluster 1 is the PPD-tolerant cassava, showing PPD symptoms of ≤ 0.8% at 2 DAH, ≤ 5.1% at 5 DAH, and an average of ≤ 2.6% (Table 2). Cassava cv. "Adira-1", "Adira-4", "Adira-4-R", "Carvita-25", "Manggu", and "Ubi Kuning" are clustered as PPD tolerance (Figure 1). Clusters 2 and 3 are PPD medium tolerant, showing PPD symptoms as presented in Table 2. However, PPD responses at 2 DAH of cassava varieties belonging to Cluster 2 differ from Cluster 3 (Table 2). Cassava cv. "Bokor" and "Kristal-Merah" (i.e., Custer 2) showed a high PPD symptom at 2 DAH (2.4 and 4.0%), while cassava cv. "Iding", "Mentega-2", "Nangka", and "Roti", i.e., Cluster 3) showed low values of PPD symptoms (i.e., ≤ 1.3%) (Table 2). However, the PPD symptoms of cassava belonging to Cluster 2 and 3 at 5 DAH are similar and range from 5.7 to 9.3, On the other hand, cassava cv. "Kristal-Merah" only shows PPD symptoms ranging from 2.0 - 3.8% at 2 - 10 DAH (Table 2). Although cassava cv. "Kristal-Merah" shows fewer PPD symptoms than the other members of Cluster 2 and 3, cassava "Kristal-Merah" cannot be grouped as PPD tolerant (Table 2) and belongs to the PPD medium tolerant. The average PPD symptoms of all cassava cultivars belonging to Clusters 2 and 3 ranged from 2.7% to 5.1% (Table 2).

Table 2. The mean value of PPD symptoms at three storage periods, microbial infection at 10 DAH, PPD status, and the cluster of 16 cassava cultivars

Cultivars	PPD symptom (%)				Microbial infection at 10 DAH (%)	PPD status	Cluster
	2 DAH	5 DAH	10 DAH	Average			
"Ubi Kuning"	0.8 de	0.6 g	2.6	1.3	0.0	Tolerant	1
""Adira-4"-R"	0.7 de	2.5 efg	0.8	1.4	38.8	Tolerant	1
"Carvita-25"	0.8 cde	3.5 defg	2.0	2.1	49.2	Tolerant	1
"Manggu"	0.5 de	5.1 fg	1.0	2.2	26.6	Tolerant	1
"Adira-4"	0.6 de	1.2 g	5.6	2.5	40.0	Tolerant	1
"Adira-1"	0.4 e	1.9 g	5.6	2.6	27.5	Tolerant	1
"Kristal-Merah"	2.4 bc	2.0 efg	3.8	2.7	0.0	Medium	2
"Bokor"	4.0 ab	5.8 bcd	0.8	3.5	38.2	Medium	2
"Roti"	1.3 cde	6.5 defg	2.4	3.4	0.0	Medium	3
"Mentega-2"	1.0 cde	5.7 cdef	4.0	3.6	0.0	Medium	3
"Iding"	0.5 de	6.2 bcde	7.2	4.6	39.3	Medium	3
"Nangka"	1.1 cde	9.3 bc	5.0	5.1	67.2	Medium	3
"Revita"	0.4 e	12.8 ab	11.4	8.2	34.5	Sensitive	4
"Iding"-R	1.8 bcd	16.6 a	7.6	8.7	43.2	Sensitive	4
"Apuy"	1.3 cde	5.3 bcd	21.6	9.4	61.4	Sensitive	5
"Menti"	6.0 a	9.3 abc	17.6	11.0	85.3	Sensitive	6
Significance	**	*	ns				

Notes: A distinct lowercase letter on the values in the same column indicated a significant difference based on DMRT (α = 0.05). ns = not significant; * = significant P <0.05, ** = highly significant P <0.01 according to F-test. DAH = days after harvest, PPD = post-harvest physiological deterioration, y = yellow, and w = white.

