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CASSAVA (*MANIHOT ESCULENTA* CRANTZ) MUTANT GENOTYPE EVALUATION FOR EARLY HARVEST AND YIELD

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SUMMARY

The harvesting period of 12 months after planting (MAP) is the major constraint in cassava (*Manihot esculenta*) cultivation, prompting the need for early-harvest (5–9 MAP) cultivars. Hence, yield potential evaluation of cassava genotypes during the early-harvest period is necessary. This study assesses the yield potential of 18 advanced cassava mutants (M1V8 generation) and five cassava commercial varieties harvested at 7 MAP. The results showed nine mutants yielded above 30.0 t ha^{-1} (ADR-24, GJ-7, GJ-10, GJ-14, GJ-16, ML-18, ML-19, ML-20, and RTM-26), and two mutants (ML-21 and RTM-25) surpassed 40.0 t ha^{-1}, notably higher than previous early-harvest studies. Despite high yields, the proportion of commercial-size roots is moderately low (4–6 roots/plant). However, selected mutants produced 10–16 total roots/plant, suggesting cultivation adjustments could improve commercial root yield. A positive correlation between production traits indicates that higher commercial-size roots correspond to increased yield potential. Of the 11 promising mutants, five (GJ-10, GJ-14, GJ-16, ML-21, and RTM-26) with low bitterness attained favor for taste. The five mutants are endorsable as early-harvesting, high-yielding, and low HCN-content cassava cultivars.

Keywords: *Manihot esculenta*, irradiation mutagenesis, early maturity, high-root productivity

Key findings: Gamma irradiation randomly affects cassava root morphological and yield changes. This evaluation found 11 early-maturity (harvesting at 7 MAP) and high-yielding advanced mutants. Moreover, the root bitterness level of the five cassava mutants is low, indicating a minimal HCN level.

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INTRODUCTION

Indonesia is the fifth biggest cassava (*Manihot esculenta*) producer in the world, after Nigeria, Thailand, Congo, and Brazil (Odoemelam *et al.*, 2020), with a contributed market share of 7.04% worldwide (Indonesian Ministry of Agriculture, 2020). Moreover, Indonesia has the highest productivity compared with the other four leading cassava producers (FAO, 2021), indicating that Indonesia plays a significant role in the worldwide cassava trade. The high-starch cassava in Indonesia mainly serves industrial purposes despite its tendency to contain high levels of hydrogen cyanide (HCN) (Sholihin *et al.,* 2019). The cassava demand is steadily increasing because cassava has many purposes, such as raw materials for food, feed, industry, and renewable energy (Tonukari *et al.,* 2015; Ayetigbo *et al.,* 2018). Thus, the need for increased cassava production capacity could come from raising the cropping intensity (Gnahoua *et al.,* 2016). Unfortunately, farmers can only grow cassava once a year to obtain the optimum yield since cassava growing takes 12 months before harvesting (Tumuhimbise *et al.,* 2015). Hence, developing early-harvesting and high-yielding cassava cultivars through sexual hybridization or mutagenesis is highly desirable.

Creating early-harvesting and high-yielding cassava cultivars has become one of the new objectives of cassava breeding in some producing countries, such as India (Suja *et al.,* 2010), Thailand (Polthanee *et al.,* 2014), and various countries in Africa (Tumuhimbise *et al.,* 2015; Chipeta *et al.,* 2016; Gnahoua *et al.,* 2016). The desirable, early-harvesting cassava varieties could optimally yield cassava roots when harvested five to nine months after planting (MAP). Therefore, these cassava varieties could advance increasing cassava cropping intensity and yearly production capacity (Suja *et al.,* 2010; Enesi *et al*., 2022), increase farmers' income (Suja *et al.,* 2010; Tumuhimbise *et al.,* 2015; Enesi *et al*., 2022), minimize biotic and abiotic stresses (Chipeta *et al.,* 2016; Maruthi *et al.,* 2020), and prolong cassava root storability (Rahmawati *et al.,* 2022).

Bulking index assessment of the available cassava cultivars showed that early harvesting yield at 9 MAP reached about 74% of the potential harvest at 12 MAP. Such data show only 26% less yield than the 12 MAP harvesting. In comparison, cassava yield losses because of cassava-brown streak virus disease (CBSD) during the 12-MAP growing season may reach up to 40% (Chipeta *et al.,* 2016). Therefore, yield losses due to early harvesting may offset the potential loss due to prolonged disease infestation in the field. For these reasons, as one of the leading cassava producers in the world, Indonesia needs to develop desirable, early-harvest cassava varieties to compete in the worldwide cassava trade.

Various constraints facing cassava breeding include high heterozygosity, low flowering rate, asynchronous male and flowering period, and low seed yield (Ceballos and Hershey, 2017). Hence, conventional cassava breeding through sexual hybridization takes a long time to complete (Ceballos *et al.,* 2013). Contrarily, reports have stated the success of selecting phenotypically superior mutants through gamma irradiation in various crops, such as a high yield of cowpea (Horn *et al.,* 2018), drought-tolerant rice (Patmi *et al.,* 2020), and disease-resistance banana and orchids (Indrayanti *et al*., 2018; Humaira *et al*., 2020). Induced mutation using gamma irradiation could generate arrays of random mutations in cassava, and the mutants could be options for superior phenotypic characteristics (Subekti *et al.,* 2018; Sholihin *et al.,* 2019; Pratama *et al*., 2023).

Induced mutation using irradiation has been initiated since 2012 and directed toward identifying cassava mutants with improved root yield and starch content (Maharani *et al.,* 2015). Such mutant arrays have continuously gained scrutiny in the field, and mutant lines showing improved essential phenotypic characters have previously incurred assessment up to the fourth generation of mutants (M1V4) (Maharani *et al.,* 2015; Subekti *et al.,* 2018). This study finalized the selected advanced cassava mutant populations to identify the phenotypically desirable ones.

Finally, 18 advanced mutants (M1V8) and five original cultivars reached evaluation for yield potential. This study aimed to select the early-maturing cassava mutants, assess their yield potential at 7 MAP, and determine the high-yielding early-maturing genotypes with low HCN content (sweet taste).

MATERIALS AND METHODS

Plant material

Planting materials of 23 cassava genotypes at the IPB - Sukamantri Field Experimental Station (560 masl), Bogor, Indonesia, commenced in June 2019. The Sukamantri field, renowned for its andosol soil type with a pH range from 3.8 to 6.4 (Sembiring, 2024), was the study's choice for its ideal conditions. The evaluated genetic materials included five original cassava cultivars and 18 advanced (M1V8) mutants (Table 1). The field experimental plots used a randomized complete block design (RCBD) with cassava cultivars and mutants as the single-factor treatment. Each treatment had three replications. The experimental unit comprised 10 cuttings (20 cm), and the total number of cuttings per genotype in the study was 30 cuttings. The rectangular planting spaces for cassava cuttings had a 1 × 1 m^2 distance. The fertilization began one month after planting (MAP), comprising urea (46% N) at 200 kg ha^{-1}, SP36 (36% P_2O_5) at 150 kg ha^{-1}, and KCl (50% K_2O) at 150 kg ha^{-1}. Standard agronomic practices continued, with seven cassava plants harvested from 7 MAP in December 2019.

Cassava root morphological characteristic evaluation

Harvesting three plant samples per replicate transpired for root characteristic morphological evaluation for each cassava genotype. The observed nine morphological cassava root characteristics and their descriptions followed the method of Fukuda *et al.* (2010), which included the extent of the peduncle, root constrictions, root shape, epidermis, parenchyma color, cortex color, ease of cortex peeling, epidermis texture, and root taste. The descriptive lists of the nine morphological cassava root characteristics are available in Table 2.

Table 1. The list of plant materials comprised 18 advanced mutant (M1V8) genotypes and five original cassava cultivars used in this study.

Cassava Genotypes	Remarks
Adira 4 (ADR)	- Adira 4, an Indonesian commercial cassava varieties (N = 1) - M1V8 generation derived from Gamma-ray irradiation of cassava cv. Adira 4 (N = 1)
ADR-24	Mutant #24
Gajah (GJ)	- Gajah, a local cassava variety from Kalimantan (N = 1) - M1V8 generation derived from Gamma-ray irradiation of cassava cv. Gajah (N = 9)
GJ-7, 8, 10, 11, 12, 13, 14, 15, and 16	Mutants #7, #8, #10, #11, #12, #13, #14, #15 and #16
Malang 4 (ML)	- Malang 4, an Indonesian commercial cassava variety (N = 1) - M1V8 generation derived from Gamma-ray irradiation of cassava cv. Malang 4 (N = 4)
ML-18, 19, 20, and 21	Mutants #18, #19, #20 and #21
Ratim (RTM)	- Ratim, a local cassava variety from Halmahera (N = 1) - M1V8 generation derived from Gamma-ray irradiation of cassava cv. Ratim (N = 3)
RTM-22, 25, 26	Mutants #22, #25 and #26
UJ-5 (UJ)	- UJ-5, an introduced cassava variety from Thailand (N = 1) - M1V8 generation derived from Gamma-ray irradiation of cassava cv. UJ-5 (N = 1)
UJ-17	Mutant #17

Note: (N) – number of cassava genotypes evaluated.

Table 2. A descriptor list of the morphological cassava root characteristics, as described by Fukuda *et al.* (2010).

No.	Morphological characteristics	Remarks
1	Extend of the peduncle (EP)	0 = sessile, 3 = pedunculate, 5 = mixed
2	Root constrictions (RC)	1 = few, 2 = some, 3 = many
3	Root shape (RS)	1 = conical, 2 = conical cylindrical, 3 = cylindrical, 4 = irregular
4	Epidermis color (EC)	1 = white/cream, 2 = yellow, 3 = light brown, 4 = dark brown
5	Parenchyma color (PC)	1 = white, 2 = cream, 3 = yellow, 4 = orange, 5 = pink
6	Cortex color (CC)	1 = white/cream, 2 = yellow, 3 = pink, 4 = purple
7	Ease of cortex peeling (CP)	1 = easy, 2 = difficult
8	Epidermis texture (ET)	3 = smooth, 5 = intermediate, 7 = rough
9	Root taste (RT)	1 = sweet, 2 = intermediate, 3 = bitter