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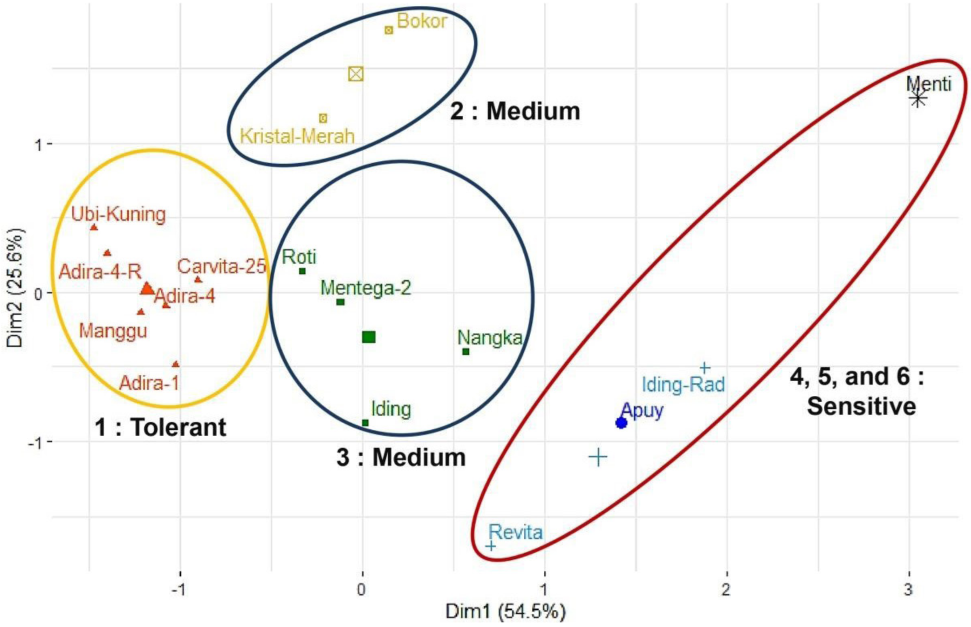

Figure 1. K-means cluster analysis of 16 cassava cultivars using PPD symptom data at 2, 5, and 10 days after harvest (DAH). The tested cassava cultivars are classified into six clusters, indicating their PPD response status. Cluster 1 is tolerant, clusters 2 and 3 are medium tolerant, and clusters 4, 5, and 6 are sensitive to PPD.

Four cassava cultivars (cassava cv. "Apuy", "Iding-R", "Menti", and "Revita") in clusters 4, 5, and 6 are considered as PPD sensitive (Figure 1). However, except for cassava cv, the four cassava cultivars show a low PPD symptom at 2 DAH. "Menti". However, the PPD symptoms of the four cassava cultivars increase during the subsequent storage period (Table 2). The PPD symptoms of cassava cv. "Revita" and "Iding-R" increase sharply at 5 DAH (i.e., 12.8 and 16.6%) while cassava cv. "Apuy" and "Menti" increase sharply at 10 DAH (i.e., 21.6 and 17.6%) (Table 2). Thus, the average PPD symptoms of the four cassava cultivars ranged from 8.2% to 11.0% (Table 2).

The lower PPD symptoms at 10 DAH than 5 DAH in the evaluated cassava cultivars (Table 2) happen because of the microbial infection. Since microbial-infected samples confound the PPD measurement, the infected samples were not used. Therefore, establishing robust PPD symptoms at 10 DAH is difficult. Previous studies have reported the same problem of establishing PPD symptoms at 10 DAH due to microbial infection (Sanchez et al., 2013; Zainuddin et al., 2023). Microbial infection also occurred in the PPD-tolerant cassava cultivars (Table 2), indicating that the cassava tuberous root's storability and robust PPD evaluation under this study condition should be done at five DAH.