Cassava yield and yield components

Three plant samples per replicate gathering for yield component reached evaluation for each cassava genotype. Cassava roots, manually cut from the harvested crops, underwent assessment for yield component characteristics. The observed traits comprised number of total roots per plant (NR), the number of commercial-size (NCS) roots per plant, and the weight of commercial-size (WCS) roots per plant. The commercial-size root criteria include a root length of at least 20 cm (Fukuda *et al.,* 2010) and a root diameter of more than 5 cm (Luna *et al.,* 2020). Calculating the potential yield estimate (Y) used the following equation:

$$Y = (WCS/plant) \times (Plant\ population/ha) \times 80\%$$

Note:
WCS/plant is the weight of commercial-size cassava roots per plant;
Plant population/ha is 10,000 plants, and the 80% is the percentage of harvested plants from the total population (Yani, 2016).

Statistical analysis

The cluster analysis constructing the root morphological characteristics used the PBSAT-CL software, employing the Gower dissimilarity and average linkage cluster as the parametric (http://www.pbstat.com/). One-way analysis of variance (ANOVA), followed by mean comparisons using Duncan's Multiple Range Test (DMRT) at $\alpha = 0.05$, helped analyze the yield component data. The Statistical Tools for Agriculture Research (STAR) software (http://bbi.irri.org/products) aided the statistical analysis. Subsequently, Spearman's correlation analysis continued for the seven root morphological characteristics, excluding the parenchyma color and ease of cortex peeling characteristics since the two variables are monomorphic. Pearson's correlation analysis also ran for yield component data. The yield component data from the selected 11 advanced mutants (M1V8) and the original three cassava cultivars received PCA-biplot analysis utilizing the FactoMineR and factoextra packages in Rstudio software (Zainuddin *et al.,* 2023).

RESULTS AND DISCUSSION

Cassava root morphological characteristics

The results of morphological characteristics evaluation for the 18 advanced cassava mutants (M1V8) and the five original cassava cultivars appear in Tables 3 and 4. Almost all the evaluated mutants show a similar extent of the peduncle, root constriction, root shape, epidermis texture, epidermis, parenchyma and cortex colors, and cortex peeling identical to the original cultivars (Table 3 and Table 4). However, changes in the extent of peduncle are visible in ADR-24 mutant; less root constriction showed in some GJ, RTM, and UJ mutants; epidermis texture differed in RTM-22 and RTM-25; epidermis color varied in RTM-26 and UJ-5, and cortex color is distinct in a few

Table 3. The root morphological characteristics of 18 advanced mutant (M1V8) genotypes and five original cassava cultivars observed in this study. The evaluated samples were from cassava harvested seven months after planting (MAP). The data averaged from three samples per genotype, with the measurement from three replications.

Genotype	Extent of Peduncle	Root Constriction	Root Shape	Epidermis Texture
Adira 4 (ADR)#	Mixed	Some	Conical	Rough
ADR-24	Pedunculate	Some	Conical-cylindrical	Rough
Gajah (GJ)#	Mixed	Some	Conical-cylindrical	Rough
GJ-7	Mixed	Few	Conical-cylindrical	Rough
GJ-8	Mixed	Few	Conical-cylindrical	Rough
GJ-10	Mixed	Few	Conical-cylindrical	Rough
GJ-11	Mixed	Few	Conical-cylindrical	Rough
GJ-12	Mixed	Some	Conical-cylindrical	Rough
GJ-13	Mixed	Some	Cylindrical	Rough
GJ-14	Mixed	Some	Conical-cylindrical	Rough
GJ-15	Mixed	Few	Conical-cylindrical	Rough
GJ-16	Mixed	Few	Conical-cylindrical	Rough
Malang 4 (ML)#	Mixed	Few	Conical-cylindrical	Rough
ML-18	Mixed	Some	Conical-cylindrical	Rough
ML-19	Mixed	Some	Conical-cylindrical	Rough
ML-20	Mixed	Few	Conical-cylindrical	Rough
ML-21	Mixed	Few	Conical-cylindrical	Rough
Ratim (RTM)#	Mixed	Some	Conical-cylindrical	Smooth
RTM-22	Mixed	Some	Cylindrical	Intermediate
RTM-25	Mixed	Some	Conical-cylindrical	Rough
RTM-26	Mixed	Few	Cylindrical	Smooth
UJ-5 (UJ)#	Mixed	Some	Conical	Smooth
UJ-17	Mixed	Few	Conical-cylindrical	Smooth

Note: # the original cassava cultivars.

Table 4. The root morphological characteristics of 18 advanced mutant (M1V8) genotypes and five original cassava cultivars observed in this study. The evaluated samples came from cassava harvested seven months after planting (MAP). The data averaged from three samples per genotype, with the measurement from three replications.

Genotype	Epidermis Color	Parenchyma Color	Cortex Color	Cortex Peeling	Root Taste
Adira 4 (ADR)#	Dark brown	White	Pink	Easy	Intermediate
ADR-24	Dark brown	White	Pink	Easy	Intermediate
Gajah (GJ)#	Dark brown	White	Purple	Easy	Sweet
GJ-7	Dark brown	White	White	Easy	Bitter
GJ-8	Dark brown	White	Purple	Easy	Sweet
GJ-10	Dark brown	White	Purple	Easy	Sweet
GJ-11	Dark brown	White	Purple	Easy	Sweet
GJ-12	Dark brown	White	Purple	Easy	Sweet
GJ-13	Dark brown	White	Pink	Easy	Sweet
GJ-14	Dark brown	White	Pink	Easy	Sweet
GJ-15	Dark brown	White	Yellow	Easy	Sweet
GJ-16	Dark brown	White	Purple	Easy	Sweet
Malang 4 (ML)#	Dark brown	White	Pink	Easy	Bitter
ML-18	Dark brown	White	Pink	Easy	Bitter
ML-19	Dark brown	White	Pink	Easy	Intermediate
ML-20	Dark brown	White	White	Easy	Bitter
ML-21	Dark brown	White	White	Easy	Sweet
Ratim (RTM)#	Light brown	White	White	Easy	Bitter
RTM-22	Light brown	White	White	Easy	Sweet
RTM-25	Light brown	White	Pink	Easy	Bitter
RTM-26	Yellow	White	White	Easy	Sweet
UJ-5 (UJ)#	Yellow	White	White	Easy	Bitter

UJ-17	Light brown	White	White	Easy	Bitter

Note: # the original cassava cultivars.

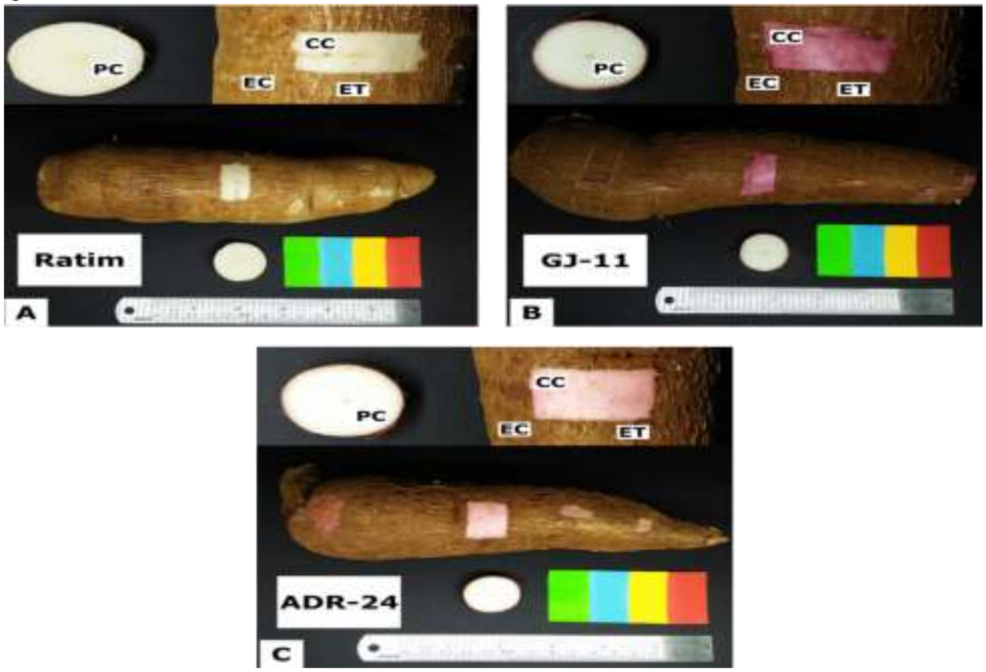

Figure 1. Representative variation in root characteristics of (A) cassava cv. Ratim, with light-brown epidermis color (EC), smooth epidermis texture (ET), and white cortex color (CC) characteristics, (B) advance mutant (V1M8) of Gajah no. 11 (GJ-11), with dark-brown EC, rough ET, and purple CC, and (C) advance mutant (V1M8) of Adira no. 24 (ADR-24), with dark-brown EC, rough ET, and pink CC. All genotypes have white parenchyma color (PC).

of Gajah, ML, and RTM mutants (Table 3 and Table 4). Examples of some morphological characteristics among the evaluated cassava genotypes are notable in Figure 1.

Moreover, the advanced mutants also exhibited some beneficial characteristics, such as changes in root taste from bitter to sweet and vice versa, as evident in mutants of GJ-7 (sweet to bitter), ML-19 (bitter to intermediate), ML-21, RTM-22, and RTM-26 (bitter to sweet) (Table 4). The bitter root taste is undesirable and indicates a high HCN content (Subekti *et al.,* 2017; Sholihin *et al.,* 2019). The root taste of the three high-yielding, original cassava cultivars (Adira-4, Malang-4, and Ratim) is intermediate or bitter (Khumaida *et al.,* 2015; Subekti *et al.,* 2017; Sholihin *et al.,* 2019). However, five advanced mutants (GJ-10, GJ-14, GJ-16, ML-21, and RTM-26) were derivatives of irradiated cassava cultivars. Gajah, Malang-4, and Ratim tasted sweet, indicating a low HCN content. Hence, these five advanced mutants could be priorities for developing high-yielding and low-HCN-content cassava cultivars in Indonesia.