Representative PPD symptom development during 2 - 10 DAH storage periods among PPD tolerant (cv. "Carvita-25"), medium tolerant (cv. "Nangka"), and sensitive (cv. "Menti") is presented in Figure 2. At 2 DAH, PPD symptoms of tolerant and medium-tolerant cassava cultivars are similar. Meanwhile, the PPD-sensitive cassava cultivars show extensive tuberous root discoloration areas (Figure 2). Subsequently, the symptom differences among PPD-tolerant, medium-tolerant, or sensitive cassava cultivars can be distinguished at 5 DAH. PPD symptoms in PPD-tolerant cassava cultivars are the lowest, and the sensitive cassava cultivars are the highest (Figure 2). Due to microbial infection, some root slice samples were discarded and resulted in the level of PPD symptoms at 10 DAH were not always consistent with the grouping of PPD responses, i.e., PPD tolerant cassava did not always show the lowest PPD symptoms nor PPD sensitive cassava cultivar showed the highest PPD symptoms.

This study also assessed PPD responses of yellow-fleshed and white-fleshed cassava tuberous roots. Previous reports have indicated a negative correlation between PPD and carotenoid content. The yellow-fleshed cassava tuberous roots have a longer shelf-life than the white-fleshed roots (Beyene et al., 2018; Nduwumuremyi et al., 2018; Udogu et al., 2021). In this study, three out of six yellow-fleshed cassava cultivars are PPD tolerant, while others are PPD medium tolerant (Table 2). Tuberous roots of the white-fleshed cassava cultivars also belong to either PPD tolerant, medium tolerant, or sensitive (Table 2). Moreover, all four PPD-sensitive cassava cultivars are white-fleshed (Table 2). This result indicated

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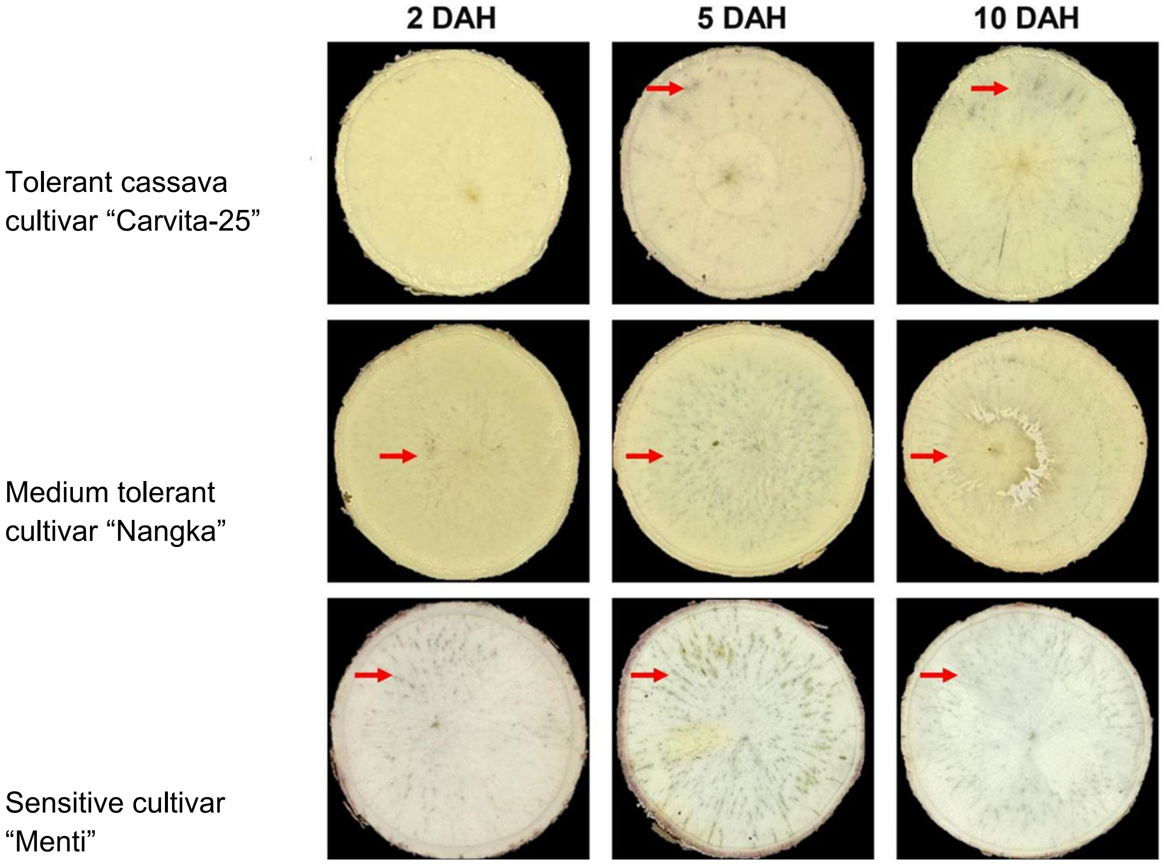