Results of the cophenetic dendrogram construction using root morphological characteristics occur in Figure 2. The evaluated genotypes clustering into two major groups (I and II) revealed each group could further become into two subgroups. Group I showed the clustering of Ratim, UJ-5, and their advanced mutant genotypes (Figure 2). However, clustering of the RTM-25 emerged in Group II (Figure 2), along with 75% of the evaluated genotypes.

The major differentiating factors among Groups I and II are the epidermal color, cortex texture, and cortex color (Tables 3 and 4). The cassava genotypes belonging to Group I showed a light brown or yellow epidermal color, smooth or intermediate cortex texture, and a uniformly white cortex color (Table 2). In contrast, cassava genotypes belonging to

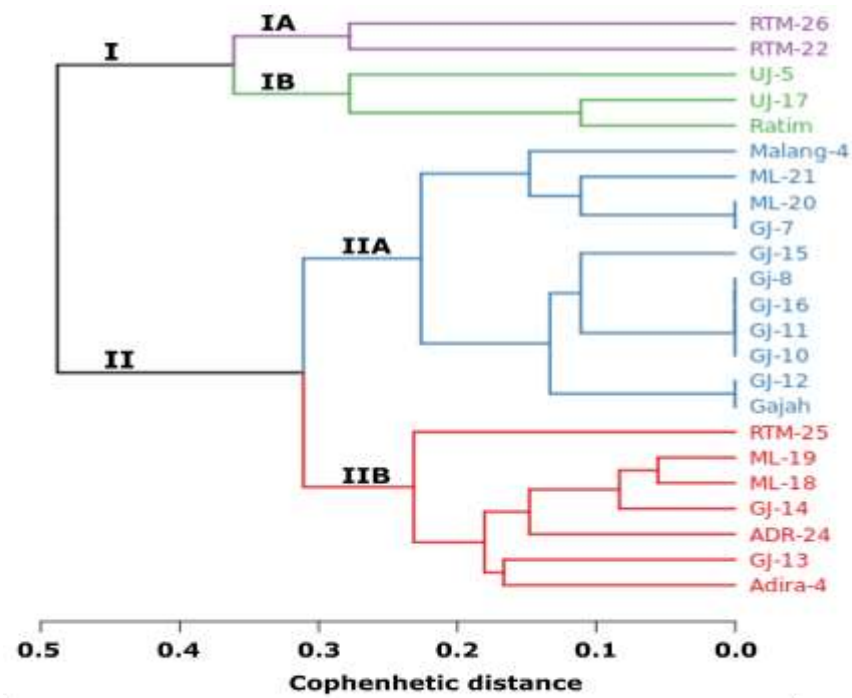

Figure 2. The constructed dendrogram using the root morphological trait data, classifying the evaluated genotypes into two main groups and two subgroups each.

Group II showed a dark brown color and rough epidermal characteristics (Tables 3 and 4). Members of Group II exhibited variations in the cortex color, such as white, yellow, pink, and purple cortex (Table 4). The Spearman's correlation analysis results among the morphological characteristics emerge in Figure 3A.

Most GJ- and ML-derived advanced cassava mutants showed clustering in subgroup IIA, while two GJ- and two ML-derived advanced mutants came together in subgroup IIB (Figure 2). The differentiating characteristics of GJ-13 and GJ-14 advanced mutants from the original cassava cultivar Gajah is the pink cortex (Table 4). In contrast, the root constrictions characteristic differentiates the ML-18 and ML-19 from the ML-20 and ML-21 advanced mutants and the original cassava cultivar Malang 4 (Table 3).

Gamma irradiation could change cassava morphological and yield characteristics (Khumaida *et al.,* 2015). Occurrences of random mutations of the genes in the cassava genomes were the target of gamma irradiation. Such random mutations may result in random phenotypic changes in the mutant population (Maharani *et al.,* 2015; Pratama *et al*., 2023). In this case, root morphological changes in the advanced mutants may have been due to the irradiation treatments. Reports of similar results have stated that gamma irradiation changed the color of young cassava leaves and stems (Lestari *et al.,* 2019), cassava root taste from a bitter parent variety to a sweet mutant or vice versa (Khumaida *et al.,* 2015; Maharani *et al.,* 2015; Sholihin *et al.,* 2019), and cassava leaf nutrient content (Pratama *et al*., 2023).

Yield and yield components

Among the evaluated genotypes at 7 MAP, the number of commercial-size (NCS) roots/plant is 3–10. The results also showed that the original cassava cultivar Gajah yielded the least, and Adira 4 yielded the most NCS roots (Table 5). Generally, the advanced mutants' average NCS roots/plant are lower than the original cultivars, affecting the weight of

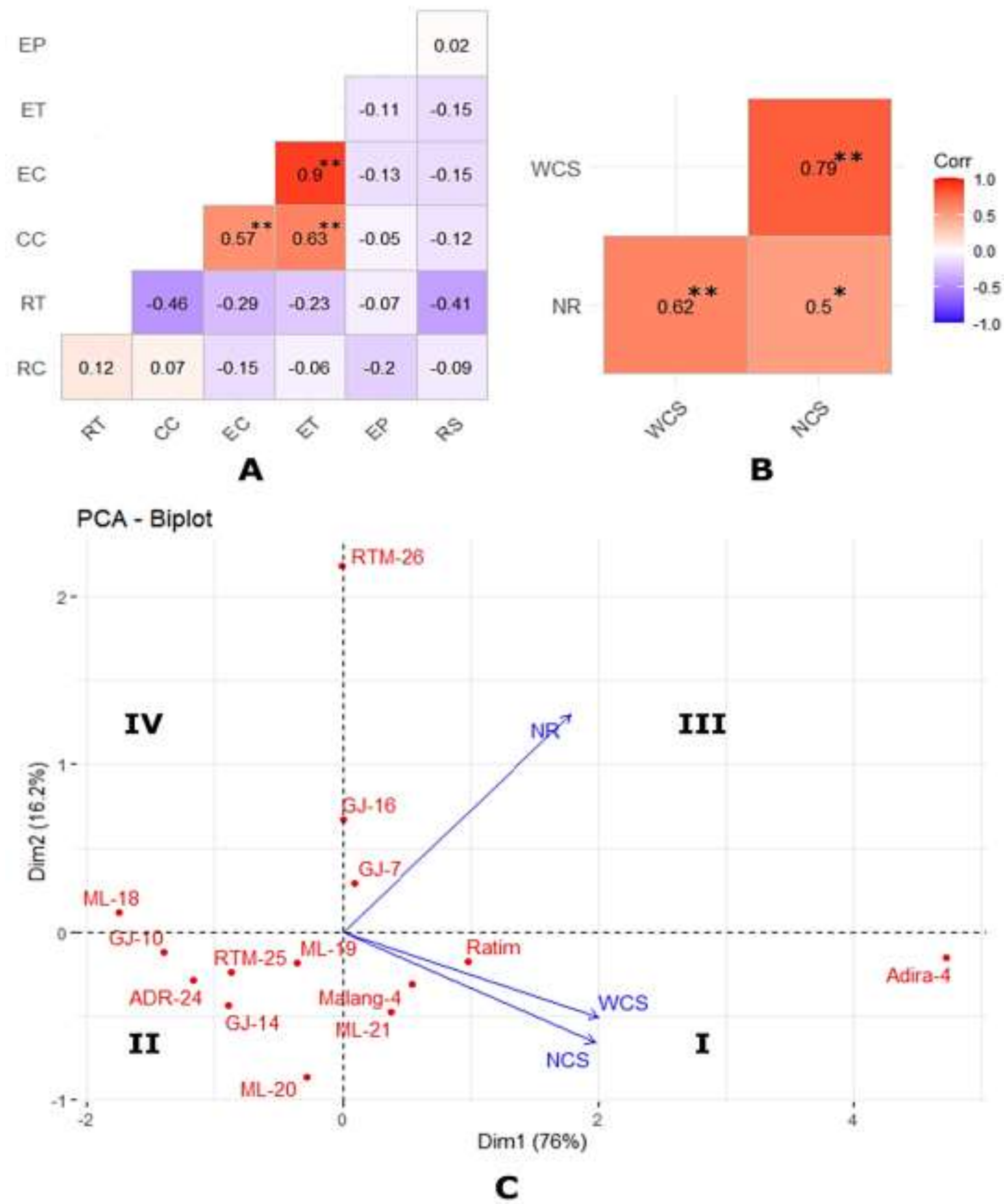

Figure 3. (A) Spearman's correlation coefficients among the cassava root morphological characteristics and (B) Pearson's correlation coefficients among the yield and yield component traits. (C) PCA-biplot of 11 advanced mutants (M1V8) as potential high-yielding and early-harvest genotypes, the original three cassava cultivars for dimension 1, and the yield characteristics for dimension 2. The plot is grouped into four quadrants (quadrants I – IV). EP: the extent of the peduncle, RC: root constrictions, RS: root shape, EC: epidermis color, CC: cortex color, ET: epidermis texture, RT: root taste, NR: number of roots per plant, NCS: number of commercial-size roots per plant, and WCS: weight of commercial-size roots per plant. * and ** are significant ($P < 0.05$) and highly significant ($P < 0.01$).

Table 5. The mean values of the number of roots (NR), number of commercial-size (NCS) roots, and weight of commercial-size (WCS) roots per plant, and yield potential of 18 advanced mutants (M1V8) and five original cassava cultivars evaluated in this study. The cassava harvest seven months after planting. The data averaged from three samples per genotype, with the measurement from three replications.