Figure 2. Representative the root slice images of three different PPD response statuses, i.e., cassava cv. "Carvita-25" is tolerant, cv. "Nangka" is medium, and cv. "Menti" is sensitive to PPD. PPD symptoms are observed at 2, 5, and 10 days after harvest (DAH).

that the yellow-fleshed cassava containing higher carotenoids showed higher tolerance to PPD than the white-fleshed cassava.

Carotenoids were essential in scavenging reactive oxygen species (ROS) during PPD, resulting in delayed PPD onset (Uarrota et al., 2014; Beyene et al., 2018). Moreover, PPD tolerance characters might be associated with the carotenoid content (Uarrota et al., 2014). Since carotenoid content is positively correlated with the yellow color of the cassava tuberous root, selecting PPD tolerance cassava could be done using cassava tuberous root flesh color (Sanchez et al., 2006). Moreover, carotenoid also has a higher heritability. Hence, early-stage selection for the carotenoid contents of cassava tuberous roots (de Carvalho et al., 2022). Yellow-fleshed cassava tuberous root is also beneficial for solving malnutrition in many countries; Yellow-fleshed cassava could be used as a biofortified food to supply provitamin A (Oluba et al., 2017; Bechoff et al., 2018).

Correlation between DMC and PPD Symptoms

High dry matter content is desirable for the cassava tuberous roots industry (Udogu et al., 2021). The evaluated tuberous roots of 16 cassava cultivars showed significantly diverse DMC (Table 3). After 2, 5, or 10 DAP storage periods, tuberous roots of cassava cv. "Apuy", "Carvita-25", "Nangka", and consistently contain higher DMC (± 40%, Table 3). The DMC of cassava cv. "Bokor" and "Manggu" tuberous roots were close to 40% at 2 and 5 DAH, while the DMC of cassava cv. "Revita" and "Ubi Kuning" were also close to 40% at 5 and 10 DAH (Table 3). The high DMC of some cassava cultivars is desirable for the cassava-based industry. The desirable DMC of cassava tuberous roots for industry ranges from 35 - 40% (Morante et al., 2010; Luna et al., 2020).

Previous studies have shown that DMC is positively correlated with PPD symptom severity, which implies that the cassava roots having high DMC are more prone to PPD onset (Beyene et al., 2022; Luna et al., 2020; Udogu et al., 2021; Lebot et al., 2023; Zainuddin et al., 2023). In line with this study, DMC positively correlated with PPD symptoms at 2 DAH with a moderate coefficient of 0.304 (Table 4). The analysis also indicated that DMC could partially define PPD onset at 2 DAH. A positive relation between DMC

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Table 3. Mean value of dry matter content of 16 cassava cultivars at three storage periods