Genotype	NR per plant	NCS roots per plant	WCS roots per plant (kg)	Yield potential (t ha^{-1})
Adira 4 (ADR)#	17.9 a*	10.0 a*	8.3 a	66.5 a
ADR-24	10.0 cd	5.3 bc	4.1 bc	33.0 bc
Gajah (GJ)#	7.7 d	4.0 bc	2.8 c	22.1 c
GJ-10	10.0 cd	4.3 bc	4.1 bc	32.5 bc
GJ-11	10.7 cd	5.3 bc	3.2 bc	25.6 bc
GJ-12	9.7 cd	3.7 bc	2.2 c	17.9 c
GJ-13	11.0 bcd	3.7 bc	3.5 bc	28.3 bc
GJ-14	10.0 cd	5.0 bc	4.6 bc	37.1 bc
GJ-15	9.0 cd	4.3 bc	2.4 c	19.2 c
GJ-16	13.5 ad	5.2 bc	4.9 bc	39.4 bc
GJ-7	13.0 ad	6.7 bc	4.0 bc	32.3 bc
GJ-8	8.0 d	4.3 bc	2.2 c	17.3 c
Malang 4 (ML)#	12.3 a-d	7.3 ab	4.8 bc	38.4 bc
ML-18	10.0 cd	3.7 bc	3.8 bc	30.7 bc
ML-19	11.3 bcd	6.0 bc	4.4 bc	34.9 bc
ML-20	10.0 cd	6.3 bc	4.9 bc	39.2 bc
ML-21	11.7 bcd	6.7 bc	5.3 bc	42.1 bc
Ratim (RTM)#	13.0 a-d	6.3 bc	6.2 b	49.9 b
RTM-22	10.7 cd	5.0 bc	3.7 bc	29.3 bc
RTM-25	10.3 cd	4.0 bc	5.3 bc	42.7 bc
RTM-26	16.7 ab	4.3 bc	4.0 bc	31.7 bc
UJ-5 (UJ)#	12.9 ad	3.0 c	3.3 bc	26.5 bc
UJ-17	15.0 abc	4.3 bc	3.5 bc	27.7 bc

Note: # the original cassava cultivars. Data in the same column followed by different lowercase letters indicated significantly different based on Duncan's Multiple Range Test (DMRT) at α = 0.05.

commercial-size (WCS) roots (Table 5). The NCS and WCS root characteristics indicated high correlations, with Pearson's correlation coefficient 0.79 at $P < 0.01$ (Figure 3B). Moreover, the PCA-biplot analysis also showed that both traits have a strong and positive association, as indicated by their close line on the plot of Dim1 (Figure 3C). Subsequently, the low WCS roots will result in less yield potential.

The results signified that the cassava tuberous root development at 7 MAP had yet to reach the optimum levels. Original cassava cultivars Adira-4 and Malang-4, with 10 and seven commercial-size roots/plants, yielded the highest NCS roots, and cultivar UJ-5 yielded the lowest (three commercial-size roots/plant). At 66.5 t ha^{-1} (Table 5) – the cassava Adira 4 cultivar at 7 MAP yielded the highest WCS roots. The cassava cultivars Malang-4 and Ratim also gave high yields, with 38.4 and 49.9 t ha^{-1}, respectively (Table 5). Meanwhile, the potential yield of cassava cultivars Gajah and UJ-5 are only 22.1 and 26.5 t ha^{-1}, respectively (Table 5). The low yield potential of cassava cultivar Gajah at 7 MAP might refer to its late maturity, as the proper harvesting time is supposedly at 12 MAP (Subekti *et al.,* 2017).

The potential root yield at 7 MAP of the advanced mutants could rise by increasing the proportion of NCS roots, especially since some selected mutants yielded more roots (NR) per plant. Still, only a few portions are commercial-size roots. The low proportion of NCS roots at 7 MAP is because of the dry matter accumulation that has yet to achieve the optimum level (Miranda *et al.,* 2019). Modifying cultivation practices might increase the ratio of NCS roots to the NR per plant.

Moreover, the positive correlation among all yield components indicates that increasing a yield component should boost other factors. Therefore, the increased proportion of NCS roots will raise yield potential at 7 MAP. However, further studies are necessary to confirm this hypothesis.

Increasing NCS roots can succeed by optimizing cultivation practices, such as N and K fertilizer applications (de Oliveira *et al.,* 2017; Chua *et al.,* 2020). A maximum application level of 226 kg N ha^{-1} (de Oliveira *et al.,* 2017) and 120 kg K ha^{-1} (Chua *et al.,* 2020) effectively increases root weight in early-harvest cassava cultivation. In this study, urea at 200 kg ha^{-1} supplied the N nutrient, and KCl at 150 kg ha^{-1} supplied the K nutrient. Under such fertilizer application, the N supply was still lower than the suggested level. Hence, applying more N fertilizer to cultivate selected advanced mutants should increase the NCS roots. Reports have indicated that optimized fertilization practices boosted the cassava yield (de Oliveira *et al.,* 2017; Chua *et al.,* 2020; Enesi *et al.,* 2022).

Moreover, N, P, and K uptake has positively associated with the root yield at 7 MAP. Thus, nutrient uptake efficiency should contribute to cassava breeding programs to select genotypes with early-harvesting and high-yielding characteristics (Suja *et al.,* 2010). Deploying the desirable cassava cultivars with effective cultivation methods still needs further studies for successful early-harvesting and high-yielding cassava production.