Cultivars	Dry matter content (%)		
	2 DAH	5 DAH	10 DAH
y-"Adira-1"	33.7 efgh	36.1 cd	40.9 ab
w-""Adira-4""	34.6 defgh	36.3 bcd	38.8 abc
w-"Adira-4-R"	38.4 bcd	36.5 bcd	35.8 cd
w-"Apuy"	39.7 ab	39.3 abc	39.7 abc
y-"Bokor"	43.1 a	42.6 a	33.1 d
y-"Carvita-25"	39.8 ab	42.6 a	42.4 ab
w-"Iding"	35.1 defg	36.8 bcd	35.8 cd
w-"Iding-R"	33.5 fgh	36.4 bcd	36.2 cd
w-"Kristal-Merah"	31.5 gh	33.6 d	32.1 d
w-"Manggu"	39.5 abc	39.6 abc	38.0 bc
y-"Mentega-2"	33.6 fgh	36.3 bcd	33.1 d
w-"Menti"	41.1 ab	41.9 ab	41.2 ab
y-"Nangka"	41.3 ab	42.9 a	40.8 ab
w-"Revita"	37.6 bcde	37.8 abcd	39.0 abc
w-"Roti"	30.7 h	34.5 cd	33.0 d
y-"Ubi Kuning"	35.8 cdef	37.3 abcd	42.8 a
Significance	**	**	**

Note: A distinct lowercase letter following values in the same column indicated significant differences based on DMRT (α = 0.05). ** = highly significant P <0.01 according to F-test. DAH = days after harvest, y = yellow, and w = white.

Table 4. Pearson's correlation analysis between PPD symptoms and DMC at three storage periods

	PPD at 2 DAH		PPD at 5 DAH		PPD at 10 DAH	
	R	P-value	R	P-value	R	P-value
DMC at 2 DAH	0.3040	0.0357*	0.0991	0.5222	0.1348	0.4197
DMC at 5 DAH	0.2072	0.1576	0.1932	0.2090	0.0719	0.6678
DMC at 10 DAH	-0.0002	0.9988	-0.0382	0.8054	0.3166	0.0528

Note: The significance of Pearson's correlation between PPD symptom and DMC are denoted with * (α = 0.05). DAH = days after harvest, DMC = dry matter content, PPD = post-harvest physiological deterioration.

and PPD offered a problematic decision for cassava breeding since both traits are essential for the post-harvest processing of cassava tuberous roots (Udogu et al., 2021).

This study has identified three cassava cultivars, namely "Carvita-25", "Manggu", and "Ubi Kuning", characterized by high DMC and tolerance to PPD. These cultivars are categorized within Cluster 1 (Figure 1), displaying PPD symptoms of ≤ 0.8% at 2 DAH and ≤ 5.1% at 5 DAH (Table 2). Additionally, their DMC ranged from 35 to 39% at 2 DAH and 37 to 42% at 5 DAH (Table 3). The relationship between high DMC and PPD tolerance may vary depending on the cultivar. Consequently, there is potential to develop cassava cultivars exhibiting both high DMC and PPD tolerance traits (Zainuddin et al., 2023). The recommended storage duration for cassava tuberous roots is five days. After this period, the stored roots maintain high DMC levels and exhibit minimal PPD symptoms. Although certain cassava cultivars may display low PPD symptoms at 10 DAH, storing tuberous roots for this extended period is not advised due to the risk of microbial infection.

Conclusion

The responses of cassava tuberous roots to PPD were categorized into PPD tolerant, medium tolerant, and sensitive groups using k-means clustering analysis. Out of sixteen cassava cultivars examined, six were identified as PPD-tolerant, consisting of three yellow-fleshed and three white-fleshed varieties. This

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suggests that PPD tolerance can be observed among both yellow-fleshed and white-fleshed cassava cultivars. However, PPD-sensitive cultivars were exclusively found among the white-fleshed cassava varieties. Additionally, this study revealed a positive correlation between DMC and PPD symptoms only at 2 DAH, with no significant correlation observed at 5 or 10 DAH. This implies that it is feasible to develop cassava cultivars with combined PPD tolerance and high DMC characteristics. Three cassava cultivars were identified that can be stored for five days and displayed low PPD symptoms (≤ 5%) and high DMC (more than 40%). These cultivars are “Carvita-25” (yellow-fleshed), “Manggu” (white-fleshed), and “Ubi Kuning” (yellow-fleshed). Furthermore, these three cassava cultivars, “Carvita-25”, “Manggu”, and “Ubi Kuning”, could serve as valuable germplasm for the development of future PPD-tolerant and high-DMC cassava varieties.

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