Six advanced mutants came from the cassava cultivar Gajah (GJ-7, GJ-10, GJ-11, GJ-13, GJ-14, and GJ-16), which yielded the WCS roots of around 4.0 kg/plant, and their potential yield is more than 30.0 t ha^{-1}. Moreover, the yield potential of the advanced mutants ML-20 and ML-21 (over 30.0 t ha^{-1}) is also higher than the original cassava cultivar Malang-4 (Table 5). The advanced mutant RTM-25 and RTM-26 can yield 42.7 and 31.7 t ha^{-1} WCS roots, respectively, and the advanced mutant ADR-24 can also yield 33.0 t ha^{-1} WCS roots (Table 5). The cassava genotypes above 30.0 t ha^{-1} at 7 MAP are candidates for the early-harvest and high-yielding cassava variety (Nedunchezhiyan *et al.,* 2006).

Results of the evaluation indicated that some of the advanced mutant arrays show reduced root yield, especially for the mutant genotypes derived from cassava cultivars Adira-4, Malang-4, and Ratim, categorized as very high-yielding. Although the evaluated advanced mutants of cassava yielded fewer NCS roots than the original cultivars, the WCS roots from 11 mutant genotypes harvested at 7 MAP are more than 30 t ha^{-1}. Therefore, according to criteria developed by Nedunchezhiyan *et al.* (2006), the selected advanced-generation mutant genotypes could create new high-yielding and early-harvesting cassava cultivars.

The assessment also implied that some cassava-advanced mutant arrays show increased root yields, especially for those derived from cassava cultivars Gajah and UJ-5. The original cassava cultivars Gajah and UJ-5 have a low-yielding category at 7 MAP (Table 5). However, the identified advanced mutants derived from the cassava cultivar Gajah yielded more NCS and WCS roots than the original cultivars at 7 MAP. Moreover, the studied advanced mutants (GJ-7, GJ-10, GJ-14, and GJ-16) yielded more than 30 t ha^{-1} NCS roots at 7 MAP, higher than the original cassava Gajah cultivar. Therefore, according to criteria developed by Nedunchezhiyan *et al.* (2006), the selected advanced mutant genotypes can also be beneficial as new high-yielding and early-harvesting cassava cultivars.

Increased or decreased yield is common among mutants derived from irradiation mutagenesis. The findings reported in this research support the previously released outcomes by Sholihin *et al.* (2019). Nine mutants (ADR-24, GJ-7, GJ-10, GJ-14, GJ-16, ML-18, ML-19, ML-20, and RTM-26) yielded WCS roots of more than 30.0 t ha^{-1}, and two mutants (ML-21 and RTM-25) yielded even more than 40.0 t ha^{-1} (Table 3). Therefore, such advanced mutants yielded cassava roots equal to or even higher than the suggested cassava cultivars intended for early harvesting in other countries. The early-harvesting cassava genotypes developed in Thailand yield as much as 28.2 t ha^{-1} cassava roots at 7 MAP (Polthanee *et al.,* 2014), in Uganda - 18.8 t ha^{-1} at 7 MAP (Tumuhimbise *et al.,* 2015), in India - 38.3 t ha^{-1} at 6 MAP (Suja *et al.,* 2010), and in Malawi - 17.8 t ha^{-1} at 9 MAP (Chipeta *et al.,* 2016). The potential yield of advanced mutants reported in this study is also higher than the reported national cassava productivity in Indonesia in 2020, which is 26.1 t ha^{-1} (FAO, 2021).

The PCA-biplot analysis only ran for the 11 advanced mutants and the original cultivars, which have yield potential ≥ 30.0 t ha^{-1}, and the results group them into four groups (Figure 3C). The first group yielded 11–17 total roots, 6–10 NCS roots, and 4–8 kg WCS roots (Table 5). The evaluated genotypes of the first group included the original Adira-4, Malang-4, and Ratim and advanced mutant ML-21. These genotypes have the potential to develop as early-harvesting and high-yielding varieties. The second group yielded 10–11 total roots, 4–6 NCS roots, and 4–5 kg WCS roots (Table 5). The evaluated genotypes belonging to the second group included ADR-24, GJ-10, GJ-14, ML-19, ML-20, and RTM-25 advanced mutants. The third group yielded 13.0–16.7 total roots, with only 4–6 NCS roots, including GJ-6, GJ-17, and RTM-26 advanced mutants (Figure 3C). The fourth group yielded 10 total roots, 3.7 NCS roots, and 3.8 kg WCS roots, including the ML-18 advanced mutant (Table 5).

CONCLUSIONS

Nine advanced mutants (M1V8), including ADR-24, GJ-7, GJ-10, GJ-14, GJ-16, ML-18, ML-19, ML-20, and RTM-26, yielded over 30.0 t ha^{-1}, while two mutants, ML-21 and RTM-25, yielded over 40.0 t ha^{-1} of commercial-size roots. Although their yield potential at 7 MAP is high, a notable disparity exists between the proportion of harvested commercial-size roots and the total root numbers. It indicates opportunities to increase their commercial-size root yield by optimizing cultivation standards. Positive correlations among yield components also suggest opportunities to enhance commercial-size roots and yield potential. Among the 11 early-harvesting and high-yielding cassava mutants, GJ-10, GJ-14, GJ-16, ML-21, and RTM-26 are preferable for their sweet root taste, presenting promising candidates for release as new cultivars with early-harvesting and low HCN content.

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